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I dedicate this dissertation to my family

With my heartfelt appreciation for their endless support

تقدیم به پدر، مادر، و ، همسرم

که با عشق و پشتیبانی در تمام مسیر زندگی به من امید و انگیزه تلاش و پیشرفت داده اند

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Abstract

This dissertation is comprised of three essays on energy and environmental economics. The first two essays of this dissertation examine sectoral energy consumption in the State of Hawaiʻi. My first essay focuses on the intermediate demand for energy consumption by economic sectors. I model Hawaiʻi's economy in a computable general equilibrium (CGE) framework and follow the footprint of efficiency improvement in the economy by looking at the energy flows in Hawaiʻi's economy. Assuming a "free" technological change becoming available to firms, this essay ranks the economic sectors with respect to their saving potential. While there are currently some energy efficiency rules and incentives in place, this essay provides insights to design alternative sector-specific energy efficiency policies that could help to achieve the State's goals. My results identify hotels, construction, accommodations, restaurants, and retail trade as the key sectors to be targeted for a successful sector-specific energy efficiency program. The above-mentioned sectors together comprise 56% of total potential reduction in energy use and GHG emissions in Hawaiʻi's economy.

In the second essay, I turn my attention to final energy consumers, contributing toward the understanding of electricity and fuel use associated with residents and visitors of Hawaiʻi. Using an Input-Output model, I analyze the difference in total energy consumption—both direct purchases and indirect demand for energy through purchases of other goods and services—of residents and visitors. I run the same analysis using both 2007 and 1997 data set to compare the consumption pattern change over time. My results show that on a per-capita basis, residents tend to consume more electricity through spending on health services, real estate rentals, professional services, and trade, while top visitor electricity-intensive expenditures include hotel, restaurants, trade (shopping), and tourism services (museums, tours and travel agencies). The results for 1997 and 2007 show a remarkable difference between residents and visitors: while total demand for fuels and electricity increased by 18% and 33%, respectively, for residents, they both fell by 4% and 9%, respectively, for visitors. Adjusting for population change, per-capita results reveal the same pattern but different magnitudes. Therefore, I conclude that the tourism industry has improved efficiency in both fuel and electricity usages by decreasing energy intensity of their

activities over the observed decade. During the observed 10-year period, energy-use visitor factor dropped for fuel from 3.5 to 2.5 (a 28% drop) and for electricity from 2.4 to 1.5 (a 38% drop). Finally, to assess the underlying driving forces influencing the observed changes in energy consumption in Hawai‘i, I used a decomposition methodology to explain the changes in sectoral energy demand between 1997 and 2007 in terms of activity, structure, and intensity effects. The findings indicate that the activity effect contributed greatly to the observed growth in energy consumption, that the structural effect was small, and that the reduction in energy intensity by sector was a clear signal of improvement in energy efficiency.

Finally, in my third essay, I look into the controversial topic of climate policy under uncertainty. The literature on hybrid climate policy could be divided in two groups: studies of one group discuss the welfare-enhancing features of hybrid policies in a qualitative framework, while the others compare the policies by measuring welfare loss in a stochastic dynamic setting. My third essay seeks to contribute to the literature by providing a theoretical welfare analysis for optimal hybrid policy under uncertainty. Moreover, I contribute to the U.S. climate policy literature using a numerical example. In this essay, I bypass the conventional price and quantity mechanisms and focus on the two common hybrid policies: Two-Step Carbon Tax as a price-driven mechanism, and Cap-and-Trade with Allowance Reserve, as a quantity-driven mechanism. I first solve for the optimal policy parameters in the context of climate change and then set the model's parameters to U.S.-specific values to quantify the solutions and compare them with respect to their expected welfare loss. The numerical analysis ranks the two-step tax policy above the cap-and-trade with allowance reserve in terms of social welfare loss, given the same cost and uncertainty parameters.

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1.1 Introduction

Background and Motivation

For decades, rapidly rising greenhouse gas emissions and its potential outcomes, including global warming and other aspects of climate change, have triggered policy responses aimed at mitigating the environmental externality. In 2007, in recognition of the significant local impacts from global climate changes, Hawai‘i became the second state in the U.S. to adopt regulatory legislation (Act 234 of 2007) similar to the Kyoto protocol, to reduce greenhouse gas (GHG) emissions to 1990 levels by 2020 (State of Hawaii, 2007). With over 90% of Hawai‘i’s greenhouse gas emissions attributable to energy sources[1] (UHERO, 2009), the path to a low-carbon economy depends upon energy efficiency, demand-side management, and renewable energy technologies. In recognizing the steps towards achieving a clean future for Hawai‘i, in 2008 the State of Hawai‘i signed an MOU with the U.S. Department of Energy for the Hawai‘i Clean Energy Initiative (HCEI) with the goal of decreasing energy consumption through increased energy efficiency (up to 30%) and increased share of renewable energies (up to 40%) in Hawai‘i’s energy supply in order to meet the 70% clean energy target of Hawai‘i’s projected demand by 2030. The two targets were enacted into law in the following years.[2]

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[1] GHG emissions are typically grouped into two main source categories: energy sources and non-energy sources. Emissions from energy sources typically occur from stationary combustion (i.e., fuel combustion in stationary equipment such as boilers, furnaces, burners, turbines, heaters, incinerators, engines, flares, etc.) and mobile combustion (i.e., fuel combustion in ground, marine, and air transportation). Non-energy sources include some industrial processes (with certain chemical reactions that produce GHG emissions from), agriculture (e.g., livestock such as cows, agricultural soils, and rice production), and land use and forestry—which could act as a sink or a source of GHG emissions.

[2] Hawai‘i enacted legislation (HB 1464) in June 2009 that established an Energy Efficiency Portfolio Standard (EEPS). Although a renewable portfolio standard was originally enacted in 2004 (SB 2474), Hawai‘i expanded the RPS in 2009 (HB 1464) to meet the goals established by the Hawai‘i Clean Energy Initiative in 2008.

Although a reasonable target is necessary to motivate the government and policymakers to act, it is not sufficient for a cost-effective solution to achieve the goal. Hence, Act 155 of 2009, which calls for creating an Energy Efficiency Portfolio Standards (EEPS) with a goal of 4.3 terawatt-hour (TWh) reduction in electricity use by 2030, also directs the Hawai‘i Public Utilities Commission (PUC) to establish incentives and penalties that promote compliance. To establish the right set of incentives, however, especially financial incentives that require government expenditures and subsidies (e.g., energy efficiency programs), policymakers require micro-level information on the economic structure to guide them on which technologies and sectors to target, where the potentials are, and where the highest possible return to those investments (i.e., government money spent on financial incentives) are. This information is not currently available to the policymakers and the stakeholders who run the efficiency programs. This study seeks to fill this gap by identifying the energy saving potential from increase in energy efficiency at sectoral level and provide policymakers with such information to help the state achieve their goal in the most cost-effective way.

Informing policymakers of the potential energy savings by economic sectors is especially important to help them evaluate the possibilities of reaching the targets. It would also enable them to design sector-specific energy efficiency policies, to reduce costs and enhance the results of those programs. An example of how such information is valuable is with China’s Top-1000 Energy-Consuming Enterprises Energy-Efficiency Program (Top-1000 program) launched in 2006. They are trying to reach the highest possible energy savings in the industrial sector by identifying and targeting the highest energy-consuming enterprises (Zhou, Levine, & Price, 2010). Hawai‘i’s current set of energy efficiency program incentives are technology-specific, but lack sector-specific policies (Hawaii Energy, 2013), which would incentivize sectors and businesses with the greatest potential.

Hawai‘i provides an attractive case study for energy efficiency and demand-side management. Due to the geographic isolation of its islands, Hawai‘i’s power grids are contained, with no intra-regional imports or exports. This allows for clear, traceable data on power generation and end use. Likewise, ground transportation fuels are bound to the economic activities within the state. Finally, as Hawai‘i sustains very little industrial activity and a fairly simple energy infrastructure, it provides detailed and tractable energy data.

In this paper, an integrated database of energy use and economic activity provides the basis to analyze demand-driven components of greenhouse gas emissions. Along with a CGE model, I develop carbon intensity measures for Hawaiʻi's economic sectors are developed, as well as energy and GHG emissions intensity measures for output, value added, and jobs. Greenhouse gas emissions elasticities are also calculated for energy conservation and efficiency scenarios. The carbon accounting methodology parallels that of the World Resources Institute's (World Resources Institute, 2004) standard of measuring corporate emissions across the value chain. In computing carbon intensity of sectors, I include scope 1 emissions (direct combustion of fossil fuel), scope 2 emissions (electricity use), and scope 3 energy emissions (other indirect emissions including air, maritime, and ground transportation). This approach provides a comprehensive analysis of energy-related carbon emissions. To avoid double counting, I allocate emissions based on the final demand for Hawaiʻi's output.

This paper models Hawaiʻi's economy in a computable general equilibrium (CGE) framework in order to analyze the scenario of energy (electricity) efficiency across economic sectors. Although many previous studies have setup CGE models for Hawaiʻi's economy, none of the studies have looked at the implications of energy efficiency for the State. Most of the existing literature has used CGE modeling to look at the impact of different scenarios or policies on Hawaiʻi's economy focusing on the tourism industry. The most common shocks in the previous studies are tourism- or labor-based shocks.

This paper attempts to follow the footprint of efficiency improvement in the economy by looking at the energy flows in Hawaiʻi's economy. Assuming a "free" technological change becoming available to firms, I rank the economic sectors with respect to their saving potential. I also find the general equilibrium effects of a marginal measure on Hawaiʻi's energy savings across economic sectors, possible costs imposed on the overall economy, and the associated greenhouse gas emission reduction.

Although it is certainly beneficial to look into the costs associated with efficiency improvement through capital-intensive technological change, there are many examples of how some 10% increase in efficiency could be achieved through very little or no cost production technology change, including but not limited to, planning encouraging incentives for corporate behavioral changes, minor monitoring and control instrument installations, or applying minor changes in the firms' operation mode that lead to energy conservation (e.g., airlines could increase their fuel efficiency by reducing the weight through eliminating some of their free features such as pillows and blankets during flights).

This will shed some light on how to target incentives or punitive policies to achieve a high rate of energy efficiency and conservation in the State. While there are already some energy efficiency rules and incentives in place, this paper provides insights to design alternative sector-specific energy efficiency policies that could help to achieve the State goals. Our results identify hotels, construction, accommodations, restaurants, and retail trade as the key sectors to be targeted for a successful sector-specific energy efficiency program. The above-mentioned sectors together comprise 56% of total potential reduction in energy use and GHG emissions in Hawai‘i's economy.

Previous studies

CGE models have been extensively used in environmental studies of the economy. The multi-sectoral nature of CGE models along with their detailed supply side specification has made them a good fit for both environmental and economic policy analysis. It has been typically used at the national or international level. Bergman was among the first group who applied CGE modeling for simulating environmental policy impacts. Using a static CGE model of an open economy, Bergman (1991) included emissions and emission control activities in his model to estimate the general equilibrium impacts of an emission control on the Swedish economy. Several years later, he reviewed and discussed in specific the CGE modeling as a tool for analysis of environmental policy and natural resource management issues, dividing this branch of CGE models into two major groups: "Externality CGE Models" and "Resource Management CGE Models" (Bergman & Henrekson, 2005). He also extensively goes over the strengths and weaknesses of environmental CGE model.

> *"CGE models obviously rest upon strong assumptions about optimizing behavior, competitive markets, and flexible relative prices. In addition lack of data usually prohibits econometric estimation of key supply and demand parameters. In view of this the validity and usefulness for policy evaluation of the results generated by CGE models might be, and often is, seriously questioned. However, there is no general answer to the question about what CGE models are good for. The usefulness of a carefully designed and implemented CGE model depends on what it is intended for and what the alternatives are."* (Bergman & Henrekson, 2005)

There are also an increasing number of regional CGE models that have tried to address environmental issues. Since Hawai‘i is truly a small open economy with highly-detailed data available on the economic sectors’ activity levels and output, it is an ideal island example for modeling and so, several studies have used the CGE modeling framework to analyze the impacts of various policies on this economy, more focusing on the tourism industry, which is one of the two main components of Hawai‘i’s economy[3].

Konan and Kim (2003) studied the economic impact of the transportation sector in Hawai‘i under a number of alternative scenarios. They developed a CGE model of the economy with a specialcus on transportation and modeled the effects of both an increase and a decrease in visitor expenditures due to the leading role of tourism in Hawai‘i’s economy. In another paper (Kim & Konan, 2004), they estimated direct and indirect demand for urban infrastructure (water, wastewater, electricity, propane, and solid waste, etc.) under alternative scenarios for population growth and visitor spending in Hawai‘i, using a CGE model. This paper uses their methodology of estimating direct and indirect demand for energy.

Konan et al. (2007) also traced the visitor economic activity through Hawai‘i’s economy using a CGE model. They simulated the changing sector-level economic activity, infrastructure demand, and greenhouse gas emissions resulting from a million dollar increase in nominal visitor expenditures, taking into account both direct and indirect visitors’ expenditures.

Konan (2011) used a regional CGE model for Hawai‘i’s economy to examine the impacts of visitor expenditure growth and labor migration on Hawai‘i’s economy. The purpose was to show how regional welfare, price levels, and production responded to alternative labor market rigidity scenarios.

In her doctoral dissertation, Coffman (2007) developed a CGE model of Hawai‘i’s economy, based on the 131-sector 1997 Hawai‘i State Input-Output Study, and analyzed the impacts of different scenarios; a 10% reduction in nominal visitor expenditures (Essay 1); a

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[3] Tourism and Military are the two top main industries in Hawai‘i’s economy.

sudden upward jump in world oil prices (Essay 2); and a set of nine scenarios, including a 10% fuel tax on petroleum manufacturing output, a 10% fuel tax on both petroleum manufacturing and electricity generation outputs, and a 50% increase in the world price of oil, each under three different cases of market competition (Essay 3).

CGE modeling, however, has not been much used for energy efficiency analysis in the U.S. in general and Hawai‘i in specific. In contrast, there have been several studies done mainly for European economies, looking at the economy-wide effects of energy efficiency improvements (Allan, Hanley, McGregor, Swales, & Turner, 2007; Barker, Ekins, & Foxon, 2007; Hanley, Mcgregor, Swales, & Turner, 2006; Turner & Hanley, 2010).

Before reviewing some of the mainstream research on the economic impact of energy efficiency, it is worth to define ‘energy efficiency’ as it has been considered in this paper. As a generic term, ‘energy efficiency’ refers to using less energy to produce the same amount of output, work, or utility. Therefore, there are different measures such as thermodynamic indicators, physical indicators, or economic indicators. In each of those contexts, energy efficiency is usually defined as the ratio of energy use per unit of output, work, or utility (Patterson, 1996; Sorrell, 2007). Hence, what usually is implied by using the term ‘energy efficiency’ is ‘improved energy efficiency’. In this paper, energy efficiency is measured with an economic indicator: energy per unit of output measured in dollar. This puts our definition in line with the common definition used in other economic studies. It is also important to note the difference between energy efficiency and economic efficiency. Maximizing economic efficiency does not necessarily imply maximizing energy efficiency. While the former implies cost minimization, the later, which is more a physical than economic concept, often comes at a cost.

Allan et al. (Allan, Gilmartin, Turner, McGregor, & Swales, 2007) identified and reviewed a series of eight CGE modeling studies that simulate energy efficiency improvements (Allan, Hanley, Mcgregor, Swales, & Turner, 2006; Dufournaud, Quinn, & Harrington, 1994; Glomsrød & Taoyuan, 2005; Grepperud & Rasmussen, 2004; Hanley et al., 2006; Semboja, 1994; Vikström, 2004; Washida, 2004). The existing literature focused on the possibility and magnitude of “rebound,” which refers to the case when energy consumption decreases less than the increase in energy efficiency, both in percentage and absolute terms (Greening, Greene, & Difiglio, 2000). Although the models in the reviewed studies differed widely in many aspects (such as the region of study, model nesting structure and parameters, or even the way they introduced energy and energy efficiency into their model), all of them found the economy-wide rebound effects to be larger than a minimum of 37%,[4] with some of them finding very large rebounds (greater than 50%) or even backfire, which is when energy consumption actually increases following the energy efficiency improvement (Greening et al., 2000). It is important to note that, similar to this study, the results of all reviewed CGE models in their paper relied upon energy efficiency improvements by producers only. So, the results neither count toward efficiency improvements by consumers nor take into account the impact of inputs' productivity improvement on energy efficiency. It is also worth mentioning that none of these studies primarily focused on emission reduction potential of energy efficiency measures in the economy, which is what has been done in this study.

1.2 Data: Energy, Emission, and the Economy

Hawai'i's mild tropical climate provides favorable conditions for energy conservation, as many homes are not designed with home heating or cooling. In 2010, Hawai'i's per capita electricity consumption (20 kWh per-day per-person on average) ranked second lowest, however, having the most expensive electricity in the nation, it is ranked number two in the U.S. in total electricity expenditures per capita (EIA, 2013). That said, the main driver for electricity conservation in the State of Hawai'i is not energy saving per se, but rather the high price of electricity—$0.34 per kilowatt hour versus $0.10/kWh nationally (EIA, 2013).

The primary concern of this study is in obtaining estimates of carbon emissions savings to be achieved from improving efficiency of electricity consumption. To facilitate this, baseline data are assembled on Hawai'i's economy, energy infrastructure, and greenhouse gas emissions. Since the latest comprehensive input-output data was developed

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[4] The magnitude of the rebound effect is measured by how much the reduction as a result of efficiency increase is offset by the increase as a result of lower price. For example, when expressed in percentage terms, a rebound effect of X% implies that a Y% increase in efficiency would only result in (100-X)Y% reduction in consumption. Hence, a 50% rebound effect occurs when a 10% increase in efficiency results in a 5% reduction in consumption.

for year 2007, it is selected as the baseline year. Yet, the fundamental features of the economy (sectoral structure) have been relatively consistent over the past few years.

The U.S. Department of Energy (EIA, 2013) estimated that nearly nine-tenths of Hawai'i's energy derives from petroleum products. This heavy reliance on petroleum is related to an energy infrastructure that has developed historically to provide capacity for air transportation. Two local refineries, located on the island of Oahu, have the facility to process 147,500 barrels of oil per day, obtaining crude oil imported largely from Asia and the Middle East and converting it into jet fuel, motor gasoline, diesel fuel, and other petroleum products. An important bi-product of the refineries' cracking process is a low-grade residual fuel oil, which has become the primary fuel for the generation of electricity.

Table 1.1: Fuel use by sector in Hawai'i, 2007 (Trillion BTUs)

Fuel \ Sector	End-use Residential	 Commercial	 Industrial	 Transport.	Total	Electric Power	Total (w/ Power)
Coal	-	-	1.8	-	**1.8**	17.2	**19.0**
Natural Gas (SNG)	0.5	1.9	0.5	-	**2.9**	-	**2.9**
LPG	0.4	0.8	0.2	-	**1.4**	-	**1.4**
Aviation Gasoline	-	-	-	0.2	**0.2**	-	**0.2**
Jet Fuel	-	-	-	72.3	**72.3**	-	**72.3**
Gasoline	-	0.1	1.3	57.9	**59.3**	-	**59.3**
Diesel	-	1.6	2.6	36.4	**40.6**	13.5	**54.1**
Fuel Oil	-	-	2.7	28.1	**30.8**	71.8	**102.6**
Other fuels*	-	-	16.0	0.4	**16.4**	-	**16.4**
Total Fuel	**0.9**	**4.4**	**25.1**	**195.3**	**225.7**	**102.5**	**328.2**
Electricity	10.9	12.0	13.2	-	**36.1**	N/A	N/A
Grand Total	**11.8**	**16.4**	**38.3**	**195.3**	**261.8**	**N/A**	**N/A**

* Includes asphalt and road oil, kerosene, lubricants, and the 16 other petroleum products as described in the Technical Notes, Section 4, "Other Petroleum Products."

Source: U.S. Department of Energy, Energy Information Administration, SEDS (EIA, 2013).

This analysis entails the compilation of data on fossil fuel use, greenhouse gas emissions, and economic activity. Table 1.1 summarizes fuel consumption by four major end-use sectors as well as fuel use for power generation; it also presents electricity use by sector. The data is obtained from the U.S. Department of Energy's EIA. Given Hawai'i's geographic isolation, jet fuel is the most significant component of the end-use fossil fuel profile. Residual fuel oil, however, is primarily used for electric power generation and, to a lesser extent, for maritime transportation. Gasoline is primarily used for highway purposes[5]. Diesel fuel uses include maritime travel, some electricity generation, and commercial and industrial activities. At only 19 trillion BTUs per year, coal as an energy fuel is relatively insignificant.

Hawaiʻi's emissions were determined for three major greenhouse gases: carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). The Intergovernmental Panel on Climate Change (Eggleston, Buendia, Miwa, Ngara, & Tanabe, 2006) established reporting tiers for the computation of greenhouse gas emissions, with tier 1 reflecting 'default' calculations. Emissions estimates are derived from fuel combustion based on national and regional energy statistics and Hawaiʻi specific emissions factors determined by fuel characteristics. Greenhouse gas emissions factors were obtained from the U.S. Energy Information Administration (2007) and reconciled with previous inventory estimates. A complete GHG profile for Hawaiʻi is available online (UHERO 2009).

Transportation leads Hawaiʻi's energy use due largely to high consumption of jet fuel for military installations and commercial airlines. Vehicle fuel consumption rates on a per capita basis are among the lowest in the nation (EIA, 2013). The geography of the islands and population density results in relatively short commuting distances.

Petroleum-fired power plants supply around 75 percent of Hawaiʻi's electricity generation. Coal and a suite of renewable energy sources including hydroelectricity, geothermal, landfill gas, and other biomass round out Hawaiʻi's electricity generation. Hawaiʻi is the only place in the United States that produces synthetic natural gas (SNG) and its consumption is largely commercial (hotels, restaurants, laundry).

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[5] Agricultural sector and small boats consume some small volumes of gasoline.

Table 1.2: Output, employment, value added, and job count, 2007

Sector	**Output** **$ million**	**Employee Compensation** **$ million**	**Value Added** **$ million**	**Job Count**
Crops production	184	61	100	5,098
Fruits, vegetables, and flowers	319	106	174	7,638
Animal production	47	16	26	982
Aquaculture, forestry, and logging	62	21	34	561
Commercial fishing	106	35	58	1,662
Mining	57	30	19	736
Construction	10,046	2,842	4,351	51,641
Petroleum manufacturing	4,668	72	365	470
Clothing manufacturing	332	29	38	1,718
Food processing	1,377	274	288	7,703
Other manufacturing	2,184	367	452	9,167
Air transportation	2,866	533	1,185	9,935
Water transportation	839	246	404	4,754
Ground transportation	220	62	97	4,568
Trucking	451	171	266	3,954
Warehousing and storage	60	35	43	948
Scenic and support activities for transportation	804	362	606	8,272
Information	2,778	772	1,751	14,576
Electricity generation	2,320	276	1,182	2,718
Natural gas	243	32	157	610
Wholesale trade	3,103	1,025	2,022	22,301
Retail trade	7,086	2,314	4,562	89,090
Rental, leasing, and others	1,462	168	1,215	5,668
Accommodations	14,425	480	10,319	34,690
Hotels	5,678	2,067	3,643	40,304
Restaurants	3,755	1,363	1,898	62,093
Fin., bus., prof. services	12,284	4,738	7,709	129,266
Travel reservations	484	199	263	6,478
Waste management services	336	98	174	1,919
Education	870	544	625	17,993
Hospitals	2,862	919	1,029	14,597
Other health services	3,903	2,107	2,787	55,835
Arts and entertainment	964	406	680	22,837
Personal and laundry services	993	304	453	24,209
Repair and maintenance	677	208	310	10,177
Organizations	1,571	608	906	16,363
State and local government	6,502	5,021	5,537	90,060
Federal government	8,935	7,773	8,485	86,280
Total	105,851	36,685	59,011	867,871

Source: Department of Business, Economic Development, and Tourism (2013).

The primary economic data used in this study come from the 2007 State Input-Output Study for Hawaiʻi (DBEDT, 2013). Intermediate and final demand values are provided for Hawaiʻi's economy at a disaggregation of 68 sectors, thus providing a detailed description of agricultural, manufacturing, and services production in Hawaiʻi. While the model calibration uses disaggregated data, for purposes of reporting, I present the findings at an aggregated 38-sector level.

Table 1.2 decomposes production costs into total output costs, employee compensation, and total value added. Hawaiʻi is a services-oriented economy, with very little manufacturing activity. Real estate (accommodations), business and professional services, government, construction, trade, and health are key economic sectors in terms of output and employment. The visitor industry is a major employer, as reflected in job counts in hotels, restaurants, retail trade, and various entertainment services. Government employment accounts for 20% of jobs and 35% of employee compensation.

1.3 Model

Using the same I-O data, described in section 2, a Computable General Equilibrium (CGE) Model is developed. CGE models solve for the equilibrium in the Arrow-Debreu Equilibrium framework (Arrow & Debreu, 1954), based on the Walrasian general equilibrium structure. Hence, the convexity of the production and expenditure sets implies existence and uniqueness of the equilibrium price vector, which clears the market, given maximizing behavior of producers and consumers and a perfectly competitive market.

A schematic representation of Hawaiʻi's general equilibrium is shown in Figure 1.1. In this model specifically, Hawai`i is assumed as a small and open economy, in which visitor expenditures generate a significant share of foreign exchange. Visitors' consumption bundle consists of goods and services, most of which are not importable such as transportation, hotel, and restaurant services. Production is assumed to be perfectly competitive using constant returns to scale technologies. Households, visitors, various government entities, and exports are sources of final demand, and prices are calibrated to clear markets.

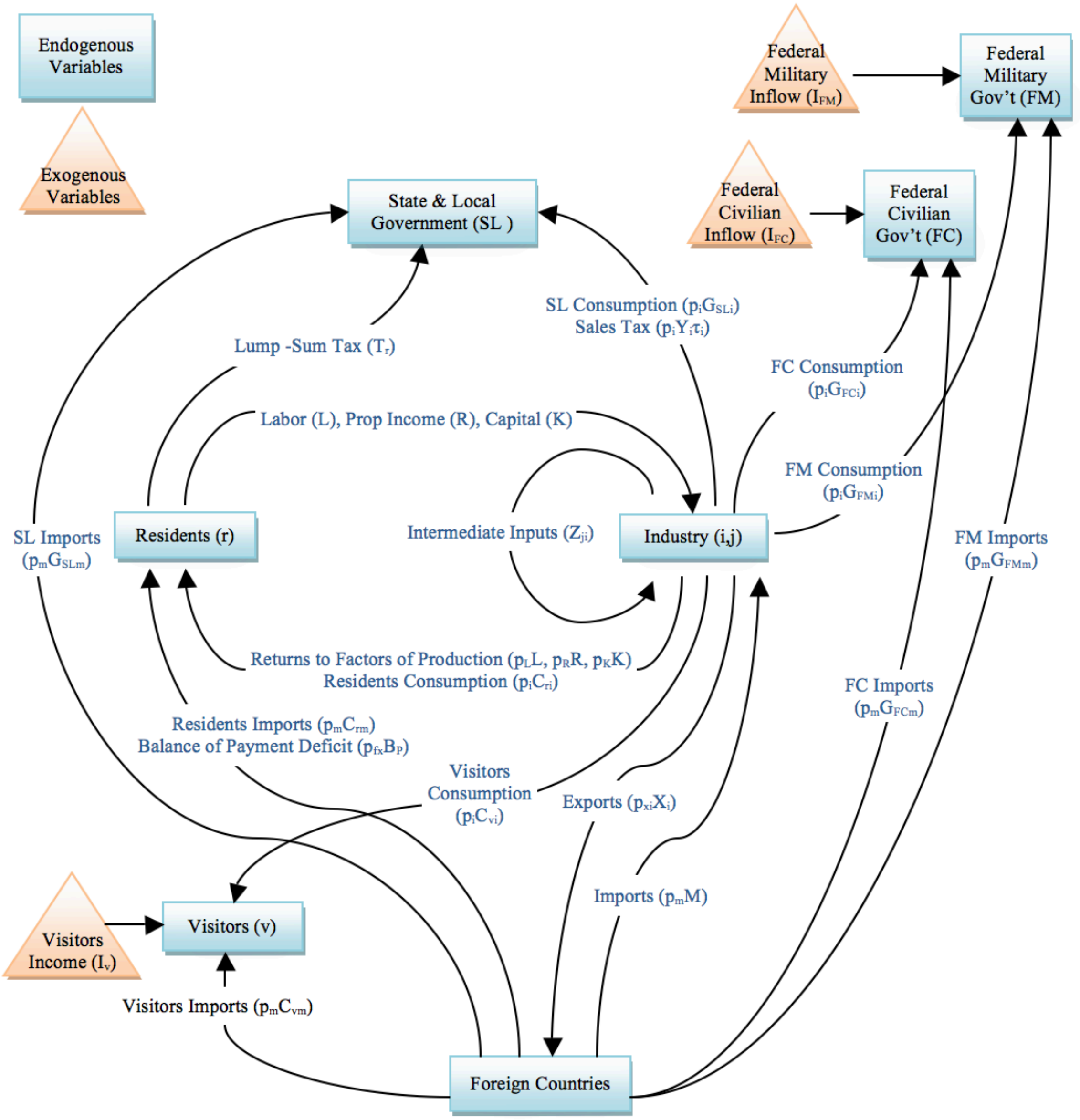

Figure 1.1: General equilibrium model of Hawai'i's economy (Konan, et al. 2007)

The approach assumes that standard equilibrium conditions are satisfied such as no excess demand for all goods and services and that all agents' expenditure equals income and in overall, the economy is in balance. The model is estimated numerically using the GAMS (General Algebraic Modeling Systems) software and the MPSGE platform (Rosenthal, 2012; Rutherford, 1999).

Production

Final output in sector i (Y_i) is produced according to a nested Leontief function, shown in Figure 1.2. In this setup, value added (V_s) is composed of capital (K_s), labor (L_s), and proprietor income (R_s) and intermediate input is made up of tradable inputs (ST_{ki}) and non-tradable inputs (SN_{ji}), which include energy inputs.

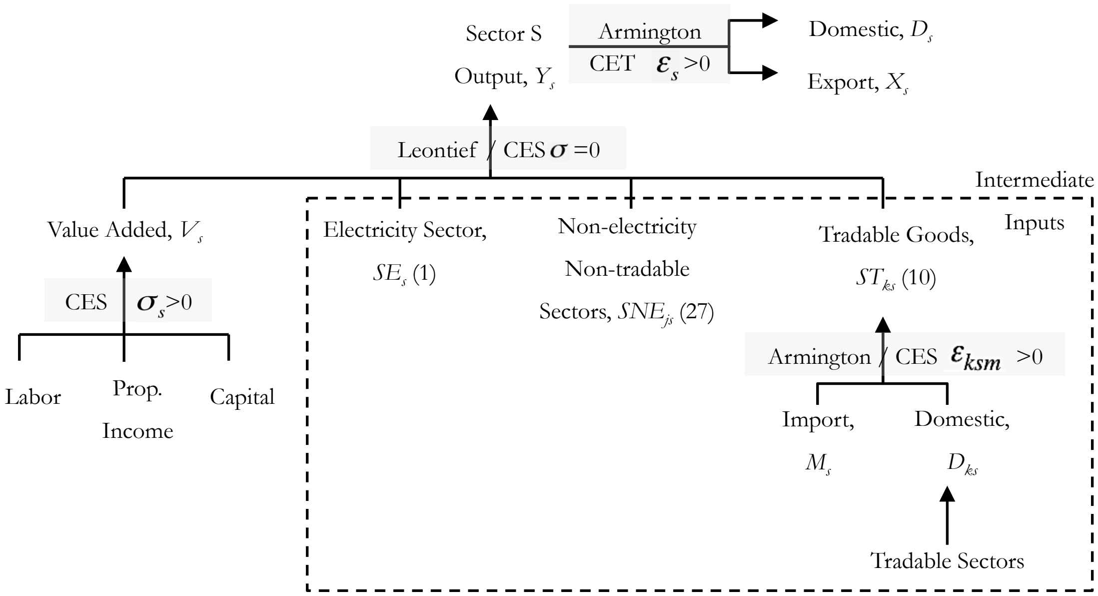

Figure 1.2: Nesting of the production function

For the purpose of modeling efficiency in using electricity in different production technologies, electricity sector (SE) is separated from other non-tradable sectors. The remaining non-electricity non-tradable sectors (SNE_{ji}) include other energy sectors (petroleum manufacturing, and gas production and distribution) and key service sectors (hotels, restaurants, health and other services). All other sectors in the economy (agriculture, commercial fishing, clothing manufacturing, food processing, etc.) are categorized as tradable sectors.

At the first level, a Leontief production function (zero elasticity of substitution) represents final output (Y_s) in sector s:

$$Y_s = \min\left[\frac{(1-\eta_s)SE_s}{\alpha_{Es}}, \frac{SNE_{1s}}{\beta_{1s}}, \cdots, \frac{SNE_{(J-1)s}}{\beta_{(J-1)s}}, \frac{ST_{1s}}{\gamma_{1s}}, \cdots, \frac{ST_{Ks}}{\gamma_{Ks}}, \frac{V_s}{\alpha_{Vs}}\right] \tag{1}$$

where $\alpha_{Es}, \beta_{js}, \gamma_{ks}$, and α_{Vs} are unit input coefficients for intermediates (electricity, non-electricity non-tradable, and tradable) and value added respectively; and η_s is the efficiency level for sector *s* used as a shock parameter for the efficiency scenario analysis.

At the second level, tradable intermediate inputs are provided by flexible domestically produced and importable commodities represented through an Armington[6] (1969) constant elasticity of substitution (CES) production nest:

$$ST_{ks} = \left[\theta_{Dks} D_{ks}^{\frac{(\varepsilon_{ksm}-1)}{\varepsilon_{ksm}}} + \theta_{Ms} M_s^{\frac{(\varepsilon_{ksm}-1)}{\varepsilon_{ksm}}} \right]^{\frac{\varepsilon_{ksm}}{(\varepsilon_{ksm}-1)}} \tag{2}$$

where ε_{ksm} is the CES substitution between domestically produced good k and imports by producer s; D_{ks} is sector k demand by producer s for domestically produced goods; M_s is imported demand in sector s; and parameter shares are represented by θ_{Dks} and θ_{Ms}, respectively.

Value added is formed through another CES nest:

$$V_s = \left[\alpha_{Ls} L_s^{\frac{(\sigma_s-1)}{\sigma_s}} + \alpha_{Ks} K_s^{\frac{(\sigma_s-1)}{\sigma_s}} + \alpha_{Rs} R_s^{\frac{(\sigma_s-1)}{\sigma_s}} \right]^{\frac{\sigma_s}{(\sigma_s-1)}} \tag{3}$$

where σ_s is the CES among value added variables and α_{Ls}, α_{Ks}, and α_{Rs} are corresponding parameter shares.

Output commodity Y_s can either be consumed domestically or exported and, under the Armington assumption, is differentiated for those markets using a constant elasticity of transformation (CET) function between domestic (D_s) sales and exports (X_s).

$$Y_s = \left[\beta_{Ds} D_s^{\frac{(\varepsilon_s-1)}{\varepsilon_s}} + \beta_{Xs} X_s^{\frac{(\varepsilon_s-1)}{\varepsilon_s}} \right]^{\frac{\varepsilon_s}{(\varepsilon_s-1)}} \tag{4}$$

where ε_s is the elasticity of transformation; and β_{Ds}, and β_{Xs} are parameter shares.

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[6] Armington assumption implies goods are differentiated by country of origin.

Electricity Efficiency

Calibrating the model using the benchmark data, it is assumed that the production functions' parameters are set reflecting status quo technologies. As equation 1 suggests, $\eta_s\%$ increase in electricity efficiency is modeled by assuming that production technologies are improved to consume $\eta_s\%$ less electricity compared to the benchmark data when producing the same amount of output.

The scenarios considered in this paper are 1) the adoption of a 10% efficiency increase in electricity consumption by all non-energy sectors[7], and 2) a 10% increase in electricity consumption efficiency in one sector only, assuming the same production function for the rest of economy, in order to compare savings potential of efficiency increase by sector. The latter scenario is run for all sectors except for the three energy sectors.

Consumption

On the demand side, the model reflects the behavior of Hawai'i residents (*r*) and visitors (*v*), both following utility-maximizing behavior represented by a Cobb-Douglas function.

$$U_h = \prod_{i=1}^{n} C_{hi}^{b_{hi}}, \qquad \sum_{i=1}^{n} b_{hi} = 1 \tag{5}$$

where C_{hj} and b_{hj} are consumption and income expenditure share of goods *i*, for consumer type *h* (*h* = *r*, *v*).

In addition, they consume both domestically produced goods (*i* = 1,…,*n*) and imported composite goods (*m*).

$$C_{hi} = \left[\theta_{Dhi} D_{hi}^{\frac{(\varepsilon_{him}-1)}{\varepsilon_{him}}} + \theta_{Mh} M_h^{\frac{(\varepsilon_{him}-1)}{\varepsilon_{him}}} \right]^{\frac{\varepsilon_{him}}{(\varepsilon_{him}-1)}} \tag{6}$$

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[7] For this analysis, I exclude the energy sectors—i.e., electricity, petroleum manufacturing, and gas manufacturing sectors—as I do not see these energy sectors' use of other energy sources for their output production to be the same as other economic sectors. Moreover, their potential to apply energy efficiency measures and programs might be different from what I envision in this paper for the rest of Hawai'i's economy.

where ε_{him} is the Armington CES between domestically produced good *i* and imports by consumer *h*; D_{hi} is sector *i* demand for domestically produced goods; M_h is demand by consumer *h* for the imported goods; and θ_{Dhi} and θ_{Mh} represent corresponding parameter shares.

A representative resident's budget constraint can be written as:

$$\sum_i p_i C_{ri} = p_L L + p_R R + p_K K + \overline{p}_{fx} BP - T_r \qquad (7)$$

where p_i represent the market prices for commodity *i*. The resident derives income from factors of production including labor (*L*), proprietor income (*R*), and capital (*K*), with p_L, p_R, and p_K being the market price of the respective factors. The resident also pays a lump-sum tax (T_r), net of transfer payments, to the state and local government (and thus household income is not necessarily equal to labor income because of transfers). The resident also receives foreign exchange ($\overline{p}_{fx} BP$) from a balance of payment deficit (described below in equation 11).

A representative visitor's budget constraint is expressed as: $I_v = \sum_i p_i C_{vi}$ (8)

where I_v represents visitor's income, which is taken to be exogenous.

Government

The IO table represents government activity through three branches: the state and local government (*SL*), the federal military government (*FM*), and the federal civilian government (*FC*). Federal military and civilian governments are then aggregated to form the federal government (*FG*) for the purpose of this analysis. Each government type purchases domestic commodities (G_{gi}) and imports (G_{gm}) according to a Leontief utility function to assure a constant level of public provision, where $g = SL, FG$.

The state and local government depends entirely on the economy for the tax base.

$$\sum_i p_i G_{SLi} + p_m G_{SLm} = \sum_i p_i Y_i \tau_i + T_r \qquad (9)$$

A primary source of revenue is the State's goods and services tax (τ_i) on the sales (Y_i) of commodity *i.*[8] The state and local government also impose a variety of taxes (T_r), such as property and income taxes, on residents.

Federal government inflows are assumed to adjust endogenously to assure neutral levels of federal government provision (i.e., unaffected by the shock). The federal public sector budget constraint is given by:

$$\sum_i p_i G_{FGi} + p_m G_{FGm} = I_{FG} \tag{10}$$

where the sum on the left-hand side represents the cost of public expenditures; and I_{FG} represents federal revenue inflows into the State.

Balance of Payments

A balance of external payments (*BP*) is maintained under the assumption of a fixed (to the dollar) exchange rate, where $\overline{p}_{fx}$ is the exchange rate with the "rest of the world." The quantity of imports (*M*) are constrained by the inflow of dollars obtained from visitor expenditures (I_v), federal government expenditures (I_{FG}), and Hawai'i exports (X_j). Because Hawai'i is a small open economy and thus a price taker, import and export prices are perfectly inelastic.

$$\overline{p}_{fx} BP = \overline{p}_m M - I_v - I_{FG} - \sum_j \overline{p}_{xj} X_j \tag{11}$$

Supply-Demand Balance

Constant returns to scale and perfect competition ensure that the producer price (p_j) equals the marginal cost of output in each sector *j*. In addition, the state and local government collects a general excise tax (τ_j) on sales. This implies that the value of total output (supply) equals producer costs, where p_L, p_R, and p_K equals the market price of labor, proprietor income, and capital, respectively.

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[8] In 2007, almost half of State's total tax revenue came from general excise tax (GET) while some 30% came from individual income tax (IIT). The remaining 20% came from a collection of other taxes. (Hawaii Department of Taxation, 2013)

$$p_j Y_j (1+\tau_j) = \sum\nolimits_{l=1}^{n} p_l Z_{lj} + p_L L_j + p_R R_j + p_K K_j + p_m M_{Yj} \tag{12}$$

In addition, sector *j* output, which is supplied to the domestic market (D_j), is demanded by consumers $h \in \{r, v\}$, government agencies $g \in \{SL, FG\}$, and industries $l = 1, \cdots, n$.

$$D_j = \sum\nolimits_h C_{hj} + \sum\nolimits_g G_{gj} + \sum\nolimits_l Z_{lj} \tag{13}$$

In equilibrium, the value of output balances the value of inter-industry, final consumer, and government agency demand.

Energy Consumption and GHG Emissions

Energy demand by various industries and by households and visitors (demand by final consumers) is estimated with standard techniques. The total estimated energy demand (D_i) can be expressed as follows:

$$D_i = \sum\nolimits_{k=1}^{n} d_{ik} + \sum\nolimits_y d_{iy} \tag{14}$$

where

i = type of energy,

n = number of industry sectors,

d_{ik} = demand for energy type *i* by the *k*th industry sector, and

d_{iy} = demand for energy type *i* by the the final sector, *y* = residents, visitors, gov., etc.

The total estimated energy demands (d_{ik} and d_{iy}) are then calculated as follows:

$$d_{ik} = D_i \times \rho_{ik} \quad \text{and} \quad d_{iy} = D_i \times \rho_{iy} \tag{15}$$

where

ρ_{ik} = share of *k*th industry sector in total consumption of energy type *i*,

ρ_{iy} = share of the final sector *y* in total consumption of energy type *i*, and

$$\sum\nolimits_{k=1}^{n} \rho_{ik} + \sum\nolimits_y \rho_{iy} = 1. \tag{16}$$

Shares are either assigned based on the energy source characteristic or are estimated based on the sectors' expenditure on three energy sectors (petroleum manufacturing, gas production and distribution, and electricity). For example, as aviation gasoline is only consumed by the air transportation sector, I will have:

$$\rho_{avgas,airtrnsp} = 1; \qquad \rho_{avgas,k} = 0, \quad \forall k \neq airtrnsp; \tag{17}$$

However, for gasoline as another example, the shares have been estimated based on sectoral expenditure on petroleum manufacturing:

$$\rho_{gasoline,k} = \frac{e_{k,pet}}{\sum_{k=1}^{n} e_{k,pet}} \tag{18}$$

where

$e_{k,pet}$ = k^{th} industry sector's expenditure on petroleum manufacturing sector's output.

Based on the above method, estimates for petroleum products (aggregating individual fuels), natural gas, and electricity consumption are derived, allowing for both the estimate of overall aggregate levels of demand for energy as well as estimates of per capita levels.

As described in section 1.2, the GHG emissions are then calculated by using standard methods established by the Intergovernmental Panel on Climate Change (Eggleston, Buendia, Miwa, Ngara, & Tanabe, 2006) for the computation of greenhouse gas emissions. This study achieves tier 2 accounting for stationary and mobile energy sources.

1.4 Simulation and Results

The macroeconomic measures of Hawai'i's economy are calculated and analyzed using a CGE model. The change in energy demand and associated energy intensities are calculated. Also, the GHG emissions and associated GHG intensity of sectors are computed as an aggregation of greenhouse gases in terms of carbon dioxide equivalent global warming potential over a 100-year time horizon following the methodologies established by the IPCC (Solomon et al., 2007).

Before looking at the results from the efficiency shock scenario, the levels and intensities of energy demand and GHG emissions by sectors are presented in Table 1.3 and Table 1.4, providing a pre-shock (or status quo) analysis of Hawai'i's economy.

Table 1.3. Energy intensity by economic activity, mmBTU and rank

Sector	(1) Final Energy Demand mmBTU	Rank	(2) Energy intensity (per $m output) mmBTU	Rank	(3) Energy intensity (per job) mmBTU	Rank	(4) Energy intensity (per $m value added) mmBTU	Rank
Crops production	428,213	33	2,326	14	84	26	4,072	17
Fruits, vegetables, and flowers	948,165	27	2,976	11	124	21	5,210	14
Animal production	64,447	38	1,358	21	66	29	2,378	22
Aquaculture, forestry, and logging	102,872	37	1,661	17	183	17	2,908	20
Commercial fishing	984,954	26	**9,319**	**5**	593	8	16,315	7
Mining	126,101	36	2,219	15	171	18	8,407	13
Construction	**10,498,840**	**3**	1,045	24	203	16	2,455	21
Petroleum manufacturing	7,430,660	6	1,592	18	**15,810**	**2**	**20,814**	**4**
Clothing manufacturing	3,714,448	12	**11,197**	**2**	**2,162**	**5**	**100,390**	**2**
Food processing	3,885,003	11	2,822	12	504	10	14,127	8
Other manufacturing	3,945,215	10	1,806	16	430	11	9,090	11
Air transportation	**30,991,025**	**2**	**10,814**	**3**	**3,119**	**4**	**36,460**	**3**
Water transportation	3,323,936	13	3,961	9	699	7	8,747	12
Ground transportation	1,745,158	21	7,922	6	382	12	**18,370**	**5**
Trucking	2,151,036	19	4,771	8	544	9	9,560	10
Warehousing and storage	142,911	35	2,386	13	151	19	3,324	18
Scenic and support activities for transportation	2,613,131	16	3,251	10	316	13	5,023	15
Information	773,308	28	278	35	53	31	468	35
Electricity generation	**101,264,413**	**1**	**43,640**	**1**	**37,263**	**1**	**104,669**	**1**
Natural gas	2,385,253	17	**9,831**	**4**	**3,907**	**3**	18,135	6
Wholesale trade	1,921,565	20	619	30	86	25	1,303	30
Retail trade	5,932,163	7	837	27	67	28	1,887	24
Rental, leasing, and others	546,491	30	374	34	96	22	655	34
Accommodations	**8,555,360**	**4**	593	31	247	15	883	31
Hotels	5,618,949	8	990	25	139	20	1,841	25
Restaurants	2,828,480	15	753	28	46	33	1,578	28
Fin., bus., prof. services	3,145,525	14	256	36	24	35	427	36
Travel reservations	591,921	29	1,223	22	91	23	2,327	23
Waste management services	1,723,691	22	5,123	7	898	6	10,575	9
Education	184,333	34	212	37	10	38	316	37
Hospitals	4,247,190	9	1,484	19	291	14	4,359	16
Other health services	2,230,500	18	571	32	40	34	831	32
Arts and entertainment	466,277	32	484	33	20	36	753	33
Personal and laundry services	1,383,826	24	1,394	20	57	30	3,169	19
Repair and maintenance	496,163	31	733	29	49	32	1,659	27
Organizations	1,476,140	23	939	26	90	24	1,690	26
State and local government	**7,477,708**	**5**	1,150	23	83	27	1,332	29
Federal government	1,119,050	25	125	38	13	37	132	38
Total indirect	**227,464,421**							
+ Final direct	133,399,566							
Total demand	**360,863,987**							
- Total electricity consumptio	36,100,000							
Total energy consumption	**324,763,987**							

Source: Author's estimation.

Table 1.3 presents direct and indirect energy required to produce final demand output levels by sector. Total energy used to produce, for example, health services would include direct fuel combusted (for transportation or in generators) as well as indirect energy demand from intermediate purchases of other goods and services. Thus, intermediate demand for energy is attributed to the sector responsible for final demand as an indirect energy use. Total final demand includes residential demand, visitor demand, state and local government demand, federal government demand, and exports.

The most significant final demand for energy is in the form of direct demand, 133.4 trillion BTU, which includes exports of fuel (mostly jet fuel for international air transport), residential purchases of gasoline, and military fuel. Indirect final demand for electricity implies energy demand of 101.2 trillion BTU. Domestic air transportation final demand uses 31 trillion BTUs. Construction (10.5 trillion), accommodations (8.5 trillion), government (7.5 trillion), and petroleum manufacturing (7.4 trillion) are among the highest sources of final energy demand measured in BTUs.

Column (2) in Table 1.3 provides an estimate of energy intensity, which includes direct purchases and indirect consumption of intermediates, required to produce $1 million of output for final demand. The power generation sector requires the highest intensity, with one million dollars of electricity requiring 43.6 billion BTU and clothing manufacturing stands next in line requiring 11.2 billion BTU. Other highly energy intensive sectors include air transportation (10.8 billion BTU), natural gas manufacturing (9.8 billion BTU), and commercial fishing (9.3 billion BTU). In terms of jobs, the most energy intensive sectors are electricity, petroleum, and natural gas manufacturing. Intensity per Hawaiʻi value added and respective rankings are also provided.

Table 1.4 provides information similar to that presented in Table 1.3, with greenhouse gas emissions, rather than energy intensity as the variable of interest. Overall, major greenhouse gas emitting sectors include electricity at 6.3 million metric tons of CO_2 equivalent (mmtCO_2e), and air transport at 2.3 mmtCO_2e. It is important to note that air transport emissions exclude those generated for ‘export’ of jet fuel for travel to foreign destinations.

Table 1.4. GHG intensity by sector, metric tons CO_2 equivalent and rank

	Total GHG emissions	**GHG intensity per $m output**		**GHG intensity per job**		**GHG intensity per $m value added**	
Sector	$mtCO_2e$	$mtCO_2e$	Rank	$mtCO_2e$	Rank	$mtCO_2e$	Rank
Crops production	28,961	157	14	6	22	275	16
Fruits, vegetables, and flowers	61,509	193	11	8	20	338	15
Animal production	4,150	87	19	4	27	153	21
Aquaculture, forestry, and logging	6,810	110	17	12	16	193	19
Commercial fishing	72,777	689	5	44	8	1,205	7
Mining	7,056	124	15	10	19	470	13
Construction	600,436	60	23	12	17	140	22
Petroleum manufacturing	506,012	108	18	1,077	2	1,417	4
Clothing manufacturing	263,475	794	3	153	5	7,121	1
Food processing	259,614	189	12	34	10	944	8
Other manufacturing	245,228	112	16	27	12	565	12
Air transportation	2,285,183	797	2	230	4	2,688	3
Water transportation	227,430	271	9	48	7	598	11
Ground transportation	127,473	579	6	28	11	1,342	5
Trucking	156,019	346	8	39	9	693	10
Warehousing and storage	9,500	159	13	10	18	221	18
Scenic and support activities for transportation	188,701	235	10	23	13	363	14
Information	45,163	16	34	3	29	27	34
Electricity generation	6,304,165	2,717	1	2,320	1	6,516	2
Natural gas	170,034	701	4	279	3	1,293	6
Wholesale trade	119,373	38	27	5	23	81	26
Retail trade	331,369	47	25	4	28	105	24
Rental, leasing, and others	36,211	25	32	6	21	43	32
Accommodations	518,156	36	28	15	15	53	30
Hotels	194,378	34	29	5	25	64	28
Restaurants	99,413	26	31	2	34	55	29
Fin., bus., prof. services	169,581	14	35	1	35	23	35
Travel reservations	27,682	57	24	4	26	109	23
Waste management services	117,598	349	7	61	6	721	9
Education	6,476	7	37	0.4	38	11	37
Hospitals	228,288	80	20	16	14	234	17
Other health services	123,090	32	30	2	32	46	31
Arts and entertainment	11,412	12	36	0.5	37	18	36
Personal and laundry services	71,727	72	21	3	30	164	20
Repair and maintenance	26,556	39	26	3	31	89	25
Organizations	31,649	20	33	2	33	36	33
State and local government	454,381	70	22	5	24	81	27
Federal government	60,316	7	38	1	36	7	38

Source: Author's estimation based on direct and indirect emissions.

Normalizing GHG emissions on a value basis provides quite a different ranking of relative impact. Per million dollars of final demand, the top three emitters include electricity, air transportation, and clothing manufacturing. Surprisingly, commercial fishing activity ranks fifth out of 38 economic sectors in GHG intensity and tops ground transportation. A million dollars of commercial fishing demand requires CO_2 equivalent emissions of 689 metric tons. This is owing to high fuel costs to power ships as well as onboard and onshore refrigeration. Low carbon intensity sectors include government services, education, arts and entertainments, and business and professional services.

Table 1.4 also reports the carbon intensity of an average worker. Electricity production results in 2.3 thousand metric tons of CO_2e per job. Petroleum manufacturing generates 1.1 thousand metric tons of CO_2e per job. Other high emitting employment sectors include natural gas manufacturing (279 metric tons), air transport (230 metric tons) and clothing manufacturing (153 metric tons). The education sector together with the art and entertainment sector share the position of lowest carbon intensity, with less than 0.5 metric ton of CO_2e per worker. The GHG intensity of value added is highest in electric clothing manufacturing, power generation, air transportation, petroleum manufacturing, and ground transportation.

Now, let us analyze the impacts of an efficiency shock on Hawai'i's economy. The efficiency shock, as explained in section 1.3, assumes the production of local goods becoming more efficient in using electricity as an input, a one-off step change in the production technology. It is worth mentioning that as the cost of efficiency improvement is not considered in this study, the results presented here would only be reflective of the benefits that would come about from this improvement as well as how the benefits are distributed across economic sectors. Hence, the energy prices are expected to decline as a result of a positive supply-side disturbance on energy sectors, i.e., the immediate effect of the efficiency improvement would results in excess supply of energy. However, the impact on other sector's output prices depend on their energy intensity, with those highly energy intensive sectors experiencing decline in their prices while the more labor intensive sectors sustained slightly higher prices as real wages rise. The net result of such lower energy prices across the economy supposedly stimulates economic activity and therefore higher total domestic output. Table 1.5, Table 1.6, and Table 1.7 present the post-shock results.

Table 1.5 presents both economy-wide and sectoral macroeconomic impacts of a 10% increase in electricity efficiency. As panel a of Table 1.5 suggests, the energy efficiency will have an overall positive impact on almost all macroeconomic measures as expected. The only exception is a drop in total value of exports (-0.22%), which is mainly due to a 0.9% decline in the exports of business and professional services sector (the largest exporting sector in Hawaiʻi's economy with more than 30% of total exports).

Table 1.5. Macroeconomic measures' changes, 10% efficiency increase scenario

(a) Economy-wide Impacts	
Macroeconomic Indicators	% Change
Domestic Output, nominal	+0.02
GSP, nominal	+0.01
Exports, nominal	-0.22
Consumer Price Index	+0.03
Wages, real	+0.25
Proprietors Income, real	+0.29
Capital Cost, real	+0.09
Visitor Exp's, real	+0.03
Visitor Price Index	-0.03
Lump Sum Transfer	+0.01
Value Added	+0.24
Resident Welfare	+0.27

(b) Sectoral Change in Output and Employment			
	Output Change		**Employment**
Sector	$ Million*	%	Δ Job Count
Agriculture	1.26	0.18	24
Manufacturing	10.27	0.26	53
Air Transportation	-0.52	-0.02	-8
Transportation	1.43	0.05	-3
Entertainment	1.27	0.13	22
Hotel	10.04	0.18	52
Real Estate Rental	28.88	0.20	7
Restaurants	8.38	0.22	120
Trade	13.24	0.13	114
Services	14.12	0.04	54
Waste	0.30	0.09	0
Government	2.46	0.02	4
Natural Gas	-0.15	-0.06	-1
Petroleum Manuf'ing	-39.52	-0.85	-5
Electricity	-100.99	-4.35	-121

Source: Author's estimation.

* In 2005 dollars.

Although electric power, petroleum manufacturing, and natural gas sectors (basically all energy sectors) would face a drop in their total output, for obvious reasons, all other sectors would have their output increase up to 0.26%. As a consequence, total domestic output would grow slightly, by 0.02%. The main contributing sectors to the economic growth, in terms of both output and employment, are manufacturing, restaurants, real estate rental, and hotels. Hawaiʻi will come across 312 new jobs, as well as 0.24-0.30% increase in residents' welfare, real wages, proprietors' income, and total value added. As explained above, the direction and magnitude of change in price indices also depend on the energy intensity of the basket of goods defining the index. As visitors and tourism industry are 1.5-2.5 times more energy intensive than residents of Hawaiʻi (Nasseri, Assane, & Konan, 2013),

Table 1.6. Energy demand and GHG emissions reduction

Sector *i*	10% electricity efficiency; all sectors				10% electricity efficiency; by sector *i*			
	(1) Electricity demand reduction in sector *i*		(2) Energy demand reduction in sector *i*		(3) Total energy demand reduction (intermed. and final)		(4) Total GHG emission reduction (direct and indirect)	
	mmBTU	Rank	mmBTU	Rank	mmBTU	Rank	$mtCO_2e$	Rank
Crops production	2,731	29	2,025	30	7,074	26	340	27
Fruits, vegetables, and flowers	9,020	22	5,872	26	20,379	23	925	23
Animal production	667	36	579	36	1,824	32	90	31
Aquaculture, forestry, and logging	863	35	1,032	34	1,937	31	89	32
Commercial fishing	-	38	1,836	31	-1	33	0	33
Mining	2,563	30	3,463	29	-3,492	34	-287	34
Construction	204,367	2	203,591	3	725,627	2	38798	2
Petroleum manufacturing	4,426	28	62,922	7	N/A	N/A	N/A	N/A
Clothing manufacturing	8,440	25	-33,458	38	-40,314	35	-3512	35
Food processing	28,242	13	15,931	20	73,474	16	3507	17
Other manufacturing	52,393	10	49,703	12	171,158	11	8981	11
Air transportation	5,736	26	11,402	27	15,594	25	729	25
Water transportation	21,707	17	16,891	19	67,881	17	3450	18
Ground transportation	1,793	32	1,146	35	5,732	28	292	28
Trucking	897	34	469	37	2,796	30	142	30
Warehousing and storage	1,126	33	1,064	33	3,319	29	166	29
Scenic activities for transportation	2,160	31	6,781	25	7,041	27	365	26
Information	13,914	19	14,281	21	51,057	19	2776	19
Electric power generation	8,950	23	3,729,251	1	N/A	N/A	N/A	N/A
Natural gas	0	37	1,426	32	N/A	N/A	N/A	N/A
Wholesale trade	25,185	16	23,716	17	88,117	15	4679	15
Retail trade	122,363	5	115,407	5	452,507	5	24363	5
Rental, leasing, and others	4,470	27	4,495	28	16,256	24	873	24
Accommodations	128,897	4	114,396	6	490,500	3	26563	3
Hotels	261,543	1	256,307	2	968,106	1	52368	1
Restaurants	129,144	3	125,772	4	474,497	4	25508	4
Fin., bus., prof. services	74,170	9	76,728	11	265,573	9	14379	9
Travel reservations	18,819	18	18,146	18	67,141	18	3572	16
Waste management services	9,829	21	8,403	24	32,940	21	1718	21
Education	8,549	24	8,476	23	31,795	22	1718	22
Hospitals	96,882	7	84,226	10	361,010	7	19379	7
Other health services	48,077	11	45,191	13	182,989	10	9916	10
Arts and entertainment	27,588	14	27,342	15	103,867	13	5646	13
Personal and laundry services	35,000	12	31,782	14	128,807	12	6903	12
Repair and maintenance	11,758	20	11,340	22	41,229	20	2187	20
Organizations	91,027	8	89,186	9	342,491	8	18502	8
State and local government	111,590	6	109,898	8	394,069	6	21020	6
Federal government	26,245	15	26,175	16	97,208	14	5225	14
Total	**1,601,129**		**5,273,194**		**5,650,196**		**301,370**	

Source: Author's estimation based on direct and indirect emissions.

visitor price index drops by 0.03 percentage point, while consumer (i.e., resident) price index rises by the same ratio (0.03%).[9]

Comparing the energy demand after applying the efficiency shock with the benchmark demand, I calculated the energy savings potential. Applying the same methodology for estimating the baseline greenhouse gas emissions on the energy consumption reduction calculations, greenhouse gas emission reductions from those scenarios are calculated and reported in Table 1.6.

Columns 1 and 2 of Table 1.6 provide electricity and energy (total of electricity, natural gas, and petroleum products) demand reductions associated with 10% electricity efficiency improvement in all sectors; and each row in columns 3 and 4 presents the total economy-wide energy saving (in mmBTU) and greenhouse gas emission reduction (in metric tons CO_2e) associated with a 10% increase in electricity efficiency in the corresponding sector.

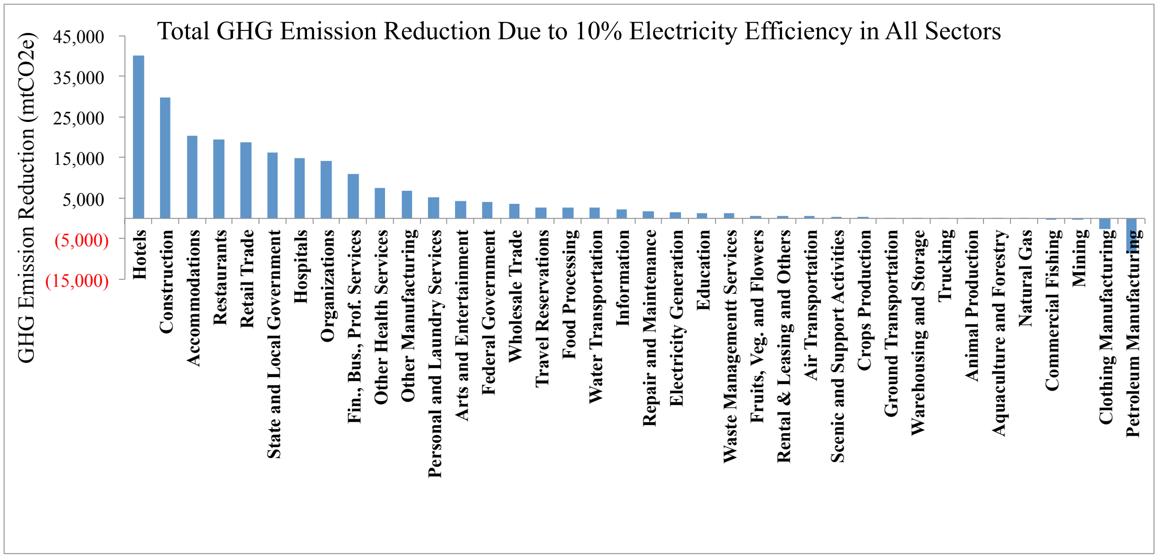

Figure 1.3. GHG emission reduction (by sector), $mtCO_2e$

The emission reductions associated with a 10% increase in electricity efficiency are shown in Figure 1.3. By far, top-5 most significant opportunities for greenhouse gas

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[9] Electricity intensive sectors' domestic output price dropped, while other sectors' prices adjusted upward. Price of hotels services, for example, adjusted by -0.16% as the main contributing factor to visitor price index adjustment.

emissions reductions from electricity conservation are in four sectors: hotels (40 thousand metric tons), construction (30 thousand mt), accommodations (20 thousand mt), restaurants (19.5 thousand mt), and retail trade (19 thousand mt), followed by government and hospitals. More than 50% of total achievable reduction (assuming the same efficiency measure applied in each sector) comes from the above 5-sectors.

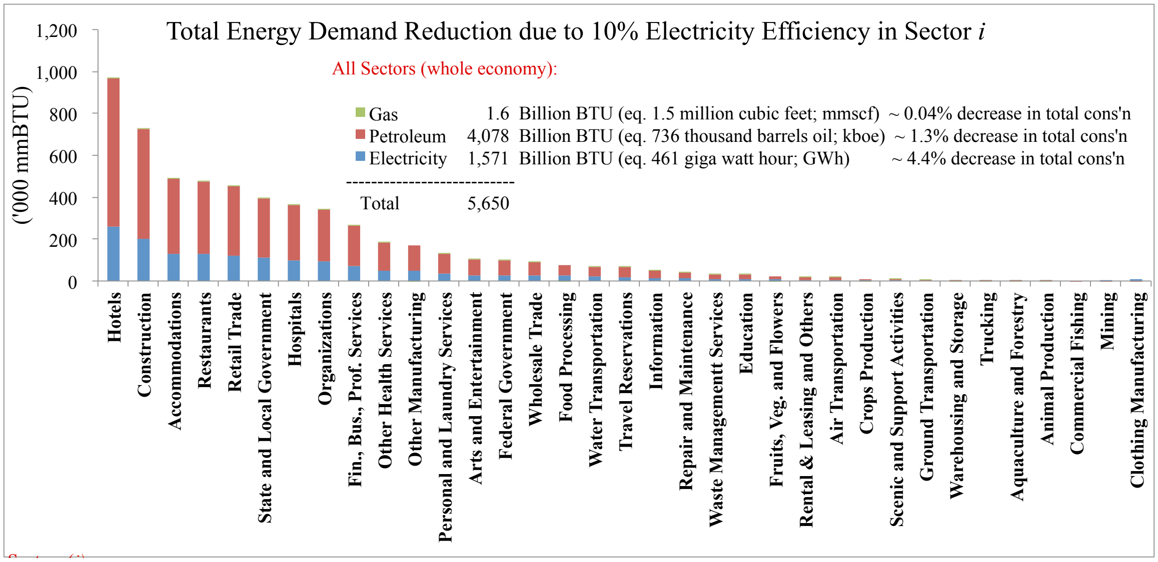


Figure 1.4. Total energy saving potential due to 10% electricity efficiency by sector

Figure 1.4 demonstrates the potential for total energy demand reduction by source associated with efficiency increase in each sector. Interestingly, a 10% efficiency increase will save the economy a larger amount of energy in petroleum products than electricity. The petroleum saving, however, is 1.3% of total petroleum consumption and mainly a reduction in intermediate demand for its products, the majority of which comes from the reduction in demand for power generation. It is worth mentioning that the larger amount of oil demand reduction generally stems from the thermal conversion loss in the power generation sector. In most of the commercial sectors with almost no direct fuel burning, hotels for example, a 10% increase in electricity efficiency will save three times as much petroleum products as electricity. This ratio implies a 33% efficiency of Hawai'i's generation system, which lies in the normal range for conversion efficiency of thermal power generation systems. In case of a 10% efficiency increase in all sectors, a total of 5.65 trillion BTUs energy will be saved, of which 4.08 trillion BTUs comes from petroleum and 1.57 trillion BTUs from electricity.

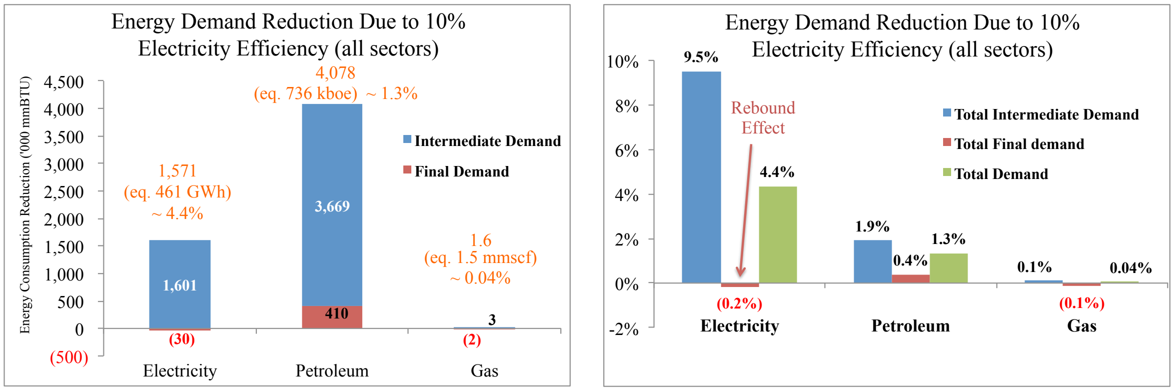
Table 1.7. Summary of industry ranking by energy and GHG intensity and savings potential due to 10% increase in electricity efficiency

Sector	Energy intensity per $m output		GHG intensity per $m output		Energy saving potential	GHG saving potential
	mmBTU	Rank	mtCO$_2$e	Rank	Rank	Rank
Electricity Generation	**43,640**	**1**	**2,717**	**1**	33	33
Clothing Manufacturing	**11,197**	**2**	**794**	**3**	38	38
Air Transportation	**10,814**	**3**	**797**	**2**	25	25
Natural Gas	**9,831**	**4**	**701**	**4**	33	33
Commercial Fishing	**9,319**	**5**	**689**	**5**	36	36
Ground Transportation	7,922	6	579	6	28	28
Waste Management Services	5,123	7	349	7	21	21
Trucking	4,771	8	346	8	30	30
Water Transportation	3,961	9	271	9	17	18
Scenic and Support Activities for Transp.	3,251	10	235	10	27	26
Fruits, Vegetables and Flowers	2,976	11	193	11	23	23
Food Processing	2,822	12	189	12	16	17
Warehousing and Storage	2,386	13	159	13	29	29
Crops Production	2,326	14	157	14	26	27
Mining	2,219	15	124	15	37	37
Other Manufacturing	1,806	16	112	16	11	11
Aquaculture, Forestry & Logging	1,661	17	110	17	31	32
Petroleum Manufacturing	1,592	18	108	18	35	35
Hospitals	1,484	19	80	20	7	7
Personal and Laundry Services	1,394	20	72	21	12	12
Animal Production	1,358	21	87	19	32	31
Travel Reservations	1,223	22	57	24	18	16
State and Local Government	1,150	23	70	22	6	6
Construction	1,045	24	60	23	**2**	**2**
Hotels	990	25	34	29	**1**	**1**
Organizations	939	26	20	33	8	8
Retail Trade	837	27	47	25	**5**	**5**
Restaurants	753	28	26	31	**4**	**4**
Repair and Maintenance	733	29	39	26	20	20
Wholesale Trade	619	30	38	27	15	15
Accommodations	593	31	36	28	**3**	**3**
Other Health Services	571	32	32	30	10	10
Arts and Entertainment	484	33	12	36	13	13
Rental & Leasing and Others	374	34	25	32	24	24
Information	278	35	16	34	19	19
Fin., Bus., Prof. Services	256	36	14	35	9	9
Education	212	37	7	37	22	22
Federal Government	125	38	7	38	14	14

Source: Author's estimation based on direct and indirect emissions

Table 1.7 summarizes and provides a comparison of rankings for the energy and GHG intensity, as well as the energy and GHG savings potential under the efficiency-increase scenario. Sectors use fuels in different ratios, and emissions factors differ across fuels, as reported in Appendix I.

Practicing energy efficiency by Hawai'i's consumers is an important tool in reducing greenhouse gas emissions. Demand-side management incentives may be considered for users of energy intensive sectors like electricity, utility gas, or transportation. Konan and Chan (2010) provided detailed analysis of the energy and greenhouse gas intensity of Hawai'i resident and visitor expenditures.



a. Total Energy Reduction ('000 mmBTU)

b. Total Energy Reduction (%)

Figure 1.5. Energy Reduction Due To 10% Electricity Efficiency Increase In All Sectors, By Source

Figure 1.5 summarizes the energy saving results in a different and interesting way. The 10% efficiency increase in all sectors saves some 5.65 trillion BTUs of energy demand in the State, mainly in intermediate demand (by producing sectors). Although the increase in electricity efficiency is only assumed to happen for producers in the form of technological change and final demand (by consuming agents) was not assumed to undergo any efficiency improvement in the analyzed scenarios, the increased final demand by 0.2% is an example of "rebound effect." However, as the presented analysis only takes into account the increased efficiency in using electricity as an input in production functions, a full rebound effect discussion is not an option here.

Panel b of Figure 1.5 also highlights the important role of final demand for electricity (by consuming agents) in total demand conservation. In other words, although 10%

efficiency increase in each sector decreases the intermediate demand for electricity by 10%, the assumed lack of efficiency in final demand, which comprised almost half of total electricity demand in 2007, and its slight rebound, offsets part of that decline and brings the total demand reduction ratio down to only 4.4%.[10]

1.5 Conclusions

This study analyzes the economic impacts and energy saving potential of an assumed 10% electricity efficiency in Hawai‘i’s economic sectors. The efficiency is assumed as a one-off step change at no cost in the production technology. Hence, the results would only be reflective of the benefits that would come about from this improvement as well as how the benefits are distributed across the economic sectors.

A CGE model is developed and a methodology is advanced to estimate the potential of GHG emissions’ reduction from efficiency-improving technological change. The reduction potentials are calculated through estimated energy demand reductions, using data on the input-output structure of the economy, detailed fossil fuel use (in BTUs). The results provide sector-level analysis for energy and greenhouse gas emissions saving potential, as well as change in macroeconomic measures under the assumed electricity efficiency scenario.

Energy and GHG intensity indices are also developed, based on which economic sectors are ranked and analyzed. The energy intensity index measures total direct and indirect energy measured in millions BTU (mmBTU) required to produce one million dollars in total output. Electricity production is the most energy intensive, requiring 43.6 billion BTU to produce $1 million of output. Clothing manufacturing, air transportation, utility gas, and commercial fishing follow, requiring 11.2 billion, 10.8 billion, 9.8 billion, and 9.3 BTUs per million dollars, respectively. As expected, the rankings of sectors are almost the same in terms of greenhouse gas emissions intensity with a few exceptions, though none of those exceptions are among the main emission-intensive sectors.

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[10] I test the impact of my choice of utility function for final consumers on their demand for electricity in reaction to the possible subsequent price change, by changing the utility function’s nesting and the CES values and find negligible impact. Appendix 1.II presents the results of sensitivity analysis.

However, when it comes to energy and GHG emission savings potential, the rankings are totally different, with hotels, construction, accommodations, restaurants, and retail trade standing in top five places, respectively, followed by state and local government and hospitals. High saving potential of emissions in tourism-related sectors implies high GHG emissions elasticity of production functions in the tourism industry. Especially considering the ratio of residents' versus visitors' population, this result implies that the visitor expenditures are more energy and carbon intensive than that of Hawai'i households on a per person basis, which is in line with the existing results in the literature (Konan and Chan 2010).

These results indicate directions for energy efficiency and greenhouse gas emissions reduction policies in service-oriented economies like Hawai'i. First, being highly carbon intensive, visitors are likely to experience larger welfare impact of any increase in the price of carbon, whether through a cap and trade, carbon tax, or other policies. However, in a tourism-based economy like Hawai'i's economy, any factor that could negatively affect visitors' welfare could ultimately impact the State's domestic product and consequently affect residents' welfare as well. Second, the effectiveness of using electricity demand-side management efforts in lowering carbon emissions is limited to a handful of industries, particularly hotels and restaurants, retail trade, and health services.

As this study only analyzes the distribution of gains from a free energy efficiency improvement throughout the Hawai'i's economy, further research is needed to look into the costs of the energy efficiency improvements in order to understand how overall benefits compare to overall costs and how gains accrue by sector. This study provides a base CGE model for future research on total welfare analysis of energy efficiency, as well as other policy tools, such as the role of gasoline taxes, carbon taxes, fuel efficiency standards, and other greenhouse gas emissions reductions plans.

1.6 Appendix 1.I. Sensitivity Analysis on Consumers' Utility Function

To address concerns about possible effects of final consumers' behavioral assumption regarding the substitution of electricity with other goods and services, I modified the consumers' utility function from its original single layer Cobb-Douglas form to a nested consumption function where the first level of the nest represent a CES demand function between electricity and other goods and at the second level all other goods are demanded through a Cobb-Douglas utility function (unit elasticity of substitution).

Table 1.I-1. Selective results for different elasticity of substitution between electricity and other goods and services

Macroeconomic Indicators (% Change)		**Original model – Electricity elasticity of substitution = 1**	**Electricity elasticity of substitution = 0.5**	**Electricity elasticity of substitution = 0.1**
Domestic output, nominal		0.02	0.01	0.01
Gross state product, nominal		0.01	0.01	0.01
Exports, nominal		-0.22	-0.21	-0.20
Visitor expenditures, real		0.03	0.03	0.03
Consumer price index		0.04	0.04	0.04
Wages, real	0.25	0.25	0.25	0.26
Proprietors income, real		0.29	0.29	0.29
Capital cost, real		0.09	0.09	0.09
Visitor price index		-0.03	-0.03	-0.03
Lump sum transfer		0.01	0.01	0.01
Value added	0.24	0.24	0.24	0.24
Resident welfare		0.27	0.27	0.27
Electricity price change		(0.69)	(0.74)	(0.80)
Energy Demand Change (Thousand mmBTU)		**Original model – Electricity elasticity of substitution = 1**	**Electricity elasticity of substitution = 0.5**	**Electricity elasticity of substitution = 0.1**
Electricity	Intermediate demand	1601 (9.5%)	1601 (9.5%)	1601 (9.5%)
	Final demand	-30 (-0.2%)	-28 (-0.2%)	-32 (-0.2%)
	Total demand	1571 (4.4%)	1574 (4.4%)	1568 (4.4%)
Petroleum	Intermediate demand	3669 (1.9%)	3675 (1.9%)	3662 (1.9%)
	Final demand	410 (0.4%)	415 (0.4%)	407 (0.4%)
	Total demand	4078 (1.3%)	4087 (1.3%)	4070 (1.3%)
Natural Gas	Intermediate demand	3 (0.1%)	3 (0.1%)	3 (0.1%)
	Final demand	-2 (-0.1%)	-2 (-0.1%)	-2 (-0.1%)
	Total demand	2 (0.0%)	2 (0.0%)	2 (0.0%)

For the upper nest, I changed the CES parameter (from 1) to 0.5 and 0.1, and presented a selection of output variables, which could be influenced by the choice of utility function, in Table 1.I-1. As the table suggests, despite small change in domestic price of electricity, lowering the substitutability of electricity with other goods and services to the final consumers change neither the total demand for energy products nor macroeconomic indicators' values.

1.7 Appendix 1.II. Linking Fuel Use and CO_2 Emissions

For GHG emission calculations, the quantity of petroleum products in terms of millions of BTU is multiplied with the greenhouse gas emission factor of each petroleum product (Table 1.II-1) (e.g., 71.689 for highway gasoline).

Table 1.II-1. Emission factor for petroleum product use

Fuel	Unit	CO_2	CH_4	N_2O	CO_2e
SNG (propane)	kg/mmBTU	56	0.0009	0.0001	56.587
Refinery Gas	kg/mmBTU	64	0.003	0.0006	64.454
Residual	kg/mmBTU	79	0.003	0.0006	79.054
Diesel	kg/mmBTU	73	0.007	0.0006	73.513
Waste Oil (Assume: blended with Residual)	kg/mmBTU	66	0.003	0.0006	66.784
Aviation Gasoline	kg/mmBTU	69	0.01	0.0006	69.619
Gasoline	kg/mmBTU	71	0.01	0.0006	71.689
Jet Fuel Kerosene	kg/mmBTU	71	0.003	0.0006	71.134
Coal	kg/mmBTU	95	0.001	0.0015	95.992
GWP		1	25	298	

Essay 2: Input-Output Study Comparing Energy Demand of Residents and Visitors for 1997 and 2007 in Hawai‘i

2.1 Introduction

Hawai‘i features a modern service-oriented economy focused largely on tourism, military, healthcare, and professional services. Tourism in particular contributes significantly to the Hawaiian economy. Each year, over seven million visitors enjoy the pristine environment and unique culture of the Hawaiian Islands. For example, in 2010, the Hawai‘i tourism industry produced $11.2 billion or 17.3% of Gross State Product (HTA, 2010). At the same time, visitors' activities require the services of the most energy-intensive industries. In 2007, the electricity consumption of an average visitor was about 2.5 times higher than that of the average resident on a daily basis. Part of the energy consumption is directly tied to consumer decisions such as the purchase of electricity, highway fuel, and natural gas utilities. A significant component of consumer demand for energy, however, is indirect and is determined by purchases of goods and services that require energy in the production process.

The objective of this study is to contribute toward the understanding of electricity and fuel use associated with resident and visitor expenditures in Hawai‘i. The study expands on a previous contribution by Konan and Chan (2010) that used input-output data and energy consumption data, in an applied general equilibrium framework to model greenhouse gas (GHG) emissions associated with economic activity in Hawai‘i. Konan and Chan (2010) identified air transportation, electricity, and other transportation forms as the main economic activity responsible for GHG emissions associated with fuel use. In addition, visitors contribute to more than 20% of the total emission and on an annual per person basis emission rates generated by visitors are relatively higher than those of residents.

A growing number of studies have successfully applied input-output methodology in the analysis of energy issues. Park (1982) developed an input-output method for measuring the direct, indirect, and income-induced energy effect of a change in final demand and estimated the effect of technical changes on energy consumption. Lenzen (1998) used an extensive input-output analysis to investigate energy and greenhouse gas flows in the Australian economy. Wu and Chen (1989) developed a static input-output framework for analyzing energy issues in the short term and they discussed problems associated in its applications. Gowdi and Miller (1991) analyzed input-output tables for the USA and Japan to estimate changes in energy efficiency during the period 1960-1980. Hawdon and Pearson (1995) used a 10-sector input-output model of UK to simulate the effects of a variety of policy issues connected with energy use and environmental impact. Park and Heo (2007) investigated indirect, direct, and total household energy requirements in Korea from 1980 to 2000 by an input-output analysis. Pachauri and Spreng (2002) used a 115-sector classification input-output tables for India over the years 1983-1984 to 1993-1994 to determine direct and indirect energy requirements of households in India. Ukidwe and Bakshi (2007) developed a thermodynamic input-output (TIO) model of the United States that accounts for the flow of industrial and ecological cumulative energy consumption in the 488-sector benchmark economic input-output model. Nässén et al. (2007) used an input-output analysis to assess direct and indirect use of carbon emission in the Swedish production phase of buildings. Panela and Villasante (2008) described a referential base for applying input-output tables of energy to estimate the energy ecological footprint (EEF) of Galacia in Northwest Spain. Yuan and Xie (2010) used an input-output analysis to analyze the influence of Chinese economy growth and energy consumption of the global financial crisis.

This study uses a condensed version of input-output data and consumption data to compare fuel and electricity demand of residents and visitors for 1997 and 2007 in Hawai'i.[11] The findings are striking and easy to summarize. First, the results indicate differences in

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[11] Whereas this paper uses 14-sector level of input-output data, the original 1997 and 2007 input-output tables for Hawai'i consisted of 131 and 68 sectors, respectively.

indirect demand for electricity from the industry sectors. On a per-capita basis, residents tend to consume more electricity through spending on health services, real estate rentals, professional services, and trade (shopping). Top visitor electricity-intensive expenditures include hotel, restaurants, trade (shopping), and tourism services (museums, tours and travel agencies). Second, when comparing data of 1997 and 2007, the differences are remarkable. Total demand for fuels and electricity increased by 18% and 33%, respectively, for residents, but both fell by 4% and 9%, respectively, for visitors.

On a person-per-daily basis, however, despite observing the same pattern, the magnitudes differ. Fuel and electricity uses increased 9% and 23%, respectively, for residents while they dropped by 21% and 24%, respectively, for visitors. Thus, the tourism industry has improved efficiency in both fuel and electricity usages by decreasing energy intensity of their activities over the observed decade. Indeed, energy-use visitor factor[12] dropped for fuel from 3.5 in 1997 to 2.5 in 2007 (a 28% drop) and for electricity from 2.4 to 1.5 (a 38% drop). To assess the underlying driving forces influencing the observed changes in energy consumption in Hawai‘i, a decomposition methodology is used to evaluate industrial energy consumption based on activity, structure, and intensity effects. The findings indicate that the activity effect contributed greatly to the observed growth in energy consumption, that the structural effect was small, and that the reduction in energy intensity by sector was a clear signal of improvement in energy efficiency.

Background

Hawai‘i's economy depends heavily upon petroleum and its energy sector is the most petroleum intensive among U.S. states. Figure 2.1 presents a flow of Hawai‘i's energy use by source. Imported crude oil accounted for 85% of the total primary energy supply in 2009. Coal imports comprised 7% of total primary energy. The remaining 8% was supplied from renewable resources (biomass, wind, and solar) and some imported liquefied petroleum gas (LPG).

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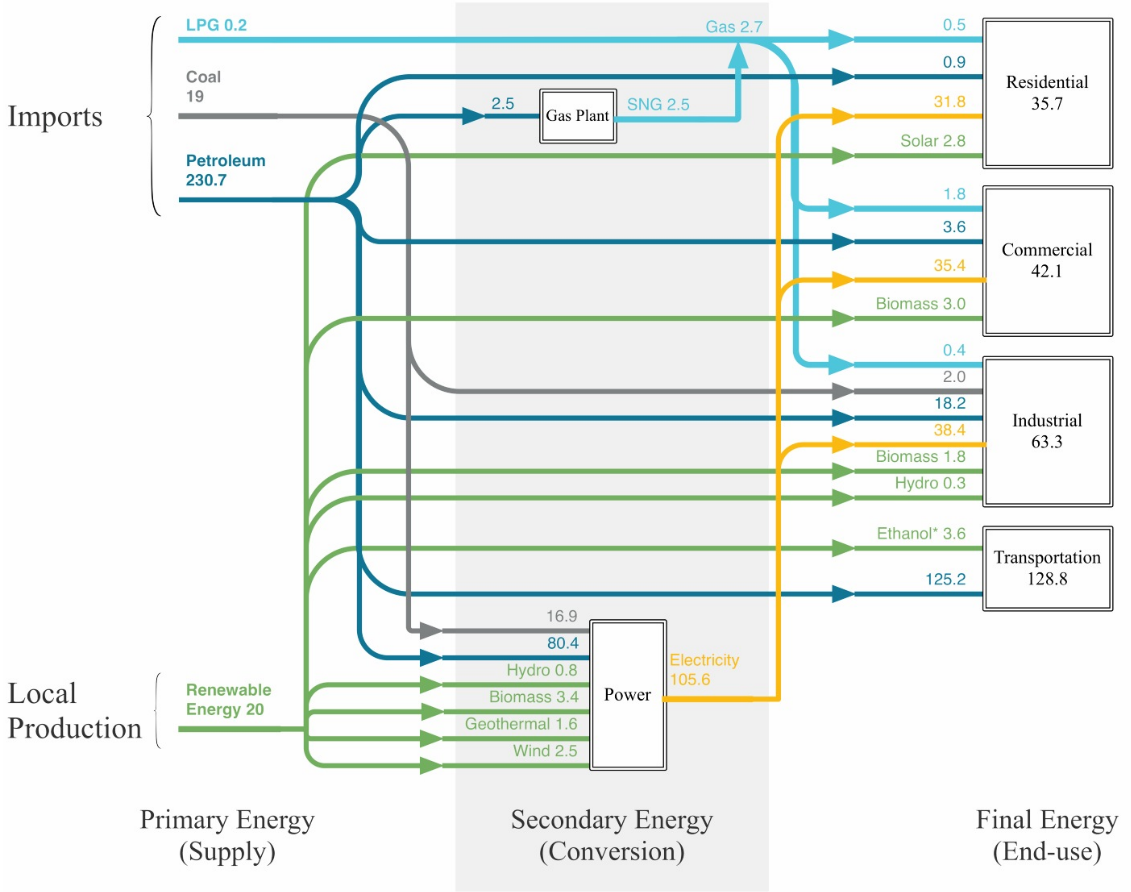
[12] Energy-use visitor factor is defined as the ratio of per-capita energy use by visitors to residents. As such, an energy-use visitor factor of two implies total energy use by each visitor is twice as much as it is for a resident of Hawai‘i.



- All values derived from U.S. EIA's State Energy Data System (SEDS) - Hawai'i 2009
- Values expressed in trillions of BTUs
- Ethanol is imported at present, not locally produced

🟩 Renewable energy		🟧 Electricity
🟦 Petroleum	⬜ Coal	🟦 LPG

Figure 2.1: Hawai'i energy flow diagram, 2009

Primary energy carriers are converted into secondary energy carriers to supply the final demand through power plants, oil refineries, and petroleum-based synthetic natural gas (SNG) plant. Hawai'i has no fossil fuel reserves; the renewable energy portfolio is relatively small, representing about 7.4% of total energy demand. Thus, Hawai'i's energy demand is supplied largely by imported crude oil, 90% of which originates from foreign sources.

Energy is primarily used for the transportation and power sectors, which account for 60% and 30% of fuels, respectively. The remaining 10% of energy use is divided between residential, commercial, and industrial sectors. Likewise, electricity use is evenly distributed across residential, commercial, and industrial consumers. Using 2007 dataset, Figure 2.2 shows Hawai'i's total fuel consumption by fuel and sector.

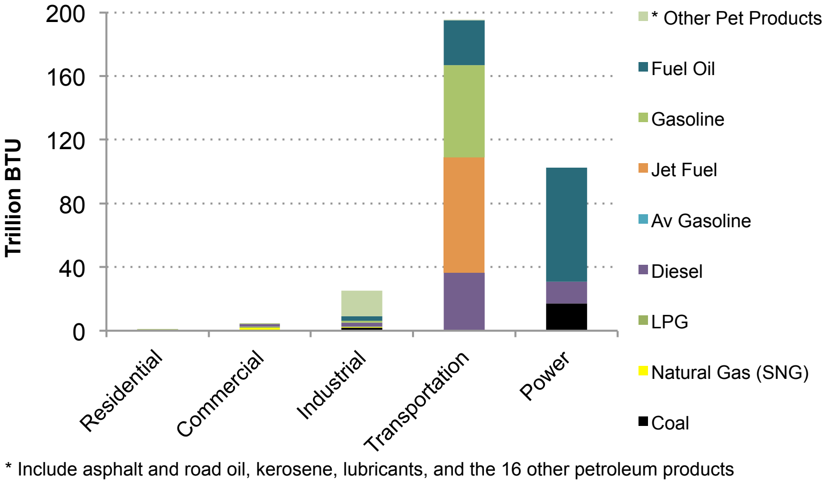
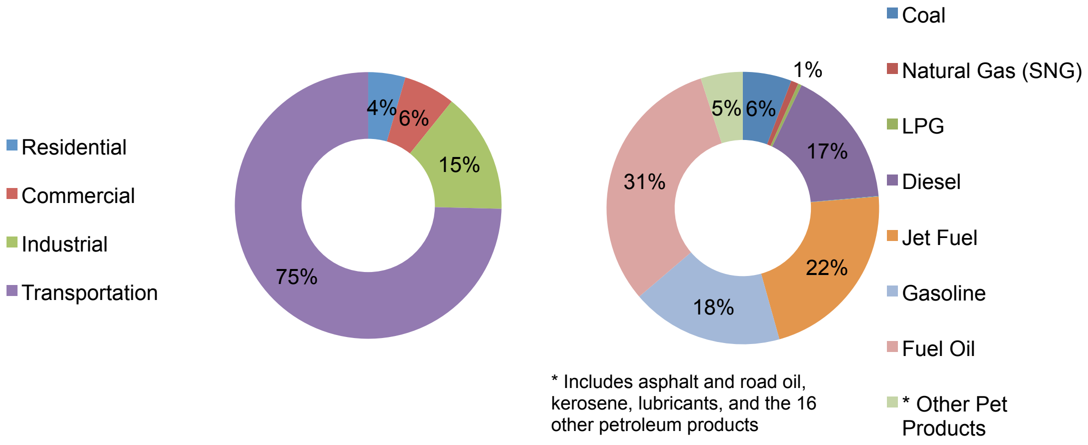


Figure 2.2: Hawai'i total fuel consumption by fuel and sector, 2007

Figure 2.3 (Panel A) shows how final energy is consumed by end-use in Hawai'i, after adding electricity to the main sectors' fuel consumption profile. The transportation sector still accounts for three quarters of final energy demand with the other three end-use sectors (residential 4%, commercial 6%, and industrial 15%) sharing the other quarter. With a highly petroleum-based power generation, less than half of the fuel demand in Hawai'i is comprised by fuel oil (31%) and diesel (17%). Jet fuel and gasoline, supplying ground and air transportation sectors, account for another 40% of the total fuel demand in Hawai'i. The fuel consumption profile is shown in Figure 2.3 (Panel B).



A. End-use Energy Consumption, 2007 B. Fuel Consumption Profile, 2007

Figure 2.3: Hawai'i sectoral energy and total fuel consumption, 2007

2.2 Methodology

In this section, I present a methodology for attributing energy consumption (fuels or electricity) to end-use agents (e.g. residents) based on intermediate and final demand. Changes in energy use over time are then decomposed to evaluate sources of change.

The Input-Output model

To understand the difference in the energy consumption behavior of residents and visitors, I develop an input-output model based on the framework set by Konan and Chan (2010).

Assume that there are *n* sectors in an economy. Denote sector *i* total output as x_i and the final demand for its output as y_i. Define unit input coefficients a_{ij} as the amount of good *i* used to produce one unit worth of good *j* for $i, j \in 1, \cdots, n$ sectors of economic activity. Total demand for sector *i* output is equivalent to the sum of intermediate and final demand.

$$x_i = \sum_{j=1}^{n} a_{ij} x_j + y_i \tag{1}$$

Define the $n \times n$ technical coefficients matrix, *A*, with elements $[a_{ij}]$. Define the $1 \times n$ column vectors for total demand, *X*, and final demand, *Y*. Equation (1) can be rewritten in matrix notation as $X = AX + Y$ and transformed as $(I - A)X = Y$, where *I* is an $n \times n$ identity matrix. Solving for *X* yields:

$$X = (I - A)^{-1} Y \tag{2}$$

where equation (2) is generally referred to as the Leontief inverse matrix or the total requirements matrix associated with exogenous final demand *Y*. Solving for the Leontief inverse matrix numerically is accomplished by defining a system of linear equations following Kalvelagen (2005).

The present analysis is concerned with energy requirements associated with production. Define the $n \times 1$ vector *S* for energy intensity with elements $[s_i]$ representing energy use per dollar of output in sector *i* and the diagonal $n \times n$ matrix $\hat{S}$ with diagonal elements $[s_i]$. Total energy consumption by sector associated with final demand *Y* is given by the vector E_Y, where:

$$E_Y \equiv \hat{S}X = \hat{S}(I - A)^{-1}Y \tag{3}$$

Thus E_Y produces an $n \times 1$ vector whose elements are the total amount of energy (all sources) used in each sector, or $[s_i x_i]$, in order to produce the exogenous final demand Y. Define the diagonal matrix $\hat{E}_Y$ of dimension $n \times n$ with diagonal elements $[s_i x_i]$.

Additionally, define a source-by-sector matrix Z with elements $[z_{ki}]$ being the share of sector i in total consumption of energy source k (for all the m energy sources: electricity and all the fossil fuels such as coal, natural gas, and petroleum products). Using matrix Z, the $m \times n$ energy requirement matrix E_{SY} divides the total required energy associated with demand Y (i.e. E_Y) into the consumption of different energy sources:

$$E_{SY} \equiv Z\hat{E}_Y = Z\hat{S}X = Z\hat{S}(I - A)^{-1}Y = \begin{bmatrix} z_{11}s_1x_1 & \cdots & z_{1n}s_nx_n \\ \vdots & \ddots & \vdots \\ z_{m1}s_1x_1 & \cdots & z_{mn}s_nx_n \end{bmatrix} \tag{4}$$

Equation (4) serves several analytical purposes. Recall that Equation (2) solves X as a function of final demand Y. Solving for Equation (2) and (4) yields a matrix E_{SY}, for exogenous final demand Y, that provides the energy inputs (by source) used directly in all sectors' production process and indirectly as energy embodied in each sector's intermediate inputs. For example, the energy used in the production of hotel services includes direct hotel purchases of energy (electricity and fuels–such as gasoline and diesel) as well indirect energy requirements embodied in the production of intermediate hotel inputs (transportation, laundry, and other services). Column sums of E_{SY} would give the total energy use by the sector represented by the column; row sums give total energy use by source across all sectors. The vector $Z\hat{S}X$ (or E_{SY}) shows energy use by category aggregated across all sectors that are associated with final demand Y.

Consider the case where final demand Y is given by an identity vector, a column vector with elements $\{1\}$. Then, E_{SY} becomes the energy intensity matrix, or the matrix of total energy (in BTUs) required to produce one dollar of final demand in each sector.

Equation (4) may also be used to show total (direct and indirect) energy use associated with individual agents, such as residential consumers, visitors, exports, government, or other sources of final demand. That is, final demand by each agent can be disaggregated into its component parts:

$$Y = Y_R + Y_V + Y_O \tag{5}$$

where Y_R, Y_V, and Y_O represent n×1 vectors of final demand by residents, visitors, and others.

A market-equilibrium state is achieved within the economy under the condition that final demand Y_l (by agent type l) is equal to total output X. In this case, the column sums of E_{SY_l} are equivalent to total industry demand for energy by source, in order to supply the final demand Y_l.

Decomposition methodology

To assess the underlying factors of the observed changes in energy consumption in Hawai‘i over time, I use the decomposition methodology. Data are obtained for two representative years, 1997 and 2007. I have assembled data on economic activity, intermediate demand (input-output coefficients), final demand, energy use, fuel type, and so on. I evaluate changes in preferences, technologies, income, and other factors that drive energy demand using decomposition analysis.

Decomposition analysis has become a useful and popular research area in energy (Ang & Liu, 2001; Ang, Liu, & Chew, 2003; Liu & Ang, 2003; Ang, 2004; Ang, 2005; Ang, Huang, & Mu, 2009). There are a variety of decomposition methods (Liu & Ang, 2003). Ang (2004) provides a detailed summary of the existing methods and their strengths and weaknesses. Recently, Ang (2005) argued that the Logarithmic Mean Divisia Index (LMDI) has a few distinct advantages and should be the preferred method. In particular, the LMDI is not path-dependent; it is a perfect decomposition (i.e., no residual); it handles data sets that contain zero values; and it enables consistent aggregation of sub-group activities to the group level. Following Ang (2005), changes in energy consumption can be decomposed into three main factors:

- Activity effect (*act*): production effect caused by change in the scale of economic activity;
- Structure effect (*str*): structural attributes due to change in economic structure; and
- Intensity effect (*int*): energy intensity attributable to change in technological level of each sector.

Total energy consumption is decomposed according to the following equation (Ang, 2005):

$$e = \sum_i e_i = \sum_i q(q_i / q)(e_i / q_i) = \sum_i q\alpha_i s_i \quad (6)$$

where *e* is the sum of sectoral energy consumptions (e_i is total energy consumption by sector *i*) measured in BTUs in this paper, q is the sum of sectoral activity levels (q_i) measured in $ millions of sectors' output in this paper, $\alpha_i (= q_i / q)$ is the output share of sector *i* in total output of the economy, and $s_i (= e_i / q_i)$ is the energy intensity of sector *i* (as in Equation 3).

Assuming that consumption of energy varies from e^0 in time 0 (base year 1997) to e^T in time T (base year 2007), I apply both additive and multiplicative decomposition of the Logarithmic Mean Divisia Index (LMDI) and derive the three factors affecting change in total energy use in the form of electricity and fuels:

$$e^T - e^0 = \Delta_{act} + \Delta_{str} + \Delta_{int} \quad (7)$$

$$e^T / e^0 = \pi_{act} . \pi_{str} . \pi_{int} \quad (8)$$

where Equation 7 decomposes the level change in total economy-wide energy consumption into its additive components and Equation 8 decomposes the percentage change in total energy consumption into its multiplicative components.

Δ_{act}, Δ_{str}, and Δ_{int} in Equation 7 represent the additive components of change with respect to the change in activity level, economic structure, and energy intensity of the output, respectively. Equations 9 to 11 show how the additive components are derived.

$$\Delta_{act} = \sum_i w_i . \ln(q^T / q^0) \quad (9)$$

$$\Delta_{str} = \sum_i w_i . \ln(\alpha_i^T / \alpha_i^0) \quad (10)$$

$$\Delta_{int} = \sum_i w_i . \ln(s_i^T / s_i^0) \quad (11)$$

where w_i is the additive sectoral weight, calculated as follows:

$$w_i = (e_i^T - e_i^0) / (\ln e_i^T - \ln e_i^0) \quad (12)$$

Likewise, π_{act}, π_{str}, and π_{int} of Equation 8 represent the multiplicative components of change derived from the change in activity level, economic structure, and energy intensity of the output, respectively. The multiplicative components are derived through Equations 13 to 15.

$$\pi_{act} = Exp(\sum\nolimits_i \omega_i . \ln(q^T / q^0)) \tag{13}$$

$$\pi_{str} = Exp(\sum\nolimits_i \omega_i . \ln(\alpha_i^T / \alpha_i^0)) \tag{14}$$

$$\pi_{int} = Exp(\sum\nolimits_i \omega_i . \ln(s_i^T / s_i^0)) \tag{15}$$

where ω_i is the multiplicative sectoral weight, calculated as follows:

$$\omega_i = \alpha_i / [(e_i^T - e_i^0) / (\ln e_i^T - \ln e_i^0)] \tag{16}$$

2.3 Energy and economic data

The empirical methodology consists of integrating energy and economic data for Hawai'i. Economic data are compiled from industrial activity and final demand from Hawai'i's Input-Output Table for years 1997 and 2007 (DBEDT, 2002, 2013).

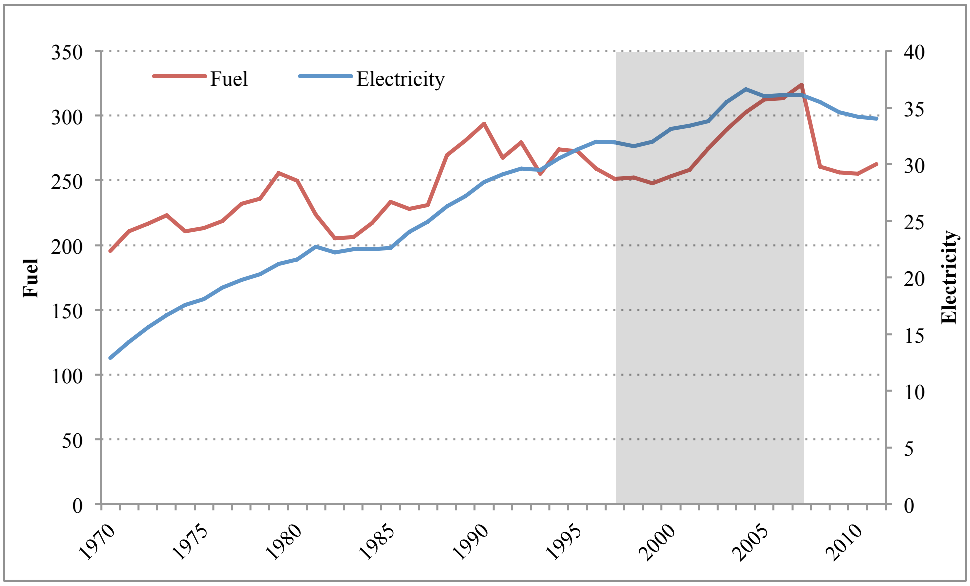
Table 2.1: Fuel consumption by end-use in Hawai'i, 2007 (Trillion BTUs)

Fuel	End-use				Total	Electric Power	Total (w/ Power)
	Residential	Commercial	Industrial	Transportation			
Coal	-	-	1.8	-	**1.8**	17.2	**19.0**
Natural Gas (SNG)	0.5	1.9	0.5	-	**2.9**	-	**2.9**
LPG	0.4	0.8	0.2	-	**1.4**	-	**1.4**
Aviation Gasoline	-	-	-	0.2	**0.2**	-	**0.2**
Jet Fuel	-	-	-	72.3	**72.3**	-	**72.3**
Gasoline	-	0.1	1.3	57.9	**59.3**	-	**59.3**
Diesel	-	1.6	2.6	36.4	**40.6**	13.5	**54.1**
Fuel Oil	-	-	2.7	28.1	**30.8**	71.8	**102.6**
Other fuels*	-	-	16.0	0.4	**16.4**	-	**16.4**
Total Fuel	**0.9**	**4.4**	**25.1**	**195.3**	**225.7**	**102.5**	**328.2**
Electricity	10.9	12.0	13.2	-	**36.1**		
Grand Total	**11.8**	**16.4**	**38.3**	**195.3**	**261.8**		

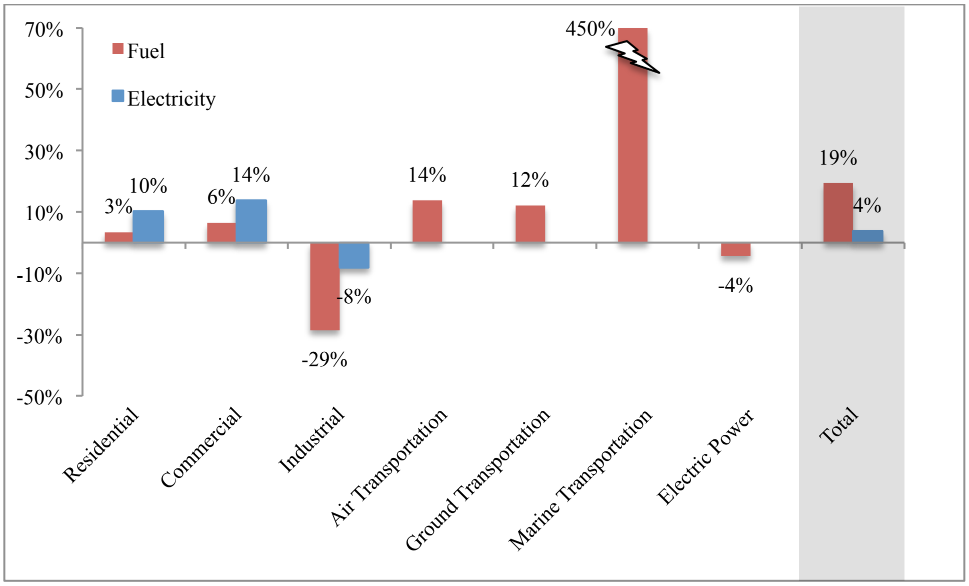
*Other fuels include naphtha, distillate fuel oil, waste oil, and fuel gas.

Source: U.S. Department of Energy, Energy Information Administration, SEDS (EIA, 2013).

Data on fuel and energy consumption are derived from U.S. Energy Information Administration's State Energy Data System (EIA, 2013). Table 2.1 presents the consumption data in BTUs. Throughout the study, while fuel consumption is measured in BTUs, electricity use is converted to and presented in kilo watt-hours (kWh).



A. Trend (1970-2011)*



B. Per-capita Change by Sector (1997-2007)

* Shaded area highlights the period of interest to this study (i.e., 1997-2007).

Data Source: U.S. Energy Information Administration, SEDS: Hawaii (EIA, 2013).

Figure 2.4: Change in Hawaiʻi energy consumption (Trillion BTU)

The study focuses on the baseline year of 2007. I then compare the results of 2007 with and update of those previously estimated by Konan and Chen (2010) for 1997. The selection of 2007 as base year to compare with estimates of 1997 was primarily guided by economic data availability. Indeed, 2007 is a reasonable choice for a benchmark year in that it represents the most recent IO table publication. Moreover, by 2007, Hawaiʻi's visitor arrivals had relatively recovered from the dramatic drop following the September 11, 2001 event. Additionally, 2007 precedes the most recent downturn in Hawai‘i's tourism and is before the 2008-2009 financial meltdown, which again affected tourism and energy consumption.[13]

As Figure 2.4 shows, Hawai‘i fuel consumption posted a record high in 2007 (panel A). From 1997, energy demand has been increasing up to 2008, when it dropped by near 20%. The uptick in fuel demand in 2007 is specifically caused by a very high demand for marine transportation fuels.[14] Although the air and ground transportations also contributed to high fuels demand in 2007, lower industrial and electric power sectors than 1997 levels, put the total 2007 fuels demand at 30% above 1997 (19% in per-capita terms). Electricity consumption, on the other hand, had already peaked in 2004 in Hawai‘i and plateaued for a few years before starting its declining trend in 2007 (panel B).

So in 2007, just before the State committed to become 30% more energy efficient by 2030 in the context of the so-called "Hawai‘i Clean Energy Initiative,"[15] demand for energy (both fuels and electricity) peaked at levels that are not expected to come back. The immediate drop in 2008 fuels consumption, however, was partly due to a year-on-year 30% increase in fuel and electricity prices (Figure 2.5)—which was then maintained in the following years as a partial result of Arab Spring of 2010 and Japan's March 2011 tsunami and earthquake,[16] and their consequent energy price hike—as well as a significant drop in the construction and tourism sectors in Hawai‘i during the global financial recession.

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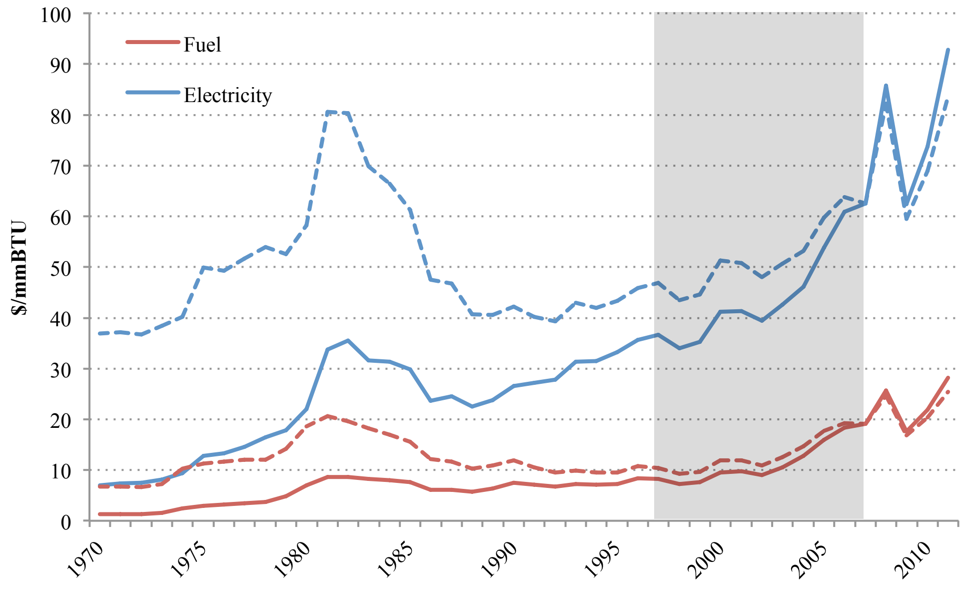
[13] In between, two IO tables exist. The 2002 table is not good due to the proximity of September 11, whereas the 2005 table was actually a semi-IO table, constructed on partial census information.

[14] Typically, most of the marine bunkering fuels in Hawai‘i serve ships that are loading or unloading cargoes in Hawai‘i. But in some years, due to specific market conditions (e.g., supply logistics and pricing) draw international marine traffic (such as the Japanese long-line fishing fleet) to Oahu specifically to purchase bunkers fuel. This accounts for the sharp peak in demand for marine transportation fuels in 2007.

[15] State of Hawai‘i signed an MOU with the U.S. Department of Energy for the Hawai‘i Clean Energy Initiative (HCEI) with the goal of decreasing energy consumption by means of increased energy efficiency (up to 30%) and increased share of renewable energies (up to 40%) in Hawai‘i's energy supply in order to meet 70% clean energy target of Hawai‘i's projected demand by 2030. Hawai‘i legislatures passed the renewable and efficiency targets into law, called RPS and EEPS.

[16] During the past 10 years, on average, the Japanese have comprised 20% of visitor arrivals and spent 20% of total visitors' expenditures (Hawai‘i Tourism Authority, 2010).



Note: Solid lines represnt prices in current $ and dotted lines are real $ prices (in $2011).

* Shaded area highlights the period of interest to this study (i.e., 1997-2007).

Data Source: U.S. Energy Information Administration, SEDS: Hawaii 1970-2011 (EIA, 2013).

Figure 2.5: Hawai‘i energy price trend, 1970-2011 ($/mmBTU)

The 2007 State of Hawai‘i Input-Output Study (DBEDT, 2013) was compiled from the census and organized according to the North American Industry Classification System (NAICS). Intermediate and final demand values are provided for Hawai‘i's economy at a disaggregation of 68 sectors. While the methodology was implemented using disaggregated data, for sake of conciseness, I present our findings at an aggregated 14-sector level.

Table 2.2 is the condensed Input-Output (I-O) transactions table for Hawai‘i where industrial classifications follow the concordance provided in the technical appendix of the DBEDT (2013) study. This table shows both Hawai‘i's domestic inter-industry transactions and final demand. The inter-industry transactions show the intermediate sales and purchases of goods and services among producers within an economy. Intermediate and final imports enter into demand as an aggregate, since sector-level import demand is not available. Final demand typically consists of the sales of commodities and services by each industry to households and other consumers (e.g., government, investors, exports, etc.).

Table 2.2: 2007 condensed input output transactions table for Hawai‘i, $ million

Industry	Agriculture	Construction	Petroleum manufacturing	Other manufacturing	Air transportation	Transportation	Electricity	Utility gas	Trade	Entertainment	Real estate and rentals	Hotel (accommodations)	Restaurant	Health services	Other services	Government	Total inter-industry demand	Personal consumption exp.	Visitor expenditures	Gross private investment	State and local government	Federal government: military	Federal government: civilian	Exports	Total Output
1 **Agriculture**	56	16	0.2	178	0.01	0.1	0	0	1	1	15	0.05	60	6	5	1	339	145	20	-	5	1	0.2	206	717
2 **Construction**	7	13	2	15	57	3	15	1	34	6	457	148	75	30	106	129	1,098	-	-	7,367	775	756	50	-	10,045
3 **Petroleum manufacturing**	45	136	135	174	702	134	940	43	115	3	132	50	25	90	128	132	2,984	884	378	9	86	91	-	187	4,667
4 **Other manufacturing**	22	676	9	309	10	19	2	0.1	110	5	76	11	246	79	203	26	1,805	793	84	165	51	71	2	918	3,882
5 **Air transportation**	4	35	5	19	2	5	0.4	0	20	1	9	9	4	15	93	37	257	529	2,002	11	35	0	0.4	30	2,858
6 **Transportation**	12	275	20	118	15	62	3	0.2	87	7	17	43	33	64	197	34	987	704	977	116	96	6	2	138	2,935
7 **Electricity**	9	131	34	59	4	19	13	0	96	18	84	171	85	96	173	89	1,081	880	-	-	320	34	4	-	2,319
8 **Utility gas**	1	15	4	7	0	2	11	3	12	2	9	20	10	11	20	10	136	83	-	-	20	2	0.2	-	243
9 **Trade**	20	982	20	247	28	44	5	0.3	156	6	119	66	140	121	280	60	2,294	4,981	1,969	624	142	22	1	150	10,188
10 **Entertainment**	0.2	4	1	3	0.4	0.3	0.1	0	-	20	-	3	8	0.3	6	0.2	47	416	472	-	-	0.3	-	29	960
11 **Real estate and rentals**	28	290	18	51	18	51	4	0.2	844	43	1,041	193	239	534	1,146	69	4,570	8,738	631	40	127	0	4	303	14,416
12 **Hotel (accommodations)**	0.4	15	4	12	1	4	1	0.1	22	1	22	11	9	26	70	12	209	404	5,046	-	17	2	-	-	5,650
13 **Restaurant**	1	67	5	48	29	15	3	0.2	52	11	20	43	43	78	150	31	595	1,695	1,448	-	-	4	0.2	10	3,737
14 **Health services**	-	-	-	-	-	1	-	-	0	0.4	-	-	-	84	3	5	94	6,517	134	-	-	8	11	-	6,764
15 **Other services**	23	1,153	100	420	189	208	38	8	892	79	1,702	834	309	859	3,281	334	10,431	6,269	676	507	259	395	16	1,451	19,996
20 **Government**	6	41	10	54	161	99	6	0.3	145	25	44	101	43	124	249	58	1,166	1,474	76	-	5,242	6,747	731	-	15,417
Total intermediate input	233	3,848	366	1,714	1,218	667	1,040	58	2,586	227	3,747	1,703	1,330	2,218	6,109	1,028	28,093	34,512	13,914	8,839	7,175	8,139	823	3,423	104,776
Imports	93	1,846	3,936	1,390	455	243	97	28	1,018	53	350	303	509	712	1,677	367	13,077	7,387	985	3,724	537	767	21	791	27,432
Comp'tion of employees	239	2,842	72	670	533	682	276	32	3,339	406	480	2,067	1,363	3,026	7,502	12,794	36,323								
Proprietor's income	43	547	14	92	(1)	61	1	0	425	124	207	75	93	404	1,569	-	3,654								
TOPILS*	(19)	75	8	32	335	448	215	25	1,966	61	629	591	105	157	567	(80)	5,115								
Other capital costs	128	887	271	(16)	318	834	691	99	854	89	9,003	910	337	229	2,572	1,308	18,514								
Output	717	10,045	4,667	3,882	2,858	2,935	2,319	243	10,188	960	14,416	5,650	3,737	6,746	19,996	15,417	104,776	41,899	14,900	12,563	7,712	8,906	844	4,214	132,208

* Note: TOPILS = Taxes on Production and Imports Less Subsidies.

Source: The Hawaii Input–Output Study, 2007 Benchmark Report, Revision 2013. (DBEDT, 2013).

In this condensed format, the major categories of purchases of goods and services by key industry sectors are shown. To review each sector's expenditure pattern, one needs to look at the column describing the sector. For example, agricultural sector producers make $56 million of agricultural purchases and spend $12 million on transportation services. Agriculture requires $9 million electric utility costs, a relatively small amount in comparison to hotels ($171 million) or construction sector ($131 million). Employee compensation accounts for $239 million of total agricultural output ($717 million). On the other hand, by looking at the row values, it is possible to see how that sector's output is distributed across other sectors of the economy. For example, the key sources of intermediate demand for agriculture include other manufacturing—mainly food processing—($178 million) and restaurants ($60 million).

Table 2.3 shows a detailed comparison of visitor and household spending on the industry sectors' output, total economic output value, and total fuel and electricity expenditure (sales, in value) across economy, by sector. Quite clearly, there is a difference in spending patterns of residents versus visitors. Top visitor expenditures include hotels, air transport, retail trade, and restaurants. Households spend proportionately more on real estate, health services, retail trade, and professional services. Interestingly, the spending on arts and entertainments by residents ($416 million) is close to that of visitors ($472 million), annually. However, in 2007, visitors spend more than 3 times as much as residents on rental cars and other leasing services and 7 times more on scenic activities and sightseeing transportation services. As noted earlier, residents make direct purchases of electricity, propane and SNG, and waste management, while visitors purchase these services indirectly through the purchase of other goods and services.

Finally, the quantity of fuel and electricity consumption by industry sectors and by the two final consuming agents, households and visitors, are estimated using standard techniques.

Table 2.3: Output and expenditures in Hawai‘i, 2007 (in $ million)

Industry Sector	Output	Residents' expenditures	Visitors' expenditures	Fuel expenditures (by sector)	Electricity expenditures (by sector)
	A	B	C	D	E
Crops production	184	14	-	7.6	1.8
Fruits, vegetables and flowers	319	74	18	16.4	6.0
Animal production	47	6	1	1.1	0.4
Aquaculture, forestry & logging	62	13	-	1.8	0.5
Commercial fishing	106	37	1	18.6	-
Mining	57	-	-	2.0	1.5
Construction	10,046	-	-	150.9	131.5
Petroleum manufacturing	4,668	884	378	139.2	33.6
Clothing manufacturing	332	94	8	60.3	6.1
Food processing	1,377	491	57	61.1	18.7
Other manufacturing	2,184	208	20	59.3	33.9
Air transportation	2,866	529	2,002	702.1	3.7
Water transportation	839	258	177	51.4	14.2
Ground transportation	220	56	94	32.7	1.2
Trucking	451	175	30	39.9	0.6
Warehousing and storage	60	-	3	2.5	0.7
Scenic and support activities for	804	51	364	48.4	1.4
Information	2,778	1,086	28	12.5	8.9
Electric	2,320	880	-	951.1	13.2
Natural gas	243	83	-	46.9	0.0
Wholesale trade	3,103	1,225	98	32.5	16.3
Retail trade	7,086	3,756	1,871	94.3	79.7
Rental & leasing and others	1,462	215	672	9.6	2.9
Real estate	14,425	8,738	631	141.2	84.4
Hotels	5,678	404	5,046	69.2	170.8
Restaurants	3,755	1,695	1,448	35.1	84.7
Fin., bus., prof. services	12,284	2,623	191	48.9	47.2
Travel reservations	484	149	211	8.5	12.3
Waste management services	336	13	-	30.8	6.4
Education	870	613	127	2.3	5.5
Hospitals	2,862	2,796	66	65.7	64.5
Other health services	3,903	3,721	69	35.0	31.4
Arts and entertainment	964	416	472	4.9	17.9
Personal and laundry services	993	777	119	20.9	23.2
Repair and maintenance	677	178	-	7.6	7.6
Organizations	1,571	830	-	14.9	60.4
State and local government	6,502	735	-	124.4	71.9
Federal government – military	6,747	-	-	-	-
Federal government – civilian	2,189	739	76	17.3	16.9

Note: Numbers listed in column D are the expenditures by each sector on the output from natural gas and petroleum manufacturing sectors.

Source: Author's calculations.

The estimated consumption of energy source k by all industry sectors (e_{ik}) and final consumers (e_{lk}) are calculated as follows:

$e_{ik} = e_k \times \rho_{ik}$ and $e_{lk} = e_k \times \rho_{lk}$ for all *i*, *k*, and *l* (17)

where *i*, *k*, and *l* represent the industry sector ($i \in 1 \dots n$), the energy source ($k \in 1 \dots m$), and the final consumer agent ($l \in \{\text{Resident, Visitor, Others}\}$), respectively.

In Equation 17, the total consumption of energy source *k*, e_k, is allocated to the industry sectors and final consumer agents using the corresponding shares, ρ_{ik} and ρ_{lk},

where: $\sum_{i=1}^{n} \rho_{ik} + \sum_{l \in \{R,V,O\}} \rho_{lk} = 1$, for each *k*. (18)

The shares, ρ_{ik} and ρ_{iy}, are estimated either based on the energy source characteristic or based on the sectors' expenditure on fuel and electricity (i.e., columns D and E of Table 2.3). For example, as jet fuel is only consumed by the air transportation sector, I have assumed $\rho_{\text{airtrnsp, jet}} = 1 \text{ and } \rho_{i,\text{ jet}} = 0, \forall i \neq \text{airtrnsp}$. For gasoline, however, as another example, the shares have been estimated based on sectoral expenditure on petroleum manufacturing:

$$\rho_{i,gasoline} = EXP_{i,pet} / \sum_{i'=1}^{n} EXP_{i',pet} \tag{19}$$

where $EXP_{i,pet}$ is the amount of expenditure on the petroleum manufacturing sector's output by the industry sector *i*.

The sectoral estimates for total fuel consumption is calculated by adding up the consumption of individual petroleum products.

2.4 Results

This section presents the empirical results of our Input-Output analysis. First, the electricity and fuel consumption patterns are analyzed for both residents and visitors using the 2007 data set. The same results are then calibrated for the 1997 data set[17]. Then, I use

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[17] The 1997 results replicate the Konan and Chen (2010) results using the same methodology and data updates that have become available.

decomposition analysis in terms of activity, structure, and intensity effects to account for changes in energy demand between 1997 and 2007.

Direct and indirect energy consumption in 2007 by residents and visitors

Table 2.4 lists our estimates of direct and indirect energy consumption in 2007. Computation of these estimates is based on the purchases of goods and services by residents and visitors, using Equations 3 and 4. For example, to derive the numbers in column 1 vector Y_R (introduced in Equation 5) is used to calculate the matrix E_{Y_R}. Then, multiplying the matrices Z (which contains the share of sectors in total electricity consumption in row k'—i.e., the row corresponding to the electricity), and $\hat{E}_{Y_R}$ (the diagonal form of the matrix E_{Y_R}) yields matrix E_{SY_R}, the total energy demand by residents, with row k' containing the values of column 1.

Columns 1 and 2 present the total consumption of electricity (in panel A) and fuel (in panel B) in order to produce goods and services demanded by residents and visitors of Hawai‘i, respectively. Final consumers' total indirect and direct demand for electricity and fuel are listed in column 3, values of which exceed the sum of columns 1 and 2 as the total also includes final consumption by the government, the military, and the exports. Columns 4, 5, and 6 illustrate the estimates on a daily per-capita basis.

Over two thirds of residential electricity demand is the direct electricity consumption of 4,015 giga watt-hours (GWh). The key sectors of indirect residential electricity use include health services (525 GWh), real estate, trade, restaurants, and other services (which include education, IT services, etc.). Note, the electricity embodied in the economic activity includes direct electricity consumption and indirect electricity demand through purchases of intermediate inputs. Column 4 presents the results per capita and shows that Hawai‘i residents consume a daily average of 8.4 kWh electricity directly and a total of 13 kWh on a daily average when their indirect electricity purchases of 4.6 kWh/person-day are added.

Table 2.4: Total and per-capita energy consumption by residents and visitors, 2007

A. Electricity	Total Consumption (MWh)			Per-capita Daily (Wh)		
	1 Resident	2 Visitor	3 Total	4 Resident	5 Visitor	6 Total
Agriculture	10,543	2,012	30,092	22	29	63
Manufacturing	109,621	21,881	260,748	228	316	543
Air transportation	14,065	53,188	69,284	29	769	144
Marine transportation	23,653	16,248	61,686	49	235	128
Ground transportation	9,331	15,539	27,925	19	225	58
Electricity	38,079	-	53,563	79	-	112
Fin., bus., prof. services	80,988	5,887	153,312	169	85	319
Trade	280,367	121,955	448,472	584	1,764	934
Real estate	395,227	28,531	445,207	823	413	927
Hotels	61,258	765,200	829,321	128	11,068	1,727
Restaurants	208,574	178,255	388,590	434	2,578	809
Health services	525,557	11,460	538,001	1,094	166	1,120
Other services	381,993	100,483	1,221,015	795	1,453	2,543
Government	73,396	3,240	405,663	153	47	845
Total indirect	2,212,650	1,323,880	4,932,878	4,607	19,149	10,272
Direct use	4,014,548	0	5,647,055	8,360	0	11,759
Total	6,227,197	1,323,880	10,579,933	12,967	19,149	22,031

B. Fuel	Total Consumption (MMBTU)			Per-capita Daily (BTU)		
Agriculture	1,140,980	164,517	2,886,786	2,376	2,380	6,011
Manufacturing	7,740,808	1,162,366	16,313,776	16,119	16,813	33,971
Air transportation	6,157,555	23,284,794	30,331,341	12,822	336,800	63,160
Marine transportation	1,320,811	907,307	3,444,637	2,750	13,124	7,173
Ground transportation	1,655,315	1,458,785	3,742,115	3,447	21,100	7,792
Electricity	34,700,353	-	48,811,174	72,258	-	101,641
Fin., bus., prof. services	1,961,828	142,613	3,713,801	4,085	2,063	7,733
Trade	6,853,750	2,861,190	10,915,924	14,272	41,385	22,731
Real estate	10,037,374	724,580	11,306,686	20,901	10,481	23,544
Hotels	876,641	10,950,576	11,868,186	1,825	158,393	24,714
Restaurants	3,660,461	3,128,369	6,819,733	7,622	45,250	14,201
Health services	11,750,237	255,227	12,028,454	24,468	3,692	25,047
Other services	6,626,782	2,904,910	30,795,230	13,799	42,018	64,126
Government	2,060,361	85,373	11,717,306	4,290	1,235	24,399
Total indirect	96,543,255	48,030,608	204,695,148	201,035	694,733	426,244
Direct use	37,414,939	648,036	123,504,852	77,910	9,373	257,178
Total	133,958,193	48,678,644	328,200,000	278,946	704,106	683,422

Source: Author's calculations.

As expected, visitors have no direct demand for electricity (column 2 in panel A, Table 2.4). However, their indirect demand is significant through purchases of hotels (765 GWh), restaurants (178 GWh), trade (122 GWh), other services (100 GWh)—which includes museums, tours and travel agencies, and IT services—and air transportation (53 GWh). Similarly, column 5 of Table 2.4 shows on daily average visitors use 19.1 kWh of electricity indirectly through their purchases of goods and services. In 2007, the average Hawai‘i visitor required 1.5 times the electricity outlay of the average resident on a per day basis. Panel B of Table 2.4 contains estimates of direct and indirect demand for fuels (petroleum products, coal, and SNG). The most significant residential fuel use is direct consumption (37.4 trillion BTU), primarily in the form of highway gasoline and diesel use. Other important residential expenditures are residents' purchase of health services, followed by real estate, manufacturing, and trade. On a per-capita daily basis, the average Hawai‘i resident requires 279 thousand BTUs of fuels (directly and through their expenditure of other goods and services).

Visitors' direct demand for fuels is limited, only 0.65 trillion BTUs, but even with a relatively smaller population size, their indirect demand is relatively higher than that of residents, especially for air transportation services (23.3 trillion BTUs) and hotels (10.9 trillion BTU). Hence, the average Hawai‘i visitor requires 704 thousand BTUs of fuels, 695 thousand BTUs of which is indirect demand to provide their expenditures. In 2007, the average Hawai‘i visitor required 2.5 times the fuel outlay of the average resident on a per capita basis, which is a decline compared to 3.5 in 1997.

Accounting for changes in energy consumption

Table 2.5 provides an overview of resident and visitor energy demand. Consider 2007 energy demand, both direct and indirect. Hawai‘i residents consume nearly five times the electricity (6.2 million MWh versus 1.3 million MWh) and three times the fuel (134.0 versus 48.7 million MMBTU) of visitors. The weight of resident demand is driven largely by their dominance in society. In 2007, approximately 1.31 million people resided in Hawai‘i and 0.19 million tourists visited Hawai‘i.[18]

Table 2.5 also distinguishes total energy demand on a per-capita basis. In 2007, the typical Hawai‘i resident consumed 4.7 MWh (13 kWh per day) of electricity and 102 MMBTU (17.6 barrels of oil equivalent) of fuel overall through direct and indirect purchases. Visitors out consume residents on a per-capita basis. Each typical visitor to Hawai‘i in 2007 consumed 7 MWh (or 19 kWh per day) of electricity and 257 MMBTU (42.9 barrels of oil equivalent) of fuel, respectively 1.5 and 2.5 times more than a typical resident.

Table 2.5: Direct, indirect, and total fuel/electricity use by residents and visitors

			2007			1997		
			Indirect	**Direct**	**Total**	**Indirect**	**Direct**	**Total**
			A. Electricity					
Total	**Resident**	**MWh**	2,212,650	4,014,548	6,227,197	1,846,958	2,822,836	4,669,794
	Visitor	**MWh**	1,323,880	-	1,323,880	1,452,477	-	1,452,477
	Visitor Factor		0.6	0.6	0.0	0.2	0.8	-
Per capita	**Resident**	**MWh**	1.7	3.1	4.7	1.5	2.3	3.9
	Visitor	**MWh**	7.0	-	7.0	9.2	-	9.2
	Visitor Factor		4.2	-	1.5	6.1	-	2.4
			B. Fuel					
Total	**Resident**	**MMBTU**	133,958,193	37,414,939	133,958,193	72,170,131	41,070,114	113,240,245
	Visitor	**MMBTU**	48,678,644	648,036	48,678,644	48,149,941	2,736,225	50,886,166
	Visitor Factor		0.4	0.5	0.1	0.2	0.4	0.1
Per capita	**Resident**	**MMBTU**	73.4	28.4	101.8	59.7	34.0	93.6
	Visitor	**MMBTU**	253.6	3.4	257.0	306.4	17.4	323.8
	Visitor Factor		3.5	0.1	2.5	5.1	0.5	3.5

Source: Author’s calculations.

Table 2.6 summarizes total residents and visitors’ demand for electricity and energy uses and their change over the decade. From 1997 to 2007, residents’ total electricity use increased by 33%, while on a per-capita basis, to adjust for the population growth, electricity use shows 23% increase. Similarly, but in a smaller magnitude, residents’ total fuel use increased by 18% from 1997 to 2007, and 9% on a per-capita basis. For visitors, indirect

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[18] In 2007, 7,496.8 thousand visitors arrived in Hawai‘i (on average, 20 thousand visitors per day) and stayed for the total of 69,135,300 days (i.e. average stay length of 9.2 days). The above statistics imply a total of 189,412 resident-equivalent visitors (i.e. a visitor staying all year in Hawai‘i).

demand for electricity was reduced by 9% in total and 24% per capita, although the fuels demand declined by only 4% in total and 21% per capita. This shows that despite all the factors contributing to the rise in residents' demand for energy, the tourism industry has greatly improved both fuels and electricity efficiency over the observed decade, but more specifically decreased the electricity intensity of their activities.

Clearly air transportation is a large component of visitor's energy demand. However, combustion of fuels for air transportation occurs largely beyond Hawai'i's borders. Moreover, it is not only an unavoidable component of visitors' energy demand, but also a component that state has very limited, if any, control over it. Hence, in order to provide a level playing field base for comparison, Table 2.6 presents the results for residents' and visitors' energy profiles including and excluding air transportation. Excluding the air transportation fuel use greatly reduces the visitors' fuel use for energy consumption both in levels and relative to that of residents.

Table 2.6: Change in total fuel use and electricity use; Hawai'i, 1997-2007

			2007	1997	Change	%Change
			A. Electricity			
Total	**Resident**	**MWh**	6,227,197	4,669,794	1,557,403	33%
	Visitor	**MWh**	1,323,880	1,452,477	(128,597)	-9%
	Visitor Less Air	**MWh**	1,270,692	1,347,279	(76,587)	-6%
	Visitor Factor		0.2	0.3		
	Visitor Factor (less Air)		0.2	0.3		
Per capita	**Resident**	**MWh**	4.7	3.9	0.9	23%
	Visitor	**MWh**	7.0	9.2	(2.3)	-24%
	Visitor Less Air	**MWh**	6.7	8.6	(1.9)	-22%
	Visitor Factor		1.5	2.4		
	Visitor Factor (less Air)		1.4	2.2		
			B. Fuel			
Total	**Resident**	**MMBTU**	133,958,193	113,240,245	20,717,949	18%
	Visitor	**MMBTU**	48,678,644	50,886,166	(2,207,522)	-4%
	Visitor Less Air	**MMBTU**	25,393,850	28,759,226	(3,365,377)	-12%
	Visitor Factor		0.4	0.4		
	Visitor Factor (less Air)		0.2	0.3		
Per capita	**Resident**	**MMBTU**	101.8	93.6	8.2	9%
	Visitor	**MMBTU**	257.0	323.8	(66.8)	-21%
	Visitor Less Air	**MMBTU**	134.1	183.0	(48.9)	-27%
	Visitor Factor		2.5	3.5		
	Visitor Factor (less Air)		1.3	2.0		

Source: Author's calculations.

Almost half of visitor's total (direct and indirect) demand for energy comes from their demand for air transportation.[19] Fuel use visitor factor drops from 3.5 to 2 for 1997 and from 2.5 to 1.3 for 2007, an almost 50% drop when air transportation is excluded.

Table 2.7 breaks down the per-capita changes in total electricity and fuel use by residents and visitors between 1997 and 2007 into their components. While columns 1 and 2 present the percentage change in direct and indirect use (by industry sectors) by residents and visitors between 1997 and 2007, columns 3 and 4 show the importance of each component by presenting the percentage share of the component in total change in per-capita use.

For example, columns 1 and 3 of Panel A show while residents' indirect demand for electricity has increased by only 10%, majority of the change in total per-capita use comes from the 31% increase in their direct use of electricity. In the same period, in Hawaiʻi, real per-capita personal income increased by 21% (UHERO, 2013). A larger increase in (direct) electricity use than in per-capita income suggests a greater-than-one (long-run) income elasticity of demand. Meanwhile, even larger income elasticity would be required, considering the negative force on the use implied by 33% increase in retail electricity price (in real terms), due to a negative price elasticity of demand (EIA, 2013). In a literature review, Espey and Espey (2004) estimated the average long-run income elasticity of electricity demand to be slightly less than 1 (average: 0.97, range: 0.02 to 5.74) and the long-run price elasticity to be greater than -1 (average: -0.85, range: -2.25 to -0.04). Although technically possible, it is not realistic to attribute the entire increase in electricity use to the income effect. Instead, a combination of behavioral and technological change in consumption pattern is more plausible explanation. For example, the emergence of Internet in the 1990s and the dot-com boom of 1997-2000, followed by the emergence and rapid adoption of smart devices (such as smart phones, TVs and tablets, etc.) by households in the 2000s introduced a new demand for electricity in the period of this study.

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[19] 123 mmBTU of visitors' per-capita demand for energy—out of total of 257 MMBTU—is for air transportation (Table 2.6).

Table 2.7: Change in per-capita fuel and electricity use, 1997-2007

	% Change in Per-capita Use; 97-07		% Share in Total Change; 97-07	
	1 Resident	2 Visitor	3 Resident	4 Visitor
	A. Electricity			
Agriculture	-49%	-37%	-1%	0%
Manufacturing	-4%	-55%	0%	6%
Air transportation	-43%	-58%	-1%	17%
Marine transportation	28%	-9%	0%	0%
Ground transportation	-51%	-46%	-1%	3%
Electricity	113%	N/A	2%	0%
Fin., bus., prof. services	-11%	66%	-1%	-1%
Trade	28%	14%	5%	-4%
Real estate	17%	66%	5%	-3%
Hotels	34%	-21%	1%	48%
Restaurants	14%	-21%	2%	11%
Health services	6%	-9%	3%	0%
Other services	-2%	-48%	-1%	22%
Government	74%	208%	3%	-1%
Total indirect	10%	-24%	18%	100%
Direct use	31%	N/A	82%	0%
Total	23%	-24%	100%	100%
	B. Fuel			
Agriculture	46%	91%	3%	-1%
Manufacturing	58%	-43%	26%	7%
Air transportation	18%	-13%	9%	27%
Marine transportation	189%	105%	8%	-4%
Ground transportation	147%	-9%	9%	1%
Electricity	0%	N/A	-1%	0%
Fin., bus., prof. services	2%	89%	0%	-1%
Trade	74%	52%	27%	-8%
Real estate	83%	159%	42%	-4%
Hotels	19%	-30%	1%	36%
Restaurants	-3%	-33%	-1%	12%
Health services	41%	21%	32%	0%
Other services	2%	-36%	1%	13%
Government	116%	303%	10%	-1%
Total indirect	23%	-17%	167%	79%
Direct use	-16%	-80%	-67%	21%
Total	9%	-21%	100%	100%

Source: Author's calculations.

Another interesting observation in Table 2.7 is the importance and contribution of the hotels' efficiency improvement in visitors' per-capita electricity use reduction, responsible for almost half of the reduction in visitors' indirect demand for electricity (Column 4 of Panel A).

For fuels, however, the story is different. A 16% decrease in direct per-capita fuel use by residents partially offsets a 23% increase in indirect use, resulting in an overall increase of 9%. Despite a possible (though much smaller) income effect that could have had some increasing effect on direct fuel use, an 83% increase in real average fuel price in Hawai'i between 1997 and 2007, as well as some expected increase in vehicle efficiency (U.S. Department of Transportation, 2011), contributed to 16% decrease in per-capita fuel use by residents. For indirect fuel use, real estate and health services are responsible for 75% of the 23% increase.

For visitors, per-capita fuel use dropped by 21%. Considerable drop in direct fuel use (by 80%) and indirect demand for fuel through purchases of goods and services from hotels (30% less) and air transportation (13% less) account for 84% of decline in visitors' per-capita fuel use.

Decomposition of the changes in energy consumption

Although the Input-Output model helps us to understand the differences in the energy consumption pattern of each sector across economy, very little is known about the underlying factors behind these changes. I thus perform an analysis of decomposition of factors based on Divisia Index approach, a way of indexing technical changes.

Table 2.8: Decomposition of variation in energy consumption by sector, 1997-2007

			Activity	Structure	Intensity	Total
			A. Electricity			
Absolute Change	**(Δ: Additive)**	**MWh**	1,536,998	(34,100)	(611,581)	891,317
Relative Change	**(D: Multiplicative)**	**%**	41%	-1%	-13%	22%
			B. Fuel			
Absolute Change	**(Δ: Additive)**	**MMBTU**	62,855,863	489,951	(21,752,404)	41,593,410
Relative Change	**(D: Multiplicative)**	**%**	41%	0%	-11%	26%

Source: Author's calculations.

Table 2.8 presents the results of decomposing change in fuel and electricity in Hawai'i's economy. Electricity and fuel consumption increased by 22% (900 GWh) and 26% (41.6 million MMBTU) from 1997 to 2007, respectively. The LMDI decomposition breaks the change in energy consumption down into three main components of activity effect, structural effect, and intensity effect. The decomposition of changes in electricity and fuel consumption in Hawai‘i shows that (i) activity effect is the dominant contributor, accounting for 41% of that margins,[20] (ii) structural changes (i.e., introduction or elimination of energy intensive sector into economy) has no effect, as expected, and (iii) a reduction in energy intensity (13% in electricity and 11% in fuel) is an indication of improvement in energy efficiency, especially when the observed period is short enough to exclude the possibility of major breakthrough in production technologies.

Decomposition by sector also confirms that over the observed period of study, Hawai‘i has improved the efficiency of energy use, with electricity use (13%) experiencing greater efficiency gains than fuel use (11%). Table 2.9 presents the sectoral change in the electricity and energy consumption as well as per-dollar intensity by sector.

Indeed, over the decade, some of the industry sectors in Hawai‘i experienced a considerable drop in their electricity and fuel intensity per value of output, while other sectors experienced greater intensity. The most noticeable sector in our analysis is hotels, showing a significant drop in both absolute and per-output consumption terms (i.e., intensity) of both electricity and fuel over the observed decade. As the main component of the tourism industry, hotels experienced the largest improvement in electricity uses. The observed trend is explained in part by a wave of renovations and new development projects in the industry during early to mid-2000, spurred by Hawai‘i's tax credit incentives[21] for such projects in the State (Toy & Mak, 2003). Nonetheless, lower per-dollar (of output) energy intensity of hotels could also partially be due to higher number of tourists in 2007 compared to 1997.[22]

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[20] Hawai‘i economy's real output expanded by 41% from 1997 to 2007, from $74.9 billion to $105.8 billion (measured in 2007 dollar).

[21] The tax credit law was passed in 1997 and expired at the end of 2005. The original legislation provided a 4% tax credit on hotel renovation projects, which was later expanded to include new hotel construction, and for an interim period of post 9/11 until mid-2003 was increased to 10% of the costs.

[22] According to the State tourism data, hotels' average statewide occupancy rate, total visitor arrivals, and visitor days were all higher in 2007 than 1997.

Table 2.9: Change in energy consumption and intensity by sector, 1997-2007

	Change in Consumption	Change in Intensity (per $ output*)
A. Electricity	**MWh**	**Wh/$**
Agriculture	(22,689)	(6.0)
Manufacturing	(41,327)	(23.8)
Air transportation	(61,731)	(15.1)
Marine transportation	13,821	17.4
Ground transportation	(18,380)	(16.1)
Electricity	28,140	9.7
Fin. bus. prof. services	26,703	0.9
Trade	129,991	12.1
Real estate	103,807	7.2
Hotels	(17,880)	(4.3)
Restaurants	32,149	7.4
Health services	69,810	5.1
Other services	437,228	12.5
Government	211,675	12.9
Total indirect	891,317	
Direct use	339,590	
Total	1,260,775	
B. Fuel	**MMBTU**	**BTU/$**
Agriculture	1,246,109	2,533
Manufacturing	5,504,764	(58)
Air transportation	2,774,194	2,316
Marine transportation	2,260,378	2,716
Ground transportation	1,655,142	406
Electricity	(786,059)	(4,982)
Fin. bus. prof. services	1,015,497	56
Trade	5,148,180	493
Real estate	5,769,214	400
Hotels	(1,739,533)	(324)
Restaurants	(548,779)	(170)
Health services	4,149,474	526
Other services	7,472,517	89
Government	7,672,312	480
Total indirect	41,593,410	
Direct use	3,612,510	
Total	45,205,920	

* 1997 outputs are calculated in 2007 dollar.

Source: Author's calculation.

2.5 Conclusions

The purpose of this study is to use the Input-Output analysis methodology and data to analyze the fuel and electricity consumption patterns by residents and visitors in Hawai‘i for the base years of 1997 and 2007.

The findings reveal differences in fuel and electricity consumption patterns for residents and visitors in Hawai‘i. For residents, high indirect electricity consumption is associated with their purchase of health services, retail trade, real estate rentals, other professional services, and manufacturing. The focus for visitors, however, relates to their purchases of hotels, restaurants, other tourist services (such as arts and museums, tours and travel agencies, etc.), air transportation, real estate rental, and retail trade.

These differences are further highlighted when data of 1997 and 2007 are compared. Whereas fuel and electricity consumption rose for residents both overall and per-capita, they drop for visitors due to improved efficiency of both fuel and electricity usage in the tourism industry. In addition, the energy-use visitor factor for energy consumption improved substantially, dropping for fuels from 3.5 times in 1997 to 2.5 in 2007 and for electricity from 2.4 times to 1.5. When excluding air transportation effect, these estimates are further reduced. To better understand the changes observed in energy consumption in Hawai‘i between 1997 and 2007 I used the Logarithmic Mean Divisia Index (LMDI) methodology that allows us to establish which factors between activity, structural, and intensity made the greater contributions toward this tendency. Activity factors (i.e., change in the scale of economic activities due to economic growth in that period) were unsurprisingly found as the dominant factors of positive change in energy consumption, whereas structural factors (i.e., change in economic structure and interdependence of sectors on each other) were of little importance, and decrease in intensity factors (i.e., change in production technologies) firmly established improvement in energy efficiency.

These results are of considerable importance for the formulation of policies that are targeted to energy consumption in Hawai‘i. It appears that residents and visitors exhibit differences in their choices of energy consumption profile. Visitors’ energy expenditures are mainly targeted at limited sectors of the economy, such as hotel industry, that relies heavily on external factors. The industry has witnessed a noticeable decrease in energy intensity in their activities. Obviously, external factors that contribute to visitor's expenditures for fuels and electricity usages are parametric to policy makers in Hawai'i. On the other hand, energy expenditures for residents are affected by the industry sectors that are in tune with the local side of the economy. These sectors tend to be less efficient in the energy intensity of their activities due to the remoteness and fragmentation of the Hawaiian Islands that can hamper economies of scope in the production process evidenced among adjacent mainland states.

There are important areas in which extension of our study is likely to be fruitful. One is a better understanding of factors underlying demand for energy in the various industries of Hawai'i's economy. Information on these sectors is vital for energy planning, especially for electrical power generation, demand side management, and energy efficiency and conservation programs.

Essay 3: Optimal Hybrid Instrument For Climate Policy Under Uncertainty; An Application For The U.S.

3.1 Introduction

Background and Motivation

Climate change policy is a controversial topic, mainly because of uncertainties in the extent of environmental impacts, damage costs, and mitigation costs. The dynamic nature of both uncertainty and climate change complicates the choice of policy instrument. In the presence of uncertainty, generally speaking, hybrid instruments—ones that combine features of price and quantity instruments—offer a more flexible approach, minimizing the risk associated with setting a specific price or quantity to restrict emissions. Several studies have discussed the welfare-enhancing features of hybrid policies in a qualitative framework. Others have compared hybrid policies by measuring welfare loss in a stochastic dynamic setting where marginal benefit and cost function parameters are randomly assigned. However, none have actually solved for the optimal hybrid policy parameters in the context of climate change. This paper seeks to fill this gap by providing a theoretical welfare analysis and to contribute to the U.S. climate policy literature using a numerical example.

To address the role of uncertainty in climate policy, the challenge lies in finding a balancing point between environmental and economic concerns (i.e., minimizing both social damage costs and distortionary burden). Japan's current situation, following the Fukushima earthquake and tsunami of 2011 provides insight into the importance of setting the right policy. Japan has been one of the leading nations in its commitment to reducing greenhouse gas emissions. In 1997, Japan immediately adopted the Kyoto protocol and extended its commitment in 2010 at the 16th Conference of Parties (King, Richards, & Tyldesley, 2011).[23] When Japan lost almost all of its nuclear supply (50 reactors totaling 44.4 GW) after Fukushima, it was forced to dramatically increase its use of fossil fuels to supply the 30% of base-load power, previously generated by nuclear (World Nuclear Association, 2013). Along with natural gas and crude oil, increasing amounts of coal—the dirtiest fuel in terms of CO_2 emissions—are being burned in existing power plants. Moreover, Japan has eased the environmental permit process to allow new coal power plants to come online sooner. Therefore, Japan, once at the forefront of reducing GHG emissions, has now taken leaps backward, giving carbon issues a lower priority behind economic growth; Japan did not renew its commitment to the Kyoto protocol's second round in 2011.

One implication of Japan's turn of events is a substantial increase in abatement costs. Having no option but to burn additional amounts of fossil fuels entails two types of abatement costs: 1) investment in advanced technologies to minimize emissions at the point of generation (e.g. clean coal technology and back-end controls); and 2) purchase of carbon credits to offset extra emissions.[24] This unexpected upward shift in the marginal cost of reducing GHG emissions provides a real world example of uncertainty and highlights the need to consider uncertainty in solving for an optimal climate policy.

There are various sources of uncertainty in climate change economics—marginal abatement cost and marginal damage costs of greenhouse gas (GHG) emissions. Martin Weitzman, who first introduced analysis of uncertainty in policy instrument choice in his 1974 article, grouped climate change uncertainties under two main categories: "known unknowns" and "unknown unknowns" (Weitzman, 2011). For example, "known unknowns" in the marginal damage cost function include, but are not limited to: unknown baseline GHG emissions; unknown effects of future policies—set by individual countries,

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[23] At the 16th Conference of the Parties (COP) held in Cancun 2010, the only two countries that committed to cut their emissions larger than 20% below 1990 levels by 2020 were Norway (30-40% below 1990 levels by 2020) and Japan (25% below 1990 levels by 2020).

[24] CO_2 emissions from Japan's power sector increased to levels 39% greater than what it was prior to the Fukushima incident. Currently, power sector is emits some 100 million tonne of CO_2 more than it used to, when the reactors were operating, increasing Japan's carbon emissions by 8% (World Nuclear Association, 2013).

unilaterally, or international agreements—on actual global GHG emissions; unknown accumulation of GHG emissions flow into GHG stock concentrations; unknown impact of GHG stock concentrations on global average temperature changes; unknown impact of increase in global average temperature on regional weather patterns; unknown impact of regional climate change adaptation and mitigation activities on a global damage/disutility function; and, unknown optimal global risk aversion and discount rate on future climate damages. On top of these "known unknowns," "unknowns unknowns" such as natural disasters, like Fukushima could shift the magnitude of costs.

Likewise, marginal abatement cost has its own "known unknowns." In a dynamic setting, where future abatement costs are modeled, any change in future baseline emissions could shift the abatement curve. Moreover, unknown levels of R&D and technological advancements are the main sources of uncertainty. In static models, such as the one offered in this study, abatement cost uncertainty could be explained by several sources, including but not limited to: unknown modeling error[25]; unknown GHG emissions measurement error[26]; unexpected change in national energy system (e.g., the above Japan example); unknown short-term energy price shocks[27] (e.g., the unexpected oil price fluctuations of 2008-2009); unknown global and national economic growth rate[28].

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[25] The economic approaches often make simplistic assumptions to model a complicated economy in order to derive their estimates. On the other hand, engineering approaches consider a limited set of technologies and overlook many other options, and even for those that they consider, they have to use the existing—and in some cases dated—information on the technology costs. Furthermore, both economic and engineering approaches make assumptions on the extent of cost-saving or no-cost emissions reduction technologies, which could be over or under estimated. In addition, to derive an economy-wide abatement cost curve, they have to make assumptions about the state of current technologies. Nordhaus (2013) gives an example of such assumption: "In an estimating the cost of reducing CO_2 emissions from power plants, they often assume that all power plants are new. This would lead for a big advantage for low-emissions gas plants over high-emissions coal plants. In reality, for existing capital, the generation costs for coal are lower than those for new gas plants."

[26] As most nation-wide GHG emissions estimates are derived from top-down calculation (based on total volume of fuels and activities) instead of bottom-up models (aggregating firm level emissions), there are many assumptions made including a similar emission factor for all activities of alike. They also include non-measured estimates of GHG emissions sources and sinks coming from land-use and land-use change, which could introduce some measurement error.

[27] Klepper and Peterson (2006) investigate the influence of world energy prices on MAC curve. They show the major influence of fossil fuel price effect on marginal abatement cost, i.e., lower fossil fuel prices shift the curve upward.

[28] Fell et al. (2012a) investigate the impact of baseline emissions and offset supply uncertainty on abatement cost uncertainty, both of which are consequences of unexpected GDP growth.

Previous Work

There is extensive literature on the importance of uncertainty in the optimal policy design with regard to various environmental issues such as air pollution, water management, and in the last decade, most prominently, climate change. The original work on the impact of uncertainty on the optimal policy design, which began in the mid-1970s, showed that the superiority of control mode with respect to social welfare loss depends on the pattern of uncertainty in the marginal benefit of emissions reduction (referred to then as 'cost of avoidance') and not the marginal damage cost (Adar & Griffin, 1976; Fishelson, 1976; Weitzman, 1974). Stavins (1996) considered uncertainties in both marginal benefits and marginal costs and tried to identify the efficient policy instrument using the statistical relationship among them.[29] He found that the preferred instrument is a quantity-based instrument when the uncertainties are positively correlated, and a price-based instrument in the opposite case.

Weitzman's seminal paper (1974) on whether to use a price instrument versus a quantity instrument concludes that "in some situations," a 'mixed' instrument could provide the best results. A series of follow up research delves into hybrid (mixed) policy instruments.

Roberts and Spence (1976), for example, introduced a two-level tax schedule, a step function, by coupling a cap-and-trade system with price collars (i.e., price floor and price ceiling). Depending on the choice of the parameters, the policy can thus mimic either a pure tax (price) or a pure cap-and-trade (quantity) system. They conclude that when the marginal benefit of emission is uncertain, such combination is superior to either price or quantity control alone, due to its advantage in better approximation of the optimal relationship between pollution levels and damages. I chose this as the first hybrid policy (Policy 1: Two-Step Carbon Tax) to solve for the optimal design. Despite having features of both instruments, this hybrid setup is closer to a price-based mechanism since it allows the market to decide the ultimate quantity when a ceiling is set on the price.

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[29] Weitzman (1974) also analyzed the role of correlated uncertainty in benefit and cost on the policy choice.

Based on Roberts and Spence's two-step hybrid system, Weitzman (1978) suggested an infinite-step version where the tax level at each step is proportional to the quadratic penalty of departure from the quantity target. Later work on carbon regulation and climate policy by Kopp, et al. (1997), McKibbin and Wilcoxen (1997a), Pizer (2002), and Newell, et al. (2005) builds upon the cap-and-trade mechanism and introduces a safety valve or trigger price that effectively caps allowance (permit) prices by providing an unlimited supply of additional permits at a predetermined high price. They showed that this mechanism could lead to more efficient price policies.

In Pizer's (2002) "Cap-and-Trade with Safety Valve" hybrid system, also based on Roberts and Spence's model, a cap-and-trade system is coupled with a price ceiling at which additional allowances can be purchased (in excess of the cap). As long as the allowance price is below the safety-valve price, this hybrid system acts like cap-and-trade, with emissions fixed and the price left to adjust. When the safety-valve price is reached, this system behaves like a tax, fixing the price but leaving emissions to adjust. Pizer claims that his hybrid policy improves the flexibility, welfare outcomes, and credibility of the instrument compared with the alternatives of pure quantity or price.

More recently, Murray et al. (2009) developed Pizer's idea further by adding a limit on the quantity of higher-priced permits (i.e., limiting the size of the 'safety valve') and called their hybrid model a "Cap-and-Trade with Allowance Reserve." The allowance reserve in their policy design addresses several shortcomings of Roberts and Spence's idea and introduces more flexibility in the elements of policy design. An important motivation for adding the allowance reserve to a hybrid policy system, among others, is the ability to capture the dynamic nature of the problem. This is particularly crucial in the early years of a program when cost uncertainty is high so initial prices should be anchored near or below the ceiling price. They believed that introducing about 10-20 percent of the cap as annual allowance reserves could sufficiently address the short-term uncertainty in the costs, while longer-term expectations would determine the near-term prices (Murray et al., 2009). I chose this design as the second hybrid policy for our analysis (Policy 2: Cap-and-Trade with Allowance Reserve). This contrasts with our first hybrid policy, which is closer to a price-based mechanism. Since the Cap-and-Trade with Allowance Reserve resembles a more quantity-based mechanism, the market decides the ultimate price when a ceiling is set on the quantity. I compare the economic efficiency of the two optimal hybrid policy designs under uncertainty, based on their expected welfare loss given the same assumptions on costs and uncertainties.

Since hybrid policies have become common policy instruments, many studies have compared them with traditional price and quantity instruments in order to find the optimal policy design. Most of the existing literature only discusses the pros and cons of the policies from economic and political aspects. For example, Burney (2010) provides a comprehensive comparison of viability and policy considerations with respect to a carbon tax or cap-and-trade policy to address the GHG emissions externality. Aldy et al. (2010) also discusses policy design options from various aspects of regulatory implementation issues. In a survey, Aldy and Stavins (2011) briefly review the major climate change policy instruments and the experiences from the few existing carbon pricing policy regimes at international, national, and regional levels.

This chapter's analysis, however, belongs to a second group of studies that goes beyond a qualitative analysis and instead quantitatively compares their impact and efficacy. Fell and Morgenstern (2010), for instance, conduct a simulation exercise using a dynamic model with stochastic baseline emissions to compare carbon policy instruments. They specifically set the parameters of their model to values relevant to proposed U.S. climate mitigation policies and find that both price collars and banking-borrowing[30] are two welfare-enhancing features compared with the simple cap-and-trade policy. Webster et al. (2010) use a Monte Carlo simulation to compare four types of second-best carbon policies—emissions cap, carbon tax, cap and trade with safety valve, and an intensity target. They draw 1,000 random samples of parameter values to run their CGE model under the four scenarios and compare with their reference case of 'no policy'. They conclude that under uncertainty in future economic growth and abatement costs, setting an emissions cap could impose high costs and welfare loss on the economy. While they argue that a carbon tax is the preferred

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[30] The banking and borrowing options allow the permit holders to use their unused allowances for future or borrowing future allowances for today's use.

economic instrument for carbon emissions, due to its political unattractiveness, they favor either cap-and-trade with safety valve or intensity target.

Meanwhile, this analysis is the first to solve parametrically for the optimal hybrid policy under uncertainty and compare the outcomes numerically with respect to their expected welfare loss. This paper replicates Weitzman's methodology, centered on maximizing welfare, to solve for two optimal hybrid policies' parameters. As opposed to the stochastic approach adopted by Fell and Morgenstern (2010) and Webster et al. (2010) to model uncertainty for the purpose of policy comparison, our approach is more realistic and easier to implement. I assume that policy makers first choose an expected benchmark for the model parameter and then limit the range of uncertainty. Although this paper solves for the optimal policy design using simple distribution functions (discrete n-point distribution), one could always apply the same method for a different distribution like continuous uniform distribution.

I bypass the conventional price and quantity mechanisms and focus on the two common hybrid policies in our analysis. Policy 1, Two-Step Carbon Tax is considered a price-driven mechanism and Policy 2, Cap-and-Trade with Allowance Reserve is a quantity-driven mechanism.

Then, to quantify the solutions and compare them with respect to their expected welfare loss, I numerically solve for both hybrid policies. To contribute to the U.S. climate policy literature, I set the model's parameters to U.S.-specific values. In our thought experiment, the two-step tax policy is ranked above the cap-and-trade with allowance reserve in terms of social welfare loss, given the same cost and uncertainty parameters.

3.2 Uncertainty

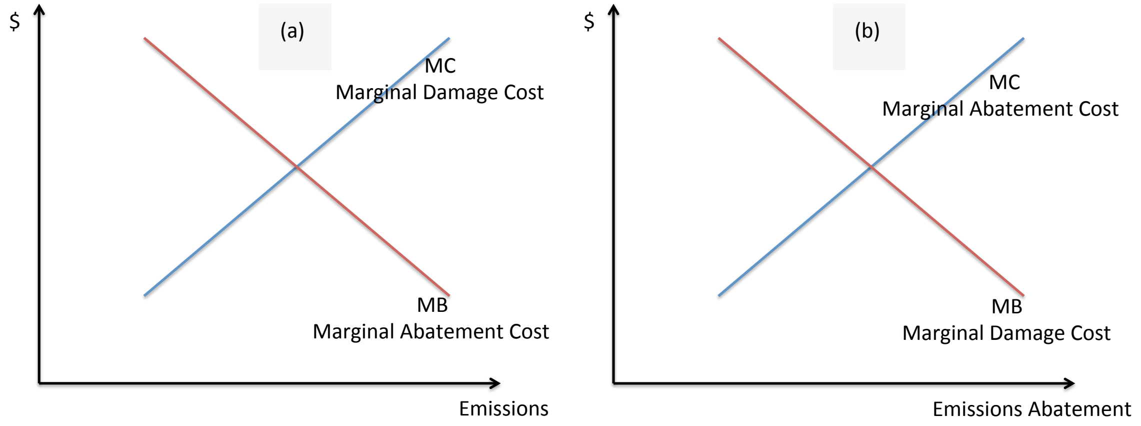
This section provides some background on the concepts of marginal benefit and marginal cost functions in the context of climate change, as well as the importance and implications of uncertainty.

In an ideal world where there is complete information and marginal cost and benefit curves are certain, the two market-based policy instruments—setting either prices (e.g., taxes or subsidies) or quantities (e.g., tradable permits)—perform equally well in terms of economic efficiency and yield the same level of output.

In the real world, however, both marginal curves are uncertain. Adding uncertainty to the marginal cost and benefit curves changes the analysis. Cost functions measure the damage cost of emissions to the environment. Future damages to the environment are often partially unknown, for which the costs are uncertain and difficult to estimate. Benefit function, on the other hand, measures the cost of emission abatements, which depends on the availability and the cost of abatement technologies. The uncertainty in future technologies could cause different abatement costs to be realized than expected today, especially at the aggregate level (as opposed to one single emission source at the firm level) for the entire economy. In the presence of uncertainty, neither prices nor quantities would achieve the first-best optimal output.

The interpretation of marginal curves depends on the control variable in the cost and benefit functions. If the control variable measures the quantity of emissions, then an upward sloping marginal cost curve would represent increasing marginal damage cost and a downward sloping marginal benefit would represent decreasing marginal abatement cost (Figure 3.1, panel a). On the other hand, assuming the control variable measures the quantity of emissions abated, then an increasing marginal cost curve would exhibit increasing abatement costs and a downward sloping marginal benefit curve would illustrate decreasing marginal damage cost (Figure 3.1, panel b). In fact, when changing the control variable from emissions to abatement, the role of marginal curves in the analyses (such as Weitzman's analysis on the relative slope of the marginal cost curve with respect to the marginal benefit curve) flips.

In this study (model and results), when cost and benefit functions are discussed, I follow the first definition (presented in panel a, Figure 3.1) and assume the control variable to be the emissions quantity.



a: Control variable is emissions

b: Control variable is emissions abatement

Figure 3.1. Interpretation of marginal benefit and marginal cost curves.[31]

Since uncertainty is a necessary part of this problem, Weitzman (1974) tried to find the preferred policy instrument in the presence of uncertainty while minimizing the expected welfare loss. Considering only abatement cost uncertainty (i.e., MB in our setup), his analysis shows that the choice of instrument relies on the relative slopes of marginal benefits and costs such that the marginal curves are linearly approximated and uncertainty shifts the marginal curves rather than their slopes. Figure 3.2 graphically presents his conclusion under the two possible situations.

In Figure 3.2, t represents the Pigouvian tax level (price instrument) to achieve the expected socially optimal emission reduction (given $MC_{expected}$) and Q is the quantity of tradable permits (quantity instrument) allocated to achieve the same goal. Assuming a different MC realization (i.e., MC_{real}), the *ex post* efficient level of emissions abatement is q^*.

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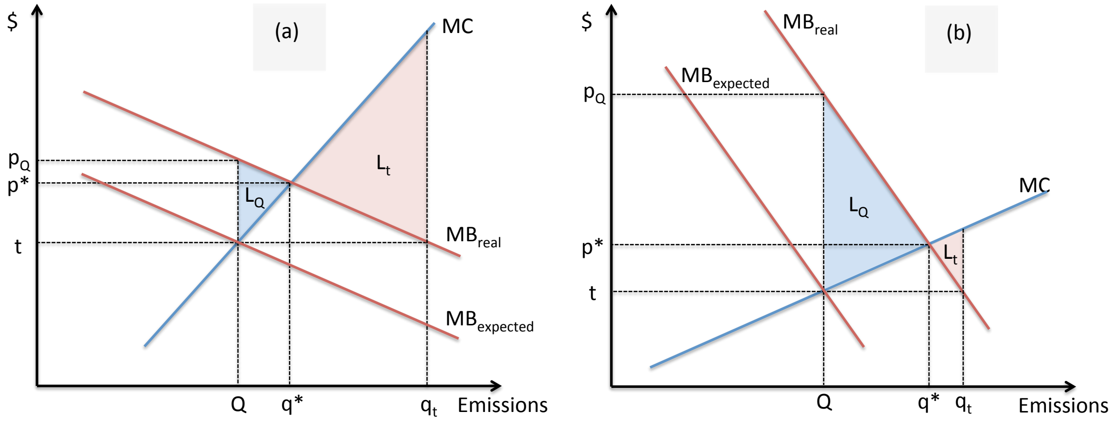
[31] In all graphical presentations in this paper, we conform to the following color coding: red lines represent marginal benefit functions, blue lines represent marginal cost functions, and solid black likes represent the policy schedule.



a: MC curve is relatively steeper than MB b: MC curve is relatively flatter than MB

Figure 3.2. Instrument efficiency under marginal cost uncertainty.

Therefore, in Figure 3.2, the blue triangles represent the efficiency loss should the emissions are capped at level *Q* while pink triangles represent the loss when the policy makers tax the emissions at $*t* per unit of emissions. Clearly, when the MC curve is relatively steeper than the MB curve, the loss associated with the quantity instrument is significantly less than that of the permit program; and a price instrument would be the preferred option when MC function is relatively flatter than the MB function.

3.3 Model

Following Weitzman (1974), almost all the existing literature on environmental regulation policy assumes linear marginal cost and benefit curves (Mason, Polasky, & Tarui, 2011; Newell & Pizer, 2003; Stranlund & Ben-Haim, 2008). This implies quadratic benefit (abatement cost) and cost (damage cost) functions.[32] I maintain the same assumptions and specify the cost and benefit functions as quadratic forms.

$$B(q) = B_0 + B_1 q + (B_2/2)q^2 \quad , \quad C(q) = C_0 + C_1 q + (C_2/2)q^2 \qquad (1)$$

where q represents the emission quantity, and B_is and C_i's are parameters where $B_2 < 0$ and $C_2 > 0$.

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[32] Weitzman's choice of quadratic costs and benefits was an approximation around the optimal quantity. He explained that as long as the approximation holds over the likely neighborhood of the parameters, the results should be valid.

Such cost and benefit functions then imply the linear marginal cost and benefit functions as follows:

$$MB(q) = B_1 + B_2 q \quad , \quad MC(q) = C_1 + C_2 q \tag{2}$$

To introduce the uncertainty into the benefit and cost functions, I follow the conventional approach in the literature to add the uncertainty parameters θ_b and θ_c to the model.[33] As in Weitzman's model (and many other studies with a static model), I assume additive uncertainty, which affects only the level and not the slope of marginal functions (see Figure 3.3). Hence, the functions with uncertainty terms are:

$$B(q) = B_0 + (B_1 + \theta_b)q + (B_2/2)q^2 \quad , \quad C(q) = C_0 + (C_1 + \theta_c)q + (C_2/2)q^2 \tag{3}$$

$$MB(q) = (B_1 + \theta_b) + B_2 q \quad , \quad MC(q) = (C_1 + \theta_c) + C_2 q \tag{4}$$

Although many studies on the impact of uncertainty in policy choice have modeled uncertainty in additive form—mainly due to mathematical convenience—Hoel and Karp (2001) derive the optimal policy under multiplicative uncertainty, assuming the slopes of marginal cost and benefit functions to be uncertain rather than the intercept. Although they argue that additive uncertainty is unable to answer questions on the optimal policy choice in a plausible and intelligent way, they cannot provide any reason for the multiplicative form of uncertainty to be any more realistic than the additive form and their analysis produced the same policy ranking as the other similar analyses with additive approaches.

More specifically, in the context of climate change where marginal cost curves are assumed to be almost flat, the above choice of uncertainty for MC function is the more appropriate method. For MB function, however, different slopes have been estimated by different studies, which could justify the use of multiplicative uncertainty. Therefore, I model multiplicative uncertainty for MB function in Appendix IV, solve for the parametric optimal solutions of section 3.5, and as a robustness check for our results in section 3.6, I derive the U.S.-specific policy designs. The results, however, show little impact on parameter values and no impact on the ranking of two policies in our numerical example.

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[33] The uncertainties are assumed to be independent of each other.

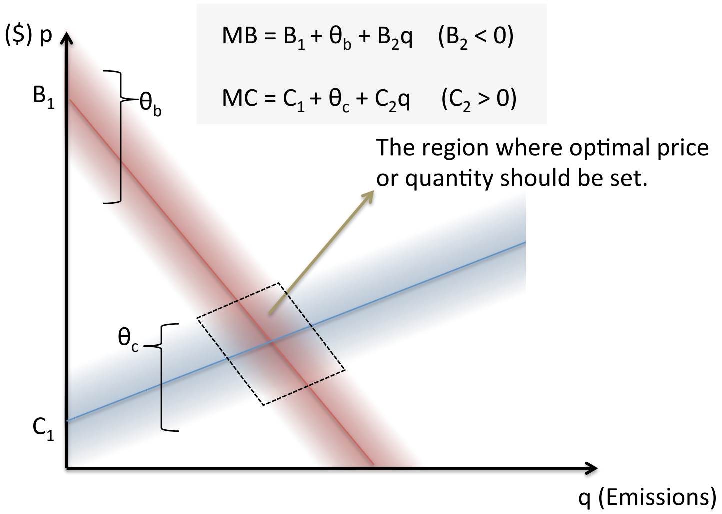

Figure 3.3. Marginal functions with uncertainty

Under uncertainty, the regulator should implement an ex-ante optimal policy; that is, design the policy with respect to the expectations about the marginal benefit and marginal cost curve. After realizing the actual costs and benefits, and depending on the outcome, the difference between the ex-ante optimal policy and the ex-post optimal policy (the optimal policy with the actual cost curves, as opposed to the expected ones used in designing the ex-ante optimal policy) is considered the social welfare loss.

Although Weitzman and other theoretical scholars have characterized uncertainty by known moments of probability distribution functions (i.e., means and variances), in this paper, for simplicity, I assume n-point discrete probability distribution for uncertainty. For example, the 2-point distribution assumes that uncertainty is limited around the mean of the marginal costs, where uncertainty in the costs enters through the upper (max) and lower (min) bounds. Figure 3.4 illustrates uncertainty modeling with a 2-point distribution.

In this simple setup, with four possible combinations of marginal benefit and cost functions presented in Figure 3.4 (i.e., high-high, high-low, low-high, and low-low), a first-best policy[34] is guaranteed when the price (or quantity) is optimal regardless of what outcome is realized. In other words, the policy line should pass through all the points where marginal

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[34] First-best policy, that by definition creates no welfare loss, sets a price on emissions at *p** or sets a cap on emissions at *Q**. Optimal price and quantity levels (i.e., *p** and *Q**) are where emissions' MC equals MB.

cost could equal marginal benefit. An example of such policy is shown graphically by solid black line in Figure 3.4. One way to implement such policy is to design a 4-tier permit system, in which four types of permits (i.e., tier 1 to 4) are provided to the market at four different prices (i.e., p_{LH}, p_{LL}, p_{HH}, and p_{HL}). Although the optimal price levels are solved as interaction of MC and MB alternatives, the amount of tier 1, tier 2, and tier 3 permits could be arbitrarily chosen as long as the levers lie properly between the optimal quantities (i.e., $Q_{LH}<q_1<Q_{LL}$, $Q_{LL}<q_2<Q_{HH}$, and $Q_{HH}<q_3<Q_{HL}$). Obviously, tier 4 permits are infinitely provided.

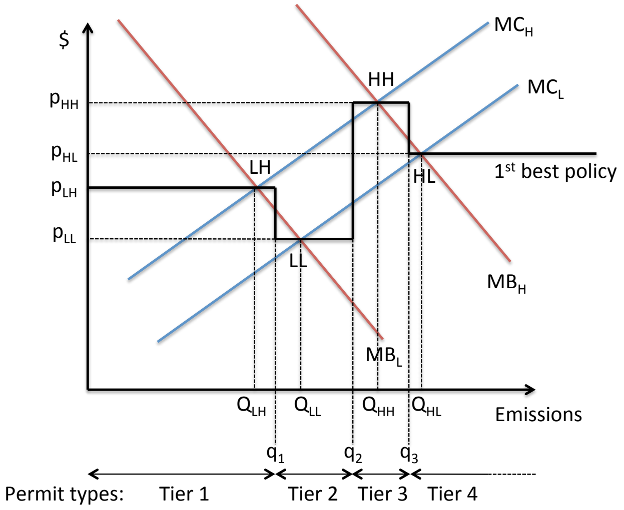

Figure 3.4. First-best policy in the two-value uncertainty case

The above policy is hard to understand, design, and implement. For example, it is not clear how to provide the market with cheaper tier 2 permits after tier 1 permits are sold at a higher price, without sending the wrong signal to emitting firms or creating inefficient outcome as a result of an unintended arbitrage opportunity. This example explains Weitzman's conclusion that setting a profile of ideal prices or quantities is a complicated and specialized contract, an expensive process, and is hard to understand, when pure instruments are "simple messages, easily comprehended, traditionally employed, and frequently contrasted" (Weitzman, 1974).

3.4 Policy Designs

Below, I first outline the two hybrid policies that are solved for the optimal design parameters under uncertainty in section 3.5. The first policy resembles a price-based mechanism in its features, while the second policy has features closer to a quantity-based mechanism.

Policy 1: Two-Step Tax Policy

The two-step tax policy (also known as cap-and-trade with price collars) is one of the first hybrid policy instruments that was proposed to address uncertainty in Robert and Spence's (1976) hybrid policy. Based on their design, many climate change economists have suggested a step-wise tax policy design for practical use in global coordination, which provides a fixed number of tradable, long-term emission permits, together with an elastic supply of short-term permits (Kopp et al., 1997; McKibbin & Wilcoxen, 1997a, 1997b; Mckibbin & Wilcoxen, 2002). While long-term emission permits restrict the total amount of emissions, the short-run elastic supply of permits with a fixed higher-price is created to avoid the loss from unexpectedly high marginal benefit of emissions.

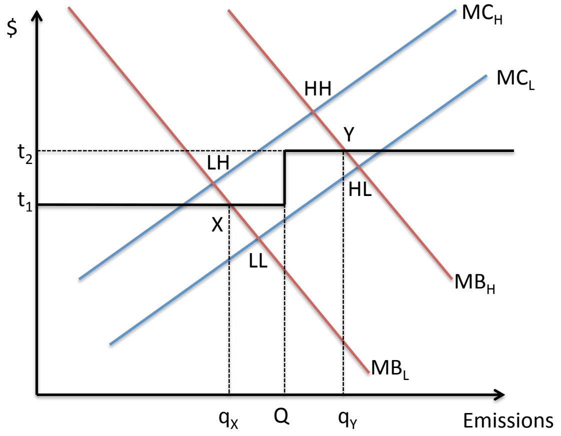

Figure 3.5. Two-step tax policy

The graphical analysis of the policy is shown in Figure 3.5. In this case, the government sets the three parameters t_1, t_2, and Q; the solutions to the optimization problem. In this setup, government sells fixed amount of emission permits (Q) at price t_1 (i.e., taxing the first Q quantity of emissions at tax level t_1). The permit holders could exchange their permits in the market as long as the price stays below t_2, as government offers unlimited emissions permits at a higher price of t_2 to the market (i.e., taxing the emission beyond Q quantity of emissions at tax level t_2).

The crucial advantages of this policy over the first-best policy design are (i) it does not depend on the market outcome so the government can set the rules prior, (ii) the central planner does not need information at the individual level to set the policy, and (iii) it is more practical in terms of administration.[35] Such characteristics make the policy more practical than the first-best solution to planners and enforcement entities. However, a major challenge the planner faces in this setup is the fair distribution of the low-price permit (Q).

In the following section (Section 3.5), I solve for the optimal design of a two-step tax policy in the presence of uncertainties, with the objective of maximizing the expected social welfare.

Policy 2: Cap-and-Trade with Allowance Reserve

"Cap-and-Trade with Allowance Reserve" hybrid system (Murray et al., 2009) is very similar to the policy adopted by the climate change bills introduced in both U.S. House[36] and Senate.[37] In this system, like the previous hybrid policy, while the total amount of emission is initially capped by long-term emission permits, the short-run elastic supply of permit at a higher price, t_2, is created to avoid the loss from unexpectedly high marginal benefit of emission. However, this supply is also limited by a specific number of allowances, called "Allowance Reserve."

The Cap-and-Trade with Allowance Reserve system has an advantage of increased environmental integrity over the previous policy. In a two-step tax policy (cap-and-trade with price collars), compared with typical cap-and-trade systems, supply of permits is more elastic and the volatility of allowance prices is reduced, especially in a dynamic framework where banking and borrowing options are available. But that also implies less certainty in environmental performance, when unlimited additional allowances are available at the price ceiling. This risk is addressed by introducing a second cap (also known as hard cap) by limiting the number of allowances to a specific "reserve," after which no additional permits

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[35] Other advantages of this hybrid instrument can be found in Mckibbin and Wilcoxen (2002), and Kopp, Morgenstern, and Pizer (1997).

[36] The American Clean Energy and Security Act of 2009 (H.R. 2454) [aka "Waxman-Markey Bill"].

[37] Clean Energy Jobs and American Power Act (S.1733) [aka "Kerry-Boxer Climate Bill"].

are available and the remaining permits in the market will be traded at a market price equal the marginal benefit of emission at that level (i.e., the maximum emission allowed by the available permits). Golub and Keohane (2012) investigate the efficacy of 'allowance reserve' using the Monte Carlo approach (by drawing random parameters for marginal abatement cost function and the size of allowance reserve). They show that such feature helps smooth out the response of prices to significant but temporary shocks. The graphical analysis of the policy is shown in Figure 3.6.

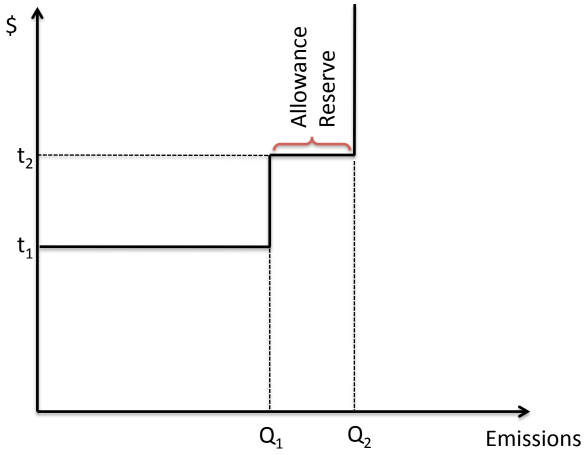

Figure 3.6. Cap-and-trade with allowance reserve hybrid system

In this case, government sets t_1, t_2, Q_1 and Q_2, which solve the optimization problem. The main difference between this setup and the two-step tax policy is the amount of allowance reserve. That is, the supply of higher-priced permits is limited to $Q_2 - Q_1$ (i.e., allowance reserve), after which those in need of permits for extra emissions should purchase them at the market from permit holders.

By increasing the amount of allowance reserve to infinity, however, I will see that the two-step hybrid system is a specific case of this system. In fact, one of the benefits of this hybrid system is that by changing the four parameters, t_1, t_2, Q_1, and Q_2, I can mimic a pure tax system (setting $Q_1 = 0$, $t_2 =$ tax/price, $Q_2 = \infty$), a pure quantity or cap-and-trade system (setting $Q_1 = Q_2 =$ cap/quantity, $t_1 = 0$), a cap-and-trade with safety valve system (setting $t_1 = 0$, $Q_1 =$ cap/quantity, $t_2 =$ safety-valve price, $Q_2 = \infty$), or a two-step hybrid system (setting t_1 = first tax level, Q_1 = cap/maximum emission allowed under first tax regime, t_2 = second tax level, $Q_2 = \infty$).

Murray et al. (2009) discussed several reasons for introducing allowance reserve to the simple two-step hybrid system. In general, the allowance reserve addresses several shortcomings of the two-step tax policy. First, a fourth parameter, Q_2, adds more flexibility in the elements of policy design to balance competing political interests. Flexibility in the size of the allowance reserve can increase the probability for a welfare-enhancing policy to be enacted. It also solves an important technical problem that arises when allowance banking occurs in a dynamic world. In general, banking can help equilibrate present value prices across different time periods and increase dynamic efficiency, but when coupled with a safety valve, can lead to a dynamic problem in policy design due to in-place plans for tightening the cap at specific future dates (similar to different proposed national legislations in the U.S.). Without the allowance reserve, higher expected future prices would lead rational firms to buy as many allowances as possible at the current low price, which could effectively overwhelm efforts to tighten the future cap, therefore undermining the optimal policy goals. Placing an upper limit on the available extra allowances, therefore addresses this potential problem.

Finally, an allowance reserve supports the notion of a flexible cap-and-trade system that seeks to achieve an inter-temporal optimum, by capturing the dynamic nature of the regulatory process. This is particularly important in the early years of a program when uncertainty is greater and every actor is still trying to understand how the new market works. Allowance reserves therefore could secure initial prices near or below the ceiling price and help the market toward equilibrium. Murray et al. (2009) introduces this hybrid system as a legitimate solution besides simply a political solution. They believe that faced with considerable uncertainties in costs and benefits of greenhouse gas mitigation today, "a cap-and-trade system with an allowance reserve is well supported by an economic view of efficient long-term climate policy."

3.5 Optimal Design Under Uncertainty

In this section, I solve for the optimal design parameters for the two policies discussed in section 3.4, given some assumptions on the uncertainty distribution of the marginal functions.

Policy 1: Two-Step Carbon Tax

The simplest setup for this design is a two-point uncertainty in both marginal cost and marginal benefit functions. Although there are possible solutions for the design parameters in the setup (presented and solved in Appendix I), it lacks a unique optimal solution.

Hence, solving for a unique set of all policy parameters requires a minimum of three-point uncertainty in marginal benefit, within the estimated uncertainty boundary (explained in Appendix 3.I). As shown in Figure 3.7, the optimization problem now entails finding points X, Y, and Z, at which the expected welfare loss is minimized.

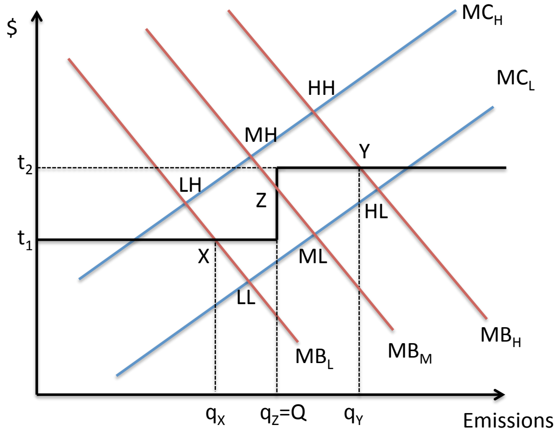

Figure 3.7. Three-point uncertainty in MB

Assume the model explained in section 3.3, with the marginal functions as in equation (4). Assume further that uncertainty parameter θ_c take only two values, high and low, and θ_b takes three values of low, medium, and high (Figure 3.7). In this case:

$$\theta_c = \begin{cases} c_L \\ c_H \end{cases} \text{with probability} \quad \begin{matrix} \pi_L^c \\ \pi_H^c = 1 - \pi^c \end{matrix} \quad , \ \theta_b = \begin{cases} b_L \\ b_M \\ b_H \end{cases} \text{with probability} \quad \begin{matrix} \pi_L^b \\ \pi_M^b \\ \pi_H^b = 1 - \pi_M^b - \pi_L^b \end{matrix} \quad .$$

Polluters decide how much to emit based on the comparison between tax (their cost) and the marginal abatement cost (i.e., *MB*); they will emit if tax < *MB*. Because the decision to emit does not depend on the *MC* schedule, government is only interested in the intersection points of the tax schedule and *MB* lines (X, Y and Z in Figure 3.7).

The objective, thus, is to find the X, Y, and Z (or rather q_X, q_Y, and q_Z) that minimize expected welfare loss. The optimization problem is:

$$Min_{q_X, q_Y, q_Z} E(L) = \sum_{s \in \{\mathrm{LL, ML, HL, LH, MH, HH}\}} \Pi(s) L(s) \tag{5}$$

where $E(L)$ is the expected welfare loss,

$\Pi(s)$ is the probability that situation s will happen,

$L(s)$ is the welfare loss under situation s, and

s is a situation among all the possible uncertainty outcomes that could be realized.

For example, let's assume that both marginal benefit and marginal cost are realized at their low level (i.e., MB_L and MC_L). The optimal emission level will always be where $MB = MC$ (i.e., at the point LL).

In this case, with probability of occurrence being $\pi_L^b \pi_L^c$, the welfare loss is $L = \int_{q_X}^{q_{LL}} \{MB_L - MC_L\} dq = \int_{q_X}^{q_{LL}} \{(B_1 + b_L + B_2 q) - (C_1 + c_L + C_2 q)\} dq$. Therefore, the overall expected welfare loss will be:

$$\begin{aligned} E(L) = {} & \pi_L^b \pi_H^c \int_{q_{LH}}^{q_X} \{MC_H - MB_L\} dq + \pi_L^b \pi_L^c \int_{q_X}^{q_{LL}} \{MB_L - MC_L\} dq \\ & + \pi_M^b \pi_H^c \int_{q_{MH}}^{q_Z} \{MC_H - MB_M\} dq + \pi_M^b \pi_L^c \int_{q_Z}^{q_{ML}} \{MB_M - MC_L\} dq \\ & + \pi_H^b \pi_H^c \int_{q_{HH}}^{q_Y} \{MC_H - MB_H\} dq + \pi_H^b \pi_L^c \int_{q_Y}^{q_{HL}} \{MB_H - MC_L\} dq \end{aligned} \tag{6}$$

Solving the optimization problem in (6), the optimum emission levels will be:

$$q_X = \frac{B_1 + b_L - C_1 - \pi_L^c c_L - \pi_H^c c_H}{C_2 - B_2} = \frac{B_1 + b_L - C_1 - E(\theta_c)}{C_2 - B_2} \tag{7}$$

$$q_Z = \frac{B_1 + b_M - C_1 - \pi_L^c c_L - \pi_H^c c_H}{C_2 - B_2} = \frac{B_1 + b_M - C_1 - E(\theta_c)}{C_2 - B_2} \tag{8}$$

$$q_Y = \frac{B_1 + b_H - C_1 - \pi_L^c c_L - \pi_H^c c_H}{C_2 - B_2} = \frac{B_1 + b_H - C_1 - E(\theta_c)}{C_2 - B_2} \tag{9}$$

It is clear that $q_Y > q_Z > q_X$, and $p_y > p_z > p_x$ (where p_i is the price corresponding to point i in Figure 3.7), so there is a unique corresponding optimal policy design which passes through X, Y, and Z. The optimal two-step tax policy then is to set the design parameters as follows:

$$t_1 = B_1 + b_L + B_2 q_X = \frac{B_1 C_2 + b_L C_2 - B_2 C_1 - B_2 E(\theta_c)}{C_2 - B_2}, \tag{10}$$

$$t_2 = B_1 + b_H + B_2 q_Y = \frac{B_1 C_2 + b_H C_2 - B_2 C_1 - B_2 E(\theta_c)}{C_2 - B_2}, \text{ and} \tag{11}$$

$$Q = q_Z = \frac{B_1 + b_M - C_1 - E(\theta_c)}{C_2 - B_2}. \tag{12}$$

Policy 2: Cap-and-Trade with Allowance Reserve

Based on the same assumptions and methodology used to solve for the optimal design of first best policy, I solve for the optimal design parameters of a cap-and-trade with the allowance reserve hybrid system, under a four-point uncertainty in *MB* and a two-value uncertainty in *MC* (see Figure 3.8).

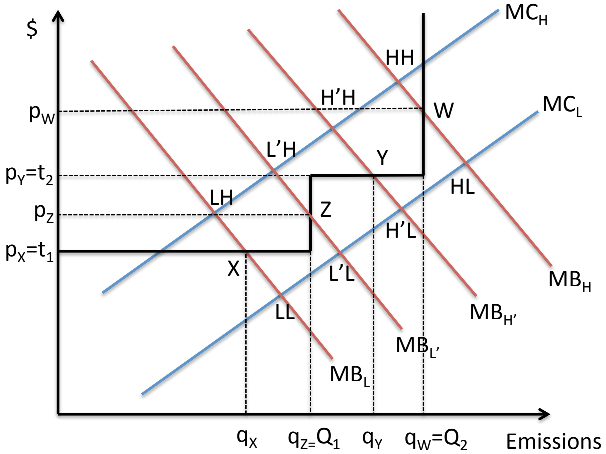

Figure 3.8. Four-point uncertainty in MB

Similar to the two-step hybrid system, having at least a four-point distribution of uncertainty in *MB* is necessary in order to obtain a unique set of design parameters for this policy scheme. Appendix 3.II shows that no unique optimal set or parameters exists with the 3-point uncertainty in *MB*.

The same model and marginal functions assumptions in policy 1 are made here. I further assume that uncertainty θ_b takes four values of low (L), medium-low (L'), medium-high (H'), and high (H). In this case, presented graphically in Figure 3.8, I will have:

$$\theta_c = \begin{cases} c_L \\ c_H \end{cases} \text{with probability} \quad \begin{array}{c} \pi_L^c \\ \pi_H^c = 1-\pi^c \end{array}, \quad \theta_b = \begin{cases} b_L \\ b_{L'} \\ b_{H'} \\ b_H \end{cases} \text{with probability} \quad \begin{array}{c} \pi_L^b \\ \pi_{L'}^b \\ \pi_{H'}^b \\ \pi_H^b \end{array}.$$

The objective is to minimize the expected loss function *E*(*L*).

$$\begin{aligned} E(L) = {} & \pi_L^b \pi_H^c \int_{q_{LH}}^{q_X} \{MC_H - MB_L\} dq + \pi_L^b \pi_L^c \int_{q_X}^{q_{LL}} \{MB_L - MC_L\} dq \\ & + \pi_{L'}^b \pi_H^c \int_{q_{L'H}}^{q_Z} \{MC_H - MB_{L'}\} dq + \pi_{L'}^b \pi_L^c \int_{q_Z}^{q_{L'L}} \{MB_{L'} - MC_L\} dq \\ & + \pi_{H'}^b \pi_H^c \int_{q_{H'H}}^{q_Y} \{MC_H - MB_{H'}\} dq + \pi_{H'}^b \pi_L^c \int_{q_Y}^{q_{H'L}} \{MB_{H'} - MC_L\} dq \\ & + \pi_H^b \pi_H^c \int_{q_{HH}}^{q_W} \{MC_H - MB_H\} dq + \pi_H^b \pi_L^c \int_{q_W}^{q_{HL}} \{MB_H - MC_L\} dq \end{aligned} \qquad (13)$$

Minimizing *E*(*L*) in equation (13) with respect to q_X, q_Y, q_Z, and q_W yields the following optimum emission levels:

$$q_X = \frac{B_1 + b_L - C_1 - \pi_L^c c_L - \pi_H^c c_H}{C_2 - B_2} = \frac{B_1 + b_L - C_1 - E(\theta_c)}{C_2 - B_2} \qquad (14)$$

$$q_Z = \frac{B_1 + b_{L'} - C_1 - \pi_L^c c_L - \pi_H^c c_H}{C_2 - B_2} = \frac{B_1 + b_{L'} - C_1 - E(\theta_c)}{C_2 - B_2} \qquad (15)$$

$$q_Y = \frac{B_1 + b_{H'} - C_1 - \pi_L^c c_L - \pi_H^c c_H}{C_2 - B_2} = \frac{B_1 + b_{H'} - C_1 - E(\theta_c)}{C_2 - B_2} \qquad (16)$$

$$q_W = \frac{B_1 + b_H - C_1 - \pi_L^c c_L - \pi_H^c c_H}{C_2 - B_2} = \frac{B_1 + b_H - C_1 - E(\theta_c)}{C_2 - B_2} \qquad (17)$$

In this case, it is clear that $q_W > q_Y > q_Z > q_X$, and $p_w > p_y > p_z > p_x$ (where p_i is the price corresponding to point *i* in Figure 3.8), and so there is only one unique corresponding optimal policy scheme which passes through all X, Y, Z and W points. Therefore, the optimal policy is to set:

$$t_1 = p_X = B_1 + b_L + B_2 q_X = \frac{B_1 C_2 + b_L C_2 - B_2 C_1 - B_2 E(\theta_c)}{C_2 - B_2}, \qquad (18)$$

$$t_2 = p_Y = B_1 + b_{H'} + B_2 q_Y = \frac{B_1 C_2 + b_{H'} C_2 - B_2 C_1 - B_2 E(\theta_c)}{C_2 - B_2}, \qquad (19)$$

$$Q_1 = q_Z = \frac{B_1 + b_{L'} - C_1 - E(\theta_c)}{C_2 - B_2}\text{, and} \tag{20}$$

$$Q_2 = q_W = \frac{B_1 + b_H - C_1 - E(\theta_c)}{C_2 - B_2}\,. \tag{21}$$

Discussion

Results for both policies' optimization problems reveal two important relationships between model parameters and policy design under uncertainty:

1. Increase (decrease) in expected intercept of marginal cost of emission will increase (decrease) the tax levels and decrease (increase) the quantities.

Proof: Derivative of t_1 and t_2 with respect to $C_1 + E(\theta_c)$ is positive (see equations 10, 11, 18, and 19), while derivative of Q, Q_1, and Q_2 with respect to $C_1 + E(\theta_c)$ is negative.

Note that in terms of uncertainty in marginal cost, when setting taxes and quotas, it is the average and not the distribution or range of the uncertainty that matters.

2. The differential between the two tax levels and the size of 'allowance reserve' (in Policy 2) increases (decreases) as the range in marginal benefit of emission increases (decreases).

Proof: Derivative of both $(t_2 - t_1)$ and $(Q_2 - Q_1)$ with respect to $(b_H - b_L)$, $(b_{H'} - b_L)$ and $(b_H - b_{L'})$ is positive (see equations 10, 11, 18, and 19).

Note that the slope of *MC* function decreases, the tax level differential (i.e., $t_2 - t_1$) decreases and assuming a constant marginal cost function (i.e., absolutely flat curve), the two tax levels would be equivalent. In the case of constant marginal cost (which some climate policy analyses have assumed for their models), the optimal solution for the first policy becomes a single tax policy and for the second one a cap-and-trade with price floor, where the tax level and price floor equal the expected marginal cost.

3.6 A Numerical Example: Hybrid Climate Policy for the U.S.

As the U.S. is the second largest contributor to GHG emissions, the overarching question is what the best climate policy for the U.S. is. I apply the optimal solutions for the hybrid policy designs in the previous section and set the parameters of our model to U.S.-specific values in order to find the solutions for a hybrid climate policy for the U.S. I make several assumptions on the *MC* and *MB* functions, which are explained below.

Marginal Cost or Marginal Damage Cost Function

There are many studies estimating the Marginal Cost or Marginal Damage Cost function. The available quantitative estimates of the social cost of carbon emissions use models with different degrees of sophistication. Following a common path, they all go from emission levels to atmospheric concentration, from concentration to temperature change, and from temperature change to damage. The last step usually involves going from temperature change to sea level rise as well.

There are two different methodologies for social cost estimation, the Cost-Benefit Analysis (CBA) approach and the Marginal Cost approach. The CBA approach is based on a CBA model, where the marginal social cost of carbon is the marginal damage imposed at the optimal level of abatement and not at any other emission/abatement level. In the Marginal Cost approach, incremental damage is measured relative to a small increase in the current level of emissions (Pearce, 2003). As Clarkson and Deyes (2002) noted, the Marginal Cost approach should yield higher estimates than the CBA approach.

In applying both of the above methods to estimate the social cost of carbon emissions, several key uncertainties are unavoidable. Clarkson and Deyes (2002) divided them into two main categories: scientific uncertainties and uncertainties associated with economic valuation. The uncertainties associated with the measurement of present emissions, prediction of future emissions, the translation of emission levels into changes in the atmospheric carbon concentration, estimating the climate impacts, and identification of the physical impacts resulting from climatic change are considered scientific uncertainties. The main economic valuation uncertainties include those associated with valuation of non-market impacts, predicting the future changes in the relative and absolute value of impacts, deciding about the national and regional income differences and how to aggregate the damage estimates across those regions, and determining the discount rate.

Although there is a wide range of estimates for the social cost of carbon and many disagreements on the way the above-mentioned uncertainties are handled, to be able to get some tangible results from our study, I need to adopt an estimate for the damage cost function. As Pearce rightly mentions (2003), and many other studies in this area have endorsed the idea, although the existing estimates might not be necessarily precise, it is always better to act on reasonable estimates than act on no estimate or no act at all, as the latter surely implies a social cost.

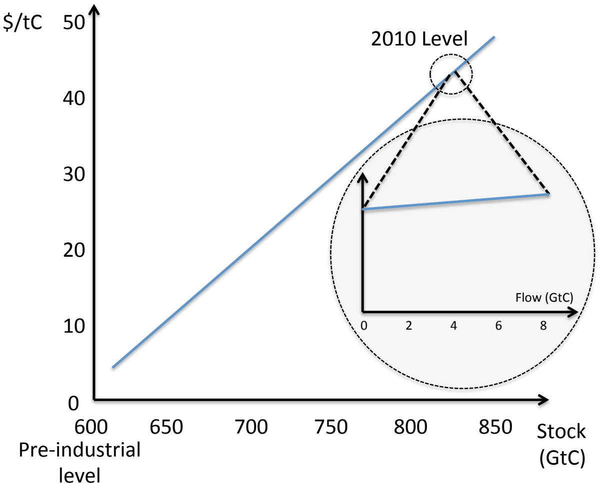

Figure 3.9. Marginal damage cost of emissions' *stock* versus *flow*[38]

Since climate change is a global issue and damages are not contained in the GHG emitting county, I derive the *MC* function from the estimate of the worldwide damage in our model. However, global warming and other adverse impacts of climate change are caused by the existing *stock* and not by the *flow* of GHG emissions in the atmosphere. Therefore, as individual country's annual flow of emissions contributes to a very small portion of the total stock of emissions, the marginal damage function for country-level emissions in one year would become relatively flat when GHG emissions flow is assumed to be the independent variable in marginal damage cost function (Figure 3.9).

Although some studies (perhaps the highly cited work by Nordhaus (1994)) have assumed constant *MC* function (i.e., absolutely flat) in their analyses, others (Fell, MacKenzie, et al., 2012a; Newell & Pizer, 2003; Pearce, 2003) have assumed a positive slope, but relatively flat compared to the MB curve. As Figure 3.9 graphically justifies and considering that the United States is a major GHG emitter in the world,[39] it is more precise

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[38] The idea for this graphical presentation is adopted from Pizer (1997).

[39] In 2010, U.S. was the second largest CO_2 emitter with 18% of total emissions, after China—25% of total (EIA, 2013b).

to assume a slightly positive slope for the MC function in order to account for the large contribution of annual U.S. emissions flow in the GHG stock in the atmosphere.

In an extensive literature survey, Tol (2005) has reviewed a list of 28 studies of marginal damage costs of carbon dioxide emissions. In this survey, he found most estimates to be in the lower part of the range \$5-125 per tC, estimated in the IPCC Second Assessment Report (1996), and higher estimates only occur through the combination of a high vulnerability with a low discount rate. These results are in line with Pearce et al. (1996), concluding that "estimates in excess of \$50/tC require relatively unlikely scenarios of climate change, impact sensitivity, and economic values."

Overall, without discriminating between the studies in terms of their assumptions, Tol (2005) suggests, "the best guess for the marginal damage costs of carbon dioxide emissions might be \$5/tC, but the mean is \$104/tC," which reflects the large uncertainty associated with the marginal damage cost estimation. More specifically, he found that studies with better methodologies yield lower estimates with a lower range of uncertainty. For example, peer-reviewed studies had a mean of \$43/tC, with a standard deviation of \$83/tC.

The wide range of uncertainty in the 28 studies is driven by two ethical parameters: discount rate (the aggregation over time) and equity weighting (the aggregation over countries). In general, applying lower social discount rates and equity weighting both lead to higher estimates and greater uncertainty (Anthoff, Hepburn, & Tol, 2009).

Damage from global warming, in terms of per-capita income, is higher in the developing world than in the developed world. In fact, equity weighting is simply differentiating the values of damage to poor and rich people. To better understand how equity weighting affects the damage cost and uncertainty, assume a utilitarian Social Welfare Function (SWF):

$$D_{world} = \sum_{i=1}^{n} D_i \left[\bar{Y} / Y_i \right]^{\varepsilon} = D_r \left[\bar{Y} / Y_r \right]^{\varepsilon} + D_p \left[\bar{Y} / Y_p \right]^{\varepsilon} \qquad (22)$$

where $\bar{Y}$ is the average world per-capita income, Y is income, D is damage, p refers to poor people, r refers to rich people, and ε is the income elasticity of the marginal utility.

For the purpose of equity weighting, what matters is the value of ε. Overall, Pearce (2003) suggests 0.5-1.2 as a reasonable range for the value of ε. Many studies, including Clarkson and Deyes (2002) choose a value of one for ε. As a support for earlier claim of higher estimates under equity weighting, Clarkson and Deyes (2002) suggest that an equity weighting with unit ε roughly doubles the unweighted estimates; however, the exact ratio depends on the distribution of absolute damages between poor and rich.

Generally, any kind of social-cost estimate is shown to be very sensitive to the discount rate. In his study, Tol (2003) finds the discount rate as the major driver for the wide range of uncertainty. Using a pure rate of time preference (PRTP) of 3%—corresponding to a 4-5% discount rate—the combined mean estimate is \$16/tC, not exceeding \$62/tC with a probability of 95%, while a lower discount rate will estimate a higher marginal damage cost, but even for a 1% pure rate to time preference, the combined mean is still \$51/tC.

Based on the discussions in Tol (2003) mentioned above, I chose the mean marginal cost of peer-reviewed studies of \$43/tC with a standard deviation of \$83/tC, which could be translated into mean of \$12/tCO_2e[40] with a standard deviation of \$23/tCO_2e. This assumption for marginal damage cost is also consistent with least-cost stabilization of atmospheric CO_2 concentrations at 550 ppm (Aldy et al., 2010).

As described above (and presented graphically in Figure 3.9), I use the existing literature on the slope of *MC* function for emissions stock as an estimate for the slope of MC function in terms of U.S. emissions flow. For the stock marginal cost slope, a great deal of literature on the U.S. climate change policy (Fell, MacKenzie, & Pizer, 2012b; Rohling, 2013) adopt the assumptions by Newel and Pizer (2003). Fell et al. (2012b), however, update their original estimate in terms of 2005\$, which is equivalent to 5.6×10^{-13} \$/(tCO_2e)^2.

So, assuming a relatively flat MC function within a year, our MC function would be:

$$MC = 12 + \theta_c + 0.0056\, q \qquad \text{(in 2005\$ per tCO}_2\text{e)} \qquad (23)$$

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[40] One metric ton of carbon is roughly equal to 3.6 metric tons of carbon dioxide equivalent.

where *q* is the emission level (in $GtCO_2e$) and θ_c is the uncertainty term in our model, assuming $E(\theta_c) = 0$.

For uncertainty range, I adopt \$5 and \$104 per ton of carbon as the lower and upper bound for constant term in *MC* (Tol, 2005), which translates into \$1.36 and \$28.33 per tCO_2e. Hence, the uncertainty term θ_c in the above *MC* function would fall in the range of -10.64 to 16.33.

Marginal Benefit or Marginal Abatement Cost Function

Marginal Abatement Cost (MAC) functions for GHG emissions have been estimated since late 1990s and several studies present their results for different countries, in different time period, and more importantly using different approaches. The two general modeling approaches used to construct MAC curves are bottom-up versus top-down models (Nordhaus, 2013). An example of the bottom-up approach is the famous GHG abatement curve by McKinsey & Company (Creyts, Derkach, Nyquist, Ostrowski, & Stephenson, 2007; Enkvist, Dinkel, & Lin, 2010), an engineering based approach, which analyzes the cost and potential for emission reductions by a suite of different technologies, such as those used in transportation devices, power plants, blast furnaces, other industrial processes, and so forth. On the other hand, top-down models are based on aggregated microeconomic models, which often are CGE models with relatively extensive details on the energy sector—most of the academic literature belongs to this group (Chen, 2005; Criqui, Mima, & Viguier, 1999; Ellerman & Decaux, 1998; Klepper & Peterson, 2006; Morris, Paltsev, & Reilly, 2011; van Vuuren, de Vries, Eickhout, & Kram, 2004; Webster et al., 2010).

Academic studies of climate policy, however, tend to prefer the economic (top-down) estimates to the engineering (bottom-up) approach for the following main reasons: 1) bottom-up models result in negative abatement costs, claiming that there exist many negative-cost options that save money. Top-down models, however, start from zero cost at zero reduction (i.e., no abatement costs for status quo), as they assume rational economic behavior (i.e., Assuming profit-maximizing behavior, negative-cost technologies should have already been adopted); and 2) bottom-up models typically result in a higher slope as they only analyze a selection of technologies and overlook some emission-reducing options (e.g., they usually do not account for behavioral changes—such as change in consumption patters to emit less).

As such, in our numerical example, I adopt an economic estimate (top-down approach) and by MIT Joint Program on the Science and Policy of Global Change (Morris et al., 2011). In their most recent estimate, Morris et al. use their EPPA model to update the previous results by MIT group (Ellerman & Decaux, 1998), as they suggest their updated model and parameters have greatly improved since the original estimate has been done. They also include all GHG emissions in their new estimate. An important feature in this estimate is that they acknowledge the concerns about the possible misuses of such curves in policy making (Kesicki & Ekins, 2011), the fairly wide range of estimates in the existing literature (Fischer & Morgenstern, 2006), the possible impact of international policies as well as possible impact by any other country's policies, and the stability of the estimates over time.

By generating the MAC function for different baseline years (i.e., 2010, 2020, and 2050), Morris et al. (2011) show that abatement cost estimates could vary dramatically due to not only technological change over time, but also the initial point they are calculated from (i.e., the lower the initial level of GHG emissions, the higher abatement costs will be). While this should be considered in dynamic analyses—with more than one period and especially when banking and borrowing of emission permits over time is allowed—as I solve a static model for optimal policy design, I use their U.S. estimates for the baseline year of 2010.

Figure 3.10 (panel a) presents Morris et al.'s (2011) estimates for U.S. greenhouse gas emissions abatement costs in terms of emissions abatement. Their original calculations,[41] however, measure the MAC in terms of percentage reduction from 2010 as the baseline year. Using total GHG emissions in 2010, I converted their estimates into a MAC in terms of total U.S. GHG emissions (panel b, Figure 3.10).[42]

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[41] The excel file provided as an online resource, presents the MAC data points as well as the charts for all regions for 2010, 2020, and 2050.

[42] Appendix 3.III present the original table, as well as our calculations to derive data for graphs in panels b, c, and d of Figure 3.10.

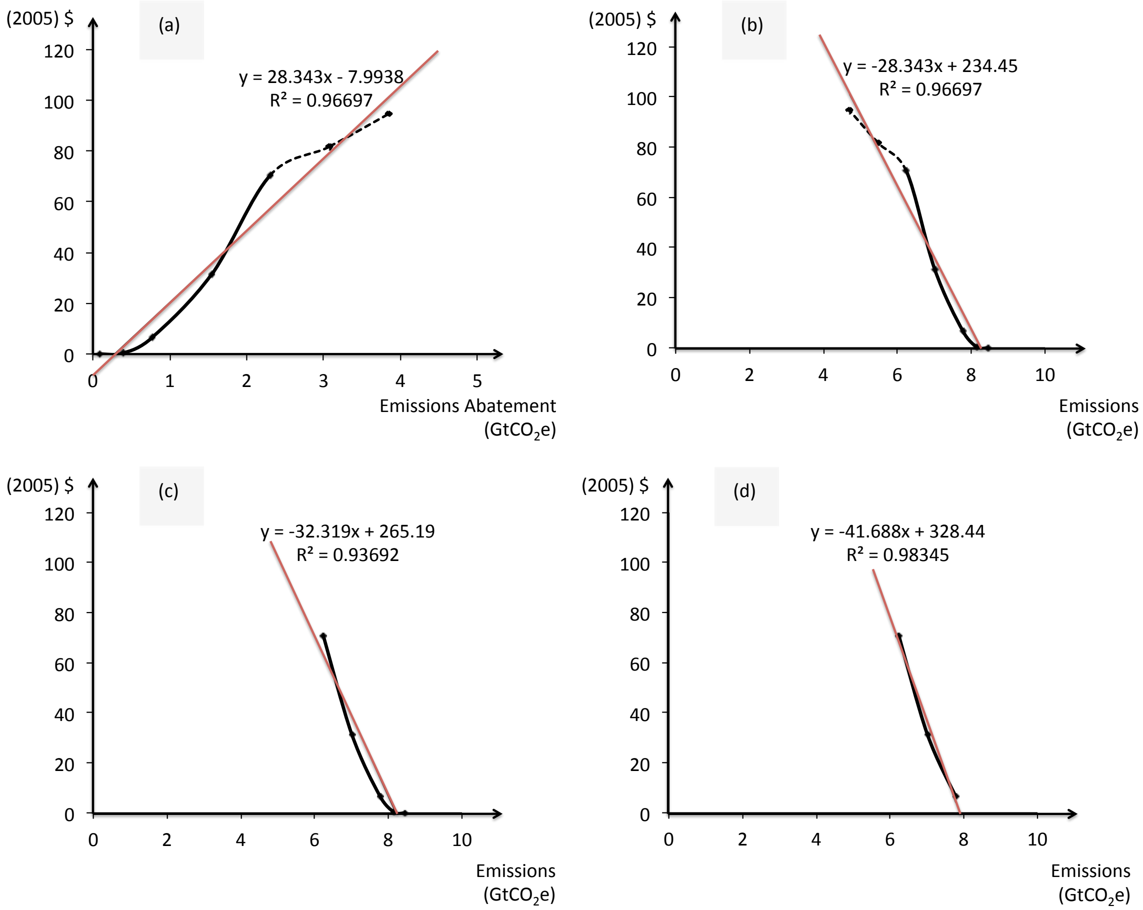

Figure 3.10. GHG marginal abatement cost estimate for the U.S., 2010

In presenting their results, Morris et al. (2011) suggest part of their estimated costs to be more relevant for the year and country being considered (U.S. 2010 in our case) by drawing more relevant results in solid line while the rest of graph is drawn in dotted lines. Keeping their method or presentation, panels a and b of Figure 3.10 present their MAC estimates with a solid part and a dotted part.

To have a better (more relevant) estimate for MAC, I first eliminated the data points corresponding to the dotted area (panel c, Figure 3.10). In the next step, to achieve a better linear approximation, I dropped the very beginning of the chart (corresponding to 0-10% abatement) and estimated the MAC function using the most relevant part of the original curve, where the costs range between $6-70 per tCO$_2$e (panel d, Figure 3.10).

Therefore, our baseline *MB* (or MAC) function for the U.S., based on the 2010 GHG emission level, would be:

$$MB = 328 + \theta_b - 42\, q \qquad \text{(in 2005\$ per tCO}_2\text{e)} \qquad (24)$$

where q is the emission level (in $GtCO_2e$) and θ_b is the uncertainty terms in our model, assuming $E(\theta_b) = 0$.

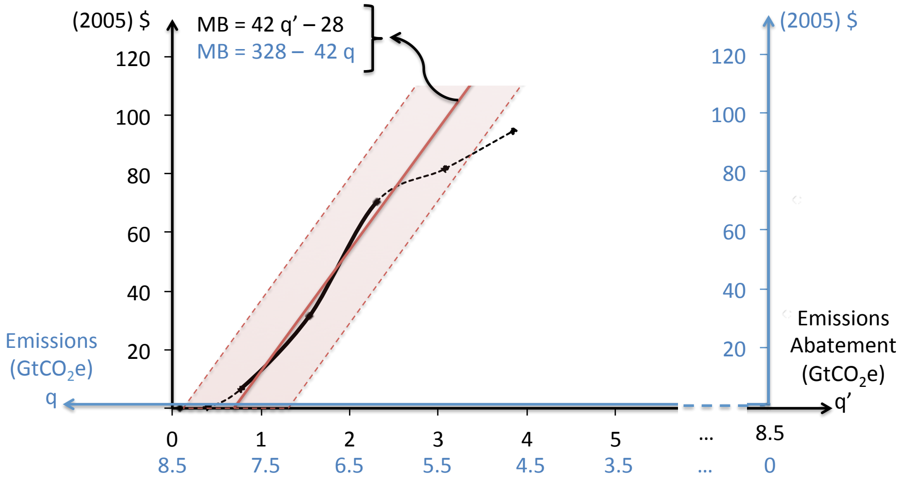

Figure 3.11. GHG marginal abatement cost uncertainty

Morris et al. (2011), however, does not provide any confidence interval or range of uncertainty with their estimates. They claim their estimates to be a rough indication of abatement costs for each country, having considered various forms of uncertainties in their model. Hence, for our numerical analysis, although rather arbitrarily, I chose a 20% uncertainty range (i.e., ± 10% of $E(B_1) = \pm 32.8$), considering the fact that the abatement cost of status quo should be zero or negative. In other words, there cannot be any positive abatement cost associated with zero abatement, but there could be some potential cost savings achievable at or below current level of emissions (i.e., there are some cost-saving emissions reduction options to start with, as many bottom-up models estimate). Figure 3.11 shows the estimated MB curve and its uncertainty as a function of both emissions (q) and emissions abatement (q'). I test the effect of this choice in a sensitivity analysis for all model parameters.

The Optimal Climate Policy

In this section, I solve the optimal policy design for the U.S., based on the *MC* and *MB* functions described in the previous two sections and assumption on the range and distribution of uncertainties (see Figure 3.12). I then compare the two policies based on their DWL and discuss our results using a sensitivity analysis.

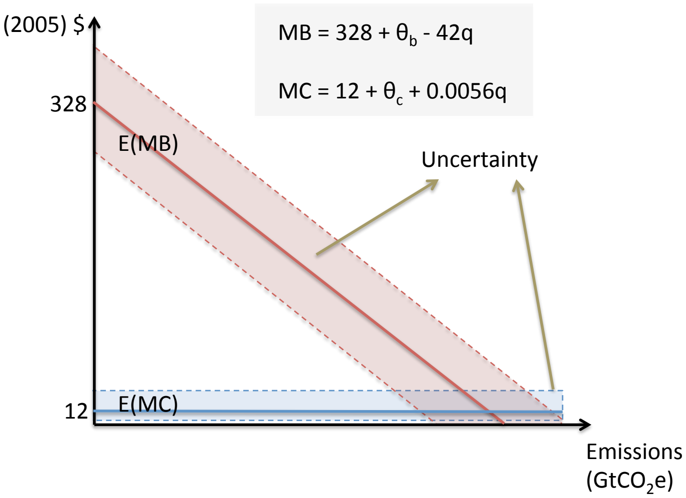

Figure 3.12. GHG emissions' marginal functions for the U.S.

It is worth mentioning that the optimality of the solutions under uncertainty refers to their minimized welfare loss (i.e., social costs) in an effort to internalize the climate change externality. As greenhouse gas emissions and climate change are global problems—i.e., each ton of GHG emissions is equally important and contributes to the global damages exactly the same regardless of the source or location—IPCC and other groups estimate the associated marginal damage cost (i.e., social cost of carbon) at global level. Therefore, to fully address climate change concerns and to avoid consequent damages, all countries should internalize the associated costs considering the same marginal cost function. However, due to individually differences in energy systems, baseline GHG emissions and GHG intensity, and technological advancement and availability, countries have different marginal abatement cost (i.e., marginal benefit) curves to avoid their contributions to global GHG emissions stock.

Optimal design for two-step tax policy: Following our discussion in previous sections, solving for a unique design for a two-step tax policy requires at least a three-point uncertainty for marginal benefit function.

Based on the results from section 3.5, assumptions on *MB* and *MC* functions (equations 23 and 24), and the following assumptions on uncertainty, the optimal policy design for the U.S. in a given year (which is assumed to be 2010 in this study) is shown in equation 25. Figure 3.13 shows this policy design graphically.

$$\theta_c = \begin{cases} -10.64 & \cdots & \pi = 1/2 \\ +16.33 & & \pi = 1/2 \end{cases}, \theta_b = \begin{cases} -32.8 & & \pi = 1/3 \\ 0 & \cdots & \pi = 1/3 \\ +32.8 & & \pi = 1/3 \end{cases} \Rightarrow \begin{cases} t_1 = \$12.038 \\ Q = 7.52 \text{ GtCO}_2\text{e} \\ t_2 = \$12.046 \end{cases} \quad (25)$$

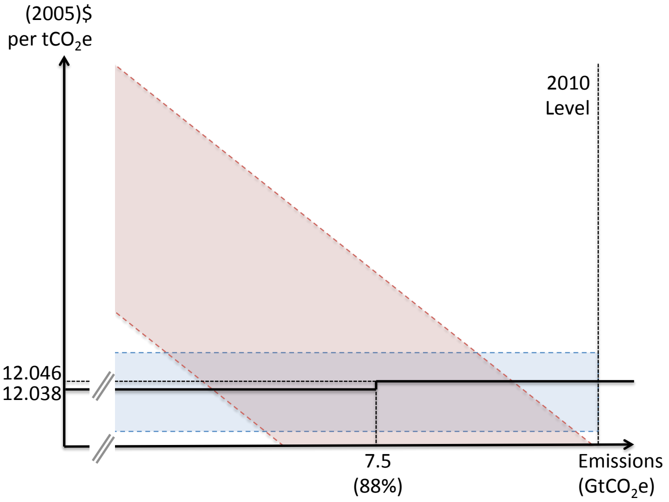

Figure 3.13. Optimal two-step tax policy design under uncertainty for the U.S.

Optimal design for a cap-and-trade system with allowance reserve: Similar to the case of Policy 1, solving for a unique design for a cap and trade with allowance reserve requires having at least a four-point uncertainty for marginal benefit function.

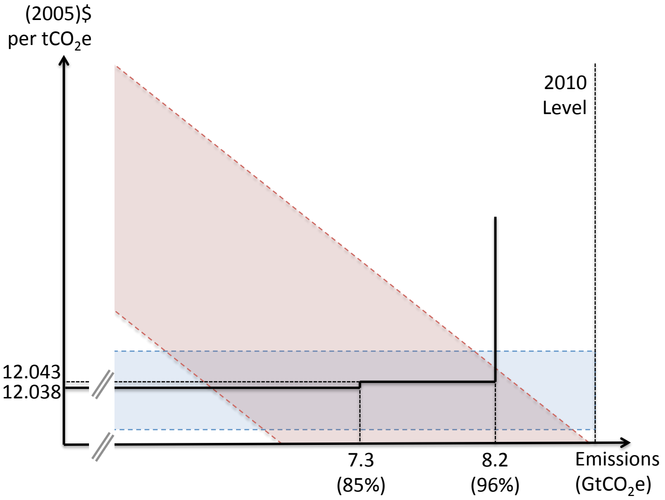

Figure 3.14. Optimal cap-and-trade with allowance reserve policy design under uncertainty for the U.S.

Based on the results from section 3.5, assumptions on MB and MC functions (equations 23 and 24), and the following assumptions on uncertainty, the optimal policy design for the U.S. in a given year (2010 in this study) is shown in equation 26. Figure 3.14 shows this policy design graphically.

$$\theta_c = \begin{cases} -10.64 & \pi = 1/2 \\ +16.33 & \pi = 1/2 \end{cases} .. ,\theta_b = \begin{cases} -32.8 & \pi = 1/4 \\ -10.9 & \pi = 1/4 \\ +10.9 & \pi = 1/4 \\ +32.8 & \pi = 1/4 \end{cases} .. \Rightarrow \begin{cases} t_1 = \$12.038 \\ Q = 7.52 \text{ GtCO}_2\text{e} \\ t_2 = \$12.046 \\ \text{Reserve} = 0.96 \text{ GtCO}_2\text{e} \end{cases} \qquad (26)$$

Discussion

As I discussed in section 3.5, the relatively flat marginal cost function implies very little difference between the two tax levels in both policies. Hence, as expected, our two optimal solutions for hybrid climate policy for the U.S. turned out to be very close to: 1) a carbon tax of some \$12/tCO$_2$e, and 2) a cap-and-trade with price floor of some \$12/tCO$_2$e with a cap of 8.2 GtCO$_2$e (96% of total GHG emissions in 2010). Of course, as I modeled our problem in a static framework, the solution sets the policy for a representative benchmark year of 2010. However, by changing the model parameters for future years, one could derive a time profile for the policy and draw a path for the carbon tax and/or the cap size and price floor for the second policy.

Our carbon price range of \$12-\$13 per ton CO$_2$ (\$44 per tC) in either of the two policies falls in the range of "right" carbon price that Hall (2010), in his commentary on U.S. climate change policy, believes it is necessary to encourage enough emission abatement for reducing emissions to the levels that stabilize atmospheric GHG concentration at a 'safe' level. He asserts that despite the \$5-\$50 per ton of CO$_2$ range suggested by energy models, the "right" price in the near term should be between \$5 and \$30 per ton of CO$_2$.

Comparing the two optimal climate policies for the U.S., using the expected welfare loss as a benchmark, I confirm the conventional wisdom of price superiority to quantity when the *MC* is flatter relative to *MB*. In fact, in case of a climate policy with almost flat MC curve, I am comparing a carbon tax with a hybrid cap-and-trade with price floor instead of comparing two hybrid policies. The comparison shows a 1% increase in the expected loss (due to uncertainty) when I move from a carbon tax to a hybrid cap-and-trade with price floor. The difference in social welfare, however, might be small enough to help policy makers to avoid the politically unpleasant but economically more efficient option (i.e., carbon tax) and justify using the hybrid policy instead.

I also ran a sensitivity analysis on the model parameters for this numerical example and found our results to be pretty robust. The ranking of two policies were the same over a wide range of intercept, slope, and uncertainty values. Moreover, in spite of the considerable change in the size of expected loss in some scenarios, the price-based policy (i.e., Policy 1) still offered a 1% advantage over the quantity-based policy (i.e., Policy 2).

3.7 Conclusion

In this paper, I investigate the optimal choice of the hybrid instrument for environmental policy, having climate policy in mind, in the presence of uncertainty. I chose additive uncertainty for the marginal functions and two common hybrid designs as representative policies, one resembling a price mechanism while the other emphasizes quantity features.

The solutions revealed that for both policies: 1) increase (decrease) in expected intercept of marginal cost of emission will increase (decrease) the tax levels and decrease (increase) the quantities; and 2) the differential between the two tax levels and the size of 'allowance reserve' (in Policy 2) increases (decreases) as the range in marginal benefit of emission increases (decreases).

I then solve for the two hybrid climate policies for the U.S., as numerical example, and compare them with regard to their expected welfare loss, given the same set of assumptions for model parameters and uncertainty. I find that a two-step tax is more favorable for the U.S. climate policy than a cap-and-trade with allowance reserve. However, the difference in social welfare (i.e., expected loss is 1% less for carbon tax than the cap-and-trade with price floor) might be small enough to justify policymakers avoiding the politically unpleasant but economically more efficient option (i.e., carbon tax) in favor of a hybrid cap-and-trade.

A sensitivity analysis shows that this result is generally robust to the alternative assumptions about the model and uncertainty parameters. However, the tax (price) and cap (quantity) values depend highly on marginal cost and marginal benefit functions, respectively. I also tested for the impact of our assumption for marginal benefit uncertainty range (i.e., changed the uncertainty range to ± 5%, ± 20%, and ± 40%). In the case of climate policy, where marginal cost function is almost flat, the marginal benefit uncertainty only proportionally affects the allowance reserve size (i.e., doubling the range of additive uncertainty in MB function doubles the size of allowance reserve). Finally, to check for the possible impact of different uncertainty probability distribution functions, I solve for the first policy assuming a 4-point distribution in MB uncertainty, assuming the same uncertainty range. While having minor impact on Q (i.e., moving the threshold for tax level change by 3%), changing the distribution from 3-point to 4-point discrete function has no impact on total expected loss of the policy. Appendix 3.V presents the results for all scenarios of the sensitivity analysis described above.

Our results suggest a carbon price of \$12-\$13 per ton CO_2 (\$44 per tC) for the U.S. in 2010 regardless of policy type, which is well positioned in the center of "right" carbon price range that literature suggests. The cap size in our second policy option, Cap-and-Trade with Allowance Reserve, averages around 95% of 2010 emissions (i.e., which limits the permit allocations to 5% below the current emissions level).

3.8 Appendix 3.I. Solving Policy 1 with 2-Point Uncertainty

Assume that uncertainty parameters θ_b and θ_c can take only two values, high and low (see Figure 3.5):

$$\theta_c = \begin{cases} c_L \\ c_H \end{cases} \text{with probability} \begin{matrix} \pi_L^c \\ \pi_H^c \end{matrix} , \ \theta_b = \begin{cases} b_L \\ b_H \end{cases} \text{with probability} \begin{matrix} \pi_L^b \\ \pi_H^b \end{matrix} .$$

Polluters decide how much to emit based on the comparison between tax (their cost) and their *MB* (they will emit if tax < *MB*). Because the decision does not depend on *MC* schedule, government cares only for the intersection points between tax schedule and *MB* lines (X and Y in Figure 3.5).

In this case, there is no unique optimal t_1, t_2 or Q. Different tax scheme can yield the same result (given the intersections between tax schedule and *MB* are the same), which all yield the same output and are shown in Figure 3.15. In panel (a), t_1 can be set as low as 0 if Q is set at X, as opposed to the panel (c), where t_2 can be set at any high number if Q is set at Y. In panel (b), however, as long as t_1 and t_2 are set at X and Y, respectively, Q can be set anywhere in between. The objective, thus, is to find the X and Y that minimize expected welfare loss.

The expected welfare loss will be:

$$\begin{aligned} E(L) = {} & \pi_L^b \pi_L^c \int_{q_{LL}}^{q_X} \left\{ MB_L - MC_L \right\} dq + \pi_L^b \pi_H^c \int_{q_{LH}}^{q_X} \left\{ MC_H - MB_L \right\} dq \\ & + \pi_H^b \pi_L^c \int_{q_{HL}}^{q_X} \left\{ MB_H - MC_L \right\} dq + \pi_H^b \pi_H^c \int_{q_{HH}}^{q_X} \left\{ MC_H - MB_H \right\} dq \end{aligned} \tag{I.1}$$

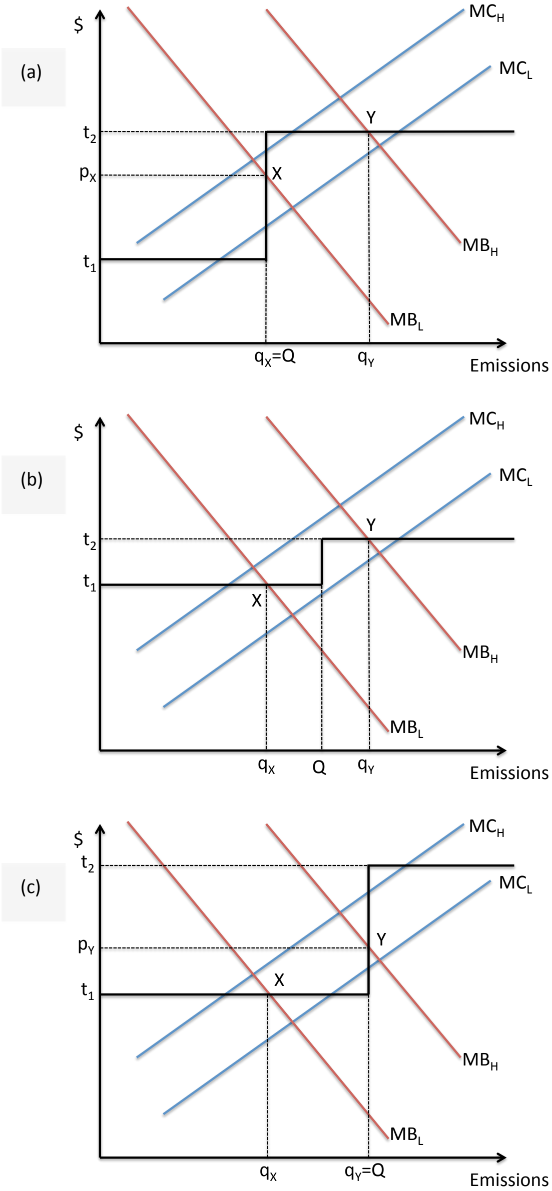

Figure 3.15. Three equivalent setups, yielding the same result

Minimizing $E(L)$ with respect to q_X and q_Y yields:

$$q_X = \frac{B_1 + b_L - C_1 - \pi_L^c c_L - \pi_H^c c_H}{C_2 - B_2} = \frac{B_1 + b_L - C_1 - E(\theta_c)}{C_2 - B_2} \tag{I.2}$$

$$q_Y = \frac{B_1 + b_H - C_1 - \pi_L^c c_L - \pi_H^c c_H}{C_2 - B_2} = \frac{B_1 + b_H - C_1 - E(\theta_c)}{C_2 - B_2} \tag{I.3}$$

Any tax path that brings about the intersection with marginal benefit at the above q_X and q_Y is considered as the optimal tax path. For example, one (but not the only) optimal (two-step hybrid) policy is to set the design parameters as follows:

$$t_1 = B_1 + b_L + B_2 q_X = \frac{B_1 C_2 + b_L C_2 - B_2 C_1 - B_2 E(\theta_c)}{C_2 - B_2}, \tag{I.4}$$

$$t_2 = B_1 + b_H + B_2 q_Y = \frac{B_1 C_2 + b_H C_2 - B_2 C_1 - B_2 E(\theta_c)}{C_2 - B_2}, \text{ and} \tag{I.5}$$

$$\frac{B_1 + b_L - C_1 - E(\theta_c)}{C_2 - B_2} \le Q \le \frac{B_1 + b_H - C_1 - E(\theta_c)}{C_2 - B_2}. \tag{I.6}$$

In the case that uncertainties can take two levels, the alternative policy suggested by McKibbin and Wilcoxen (1997a; 2002), can also be implemented; government can set Q equal to q_X, and $t_2 = \frac{B_1 C_2 + b_H C_2 - B_2 C_1 - B_2 E(\theta_c)}{C_2 - B_2}$.

Given Q, if MB is MB_L, then corresponding price of long-term permit will be t_1. If MB is at MB_H, then corresponding price will be more than t_2. Firms will turn away from long-term permits and will buy only short-term permits.

3.9 Appendix 3.II. Solving Policy 2 with 2-Point Uncertainty

Using the same model and optimization problem in Appendix I, I get the results for q_X, q_Y:

$$q_X = \frac{B_1 + b_L - C_1 - \pi_L^c c_L - \pi_H^c c_H}{C_2 - B_2} = \frac{B_1 + b_L - C_1 - E(\theta_c)}{C_2 - B_2} \tag{II.1}$$

$$q_Y = \frac{B_1 + b_{H'} - C_1 - \pi_L^c c_L - \pi_H^c c_H}{C_2 - B_2} = \frac{B_1 + b_{H'} - C_1 - E(\theta_c)}{C_2 - B_2} \tag{II.2}$$

$$p_X = B_1 + b_L + B_2 q_X = \frac{B_1 C_2 + b_L C_2 - B_2 C_1 - B_2 E(\theta_c)}{C_2 - B_2}, \text{and} \tag{II.3}$$

$$p_Y = B_1 + b_H + B_2 q_Y = \frac{B_1 C_2 + b_H C_2 - B_2 C_1 - B_2 E(\theta_c)}{C_2 - B_2}. \tag{II.4}$$

Different designs can yield the same result (given the intersections between price/quantity scheme and MB are the same). Figure 3.16 shows the possible different policy schemes that yield the same output in all cases.

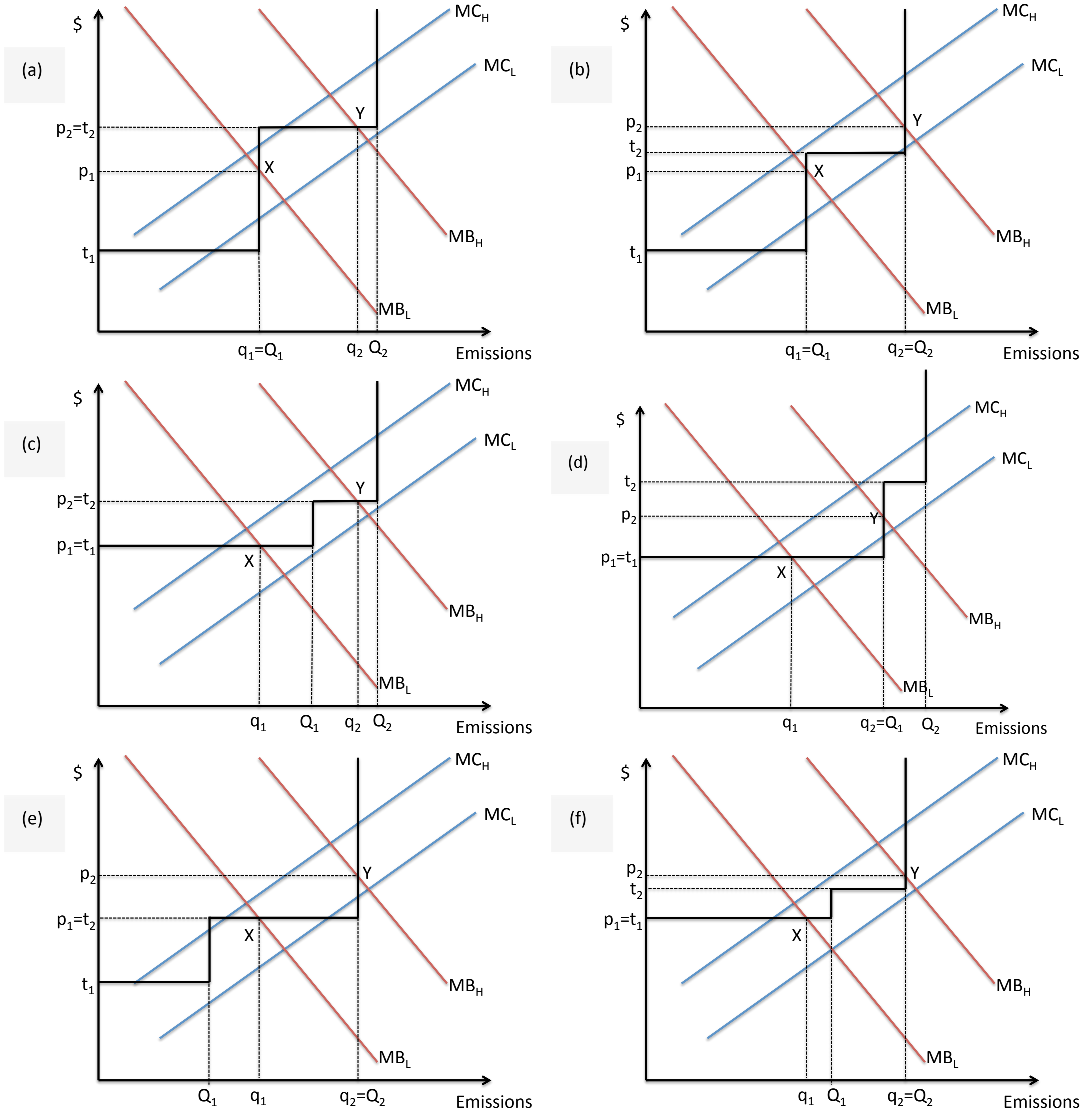

Figure 3.16. Six equivalent setups, yielding the same results

Since I have four design parameters here (t_1, t_2, Q_1, and Q_2), I will see six possible designs with similar results instead of three. In each possible solution, two parameters can be set using E_1 and E_2, the results from solving the minimization, and two can be set arbitrarily, within a specific interval.

In panel (a), t_1 can be set anything between 0 and MB_1 (i.e., Marginal Benefit at emission level E_1) and Q_2 can accept any value greater than emission level Y. Similarly, each panel has two degrees of freedom in design parameters while they all end in the same result, which is optimal emission level at E_1 and E_2, given two-point uncertainty in *MB* and *MC*. Thus again, the objective changes to finding X and Y that minimize expected welfare loss.

3.10 Appendix 3.III. Estimating MAC function

Table 3.1 presents Morris et al.'s (2011) estimates for the U.S. emissions abatement.

Table 3.1. Marginal abatement costs for GHG emissions reduction for the U.S.; results from EPPA model (2005$/tCO$_2$e)

	2010		**2020**		**2050**	
% Reduction	MAC 2005$	GHG Reduction Million tCO_2e	MAC 2005$	GHG Reduction Million tCO_2e	MAC 2005$	GHG Reduction Million tCO_2e
1%	0.00	85.54	0.02	99.11	0.22	158.05
5%	0.25	393.21	0.05	442.00	0.22	689.38
10%	6.55	775.23	2.66	869.19	0.22	1353.54
20%	31.35	1542.48	23.14	1727.75	12.95	2680.17
30%	70.52	2309.76	57.19	2586.63	16.35	4008.31
40%	81.70	3077.62	76.96	3445.97	49.79	5335.18
50%	94.61	3845.48	94.89	4305.37	70.40	6662.85

Source: Morris et al. (2011).

Table 3.2. Estimated marginal abatement costs for the U.S. 2010 (2005$/tCO$_2$e)

	1-50% reduction		**1-30% reduction**		**10-30% reduction**	
% Reduction	MAC 2005$	Emissions (*q*) $GtCO_2e$	MAC 2005$	Emissions (*q*) $GtCO_2e$	MAC 2005$	Emissions (*q*) $GtCO_2e$
1%	0.00	8.47	0.00	8.47		
5%	0.25	8.16	0.25	8.16		
10%	6.55	7.78	6.55	7.78	6.55	7.78
20%	31.35	7.01	31.35	7.01	31.35	7.01
30%	70.52	6.24	70.52	6.24	70.52	6.24
40%	81.70	5.48				
50%	94.61	4.71				
Fitted Line	$MAC = 234.45 - 28.343q$ $R^2 = 0.96697$		$MAC = 265.45 - 32.319q$ $R^2 = 0.93692$		$MAC = 328.44 - 41.688q$ $R^2 = 0.98345$	

Source: author's calculations.

Assuming 2010 as our baseline, I converted their results to MAC in terms of levels of emissions for the U.S. (presented in Table 3.2) in order to estimate a linear MAC function. For consistency, I calculated total U.S. GHG emissions in 2010 from their results.[43]

3.11 Appendix 3.IV. Multiplicative (slope) uncertainty in MB

This appendix tries to address concerns about the additive approach to model uncertainty for MB function. Although shifting MC curve (up and down) would probably be the best way to introduce damage cost uncertainty due specifically to its almost flat nature (only in Climate Policy), various studies on marginal abatement cost function have estimated different slopes for MB function, showing the existence of uncertainty on the slope of that function. As such, I modify the model for MB uncertainty to multiplicative approach and solve for the optimal policy designs under such setup.

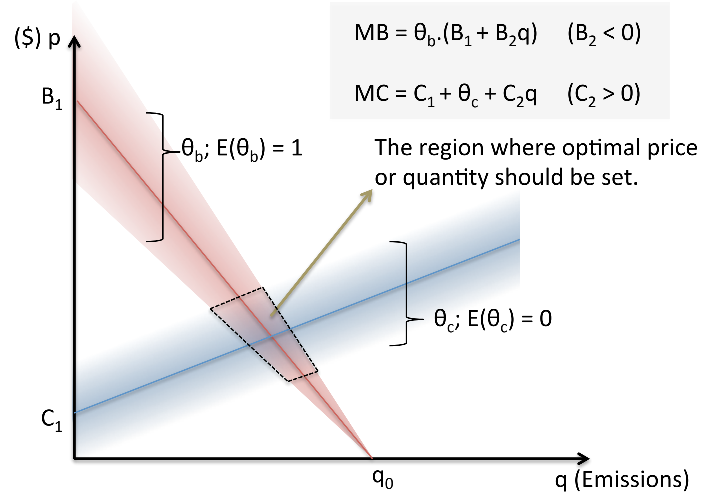

Figure 3.17. Additive MC uncertainty; multiplicative MB uncertainty

Assuming additive uncertainty in MC and multiplicative uncertainty in MB, I will have: $MB(q) = \theta_b (B_1 + B_2 q)$, $MC(q) = (C_1 + \theta_c) + C_2 q$ (IV.1)

where $E(\theta_b) = 1$ and $E(\theta_c) = 0$. Figure 3.17 presents the marginal functions graphically.

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[43] One percent GHG reduction of 85.54 million tCO_2e implies total GHG emissions of 8.554 $GtCO_2e$ for the U.S. in 2010.

Policy 1: Two-Step Carbon Tax

Similar to the setup explained in section 3.5, I solve for a unique set of all policy parameters requires a minimum of three-point uncertainty in marginal benefit, within the estimated uncertainty boundary. The optimization problem solves for the points X, Y, and Z, at which the expected welfare loss is minimized (see Figure 3.18).

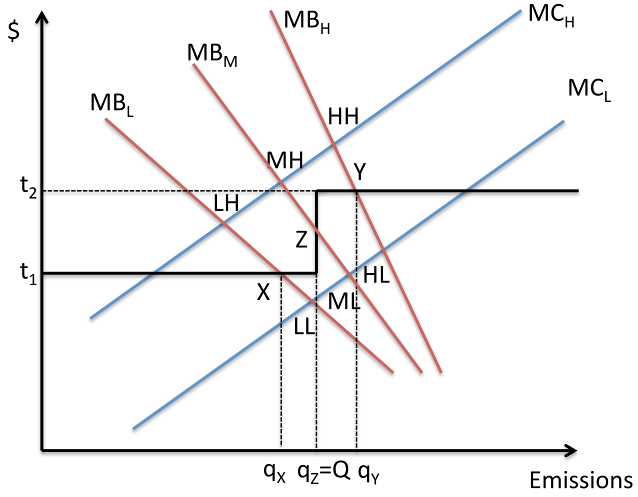

Figure 3.18. Three-point multiplicative uncertainty in MB

Solving the optimization problem in (6), assuming the same probability distribution functions for uncertainty terms, the optimum emission levels will be:

$$q_X = \frac{B_1 b_L - C_1 - E(\theta_c)}{C_2 - B_2 b_L} \tag{IV.2}$$

$$q_Z = \frac{B_1 b_M - C_1 - E(\theta_c)}{C_2 - B_2 b_M} \tag{IV.3}$$

$$q_Y = \frac{B_1 b_H - C_1 - E(\theta_c)}{C_2 - B_2 b_H} \tag{IV.4}$$

As I have $q_Y > q_Z > q_X$, there is a unique corresponding optimal policy design which passes through X, Y, and Z. The optimal two-step tax policy then is to set the design parameters as follows:

$$t_1 = b_L(B_1 + B_2 q_X) = \frac{B_1 b_L C_2 - B_2 b_L (C_1 - E(\theta_c))}{C_2 - B_2 b_L}, \tag{IV.5}$$

$$t_2 = b_H(B_1 + B_2 q_Y) = \frac{B_1 b_H C_2 - B_2 b_H (C_1 - E(\theta_c))}{C_2 - B_2 b_H}, \text{ and} \tag{IV.6}$$

$$Q = q_Z = \frac{B_1 b_M - C_1 - E(\theta_c)}{C_2 - B_2 b_M}. \tag{IV.7}$$

Policy 2: Cap-and-Trade with Allowance Reserve

Similar to the setup explained in 3.5, I solve for a unique set of all policy parameters requires a minimum of four-point uncertainty in marginal benefit, within the estimated uncertainty boundary. The optimization problem solves for the points W, X, Y, and Z, at which the expected welfare loss is minimized (see Figure 3.19).

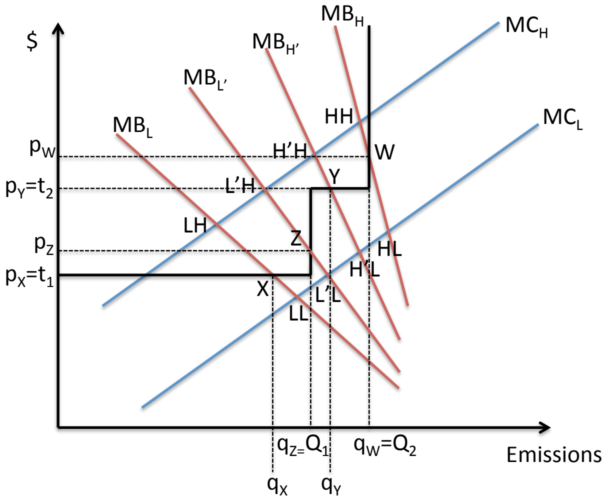

Figure 3.19. Four-point multiplicative uncertainty in MB

Solving the optimization problem in (13), assuming the same probability distribution functions for uncertainty terms, the optimum emission levels will be:

$$q_X = \frac{B_1 b_L - C_1 - E(\theta_c)}{C_2 - B_2 b_L} \tag{IV.8}$$

$$q_Z = \frac{B_1 b_{L'} - C_1 - E(\theta_c)}{C_2 - B_2 b_{L'}} \tag{IV.9}$$

$$q_Y = \frac{B_1 b_{H'} - C_1 - E(\theta_c)}{C_2 - B_2 b_{H'}} \tag{IV.10}$$

$$q_W = \frac{B_1 b_H - C_1 - E(\theta_c)}{C_2 - B_2 b_H} \tag{IV.11}$$

Given $q_W > q_Y > q_Z > q_X$, there is only unique corresponding optimal policy scheme which pass through all X, Y, Z and W points:

$$t_1 = b_L(B_1 + B_2 q_X) = \frac{B_1 b_L C_2 - B_2 b_L (C_1 - E(\theta_c))}{C_2 - B_2 b_L}, \tag{IV.12}$$

$$t_2 = b_{H'}(B_1 + B_2 q_Y) = \frac{B_1 b_{H'} C_2 - B_2 b_{H'} (C_1 - E(\theta_c))}{C_2 - B_2 b_{H'}}, \tag{IV.13}$$

$$Q_1 = q_Z = \frac{B_1 b_{L'} - C_1 - E(\theta_c)}{C_2 - B_2 b_{L'}}, \text{ and} \tag{IV.14}$$

$$Q_2 = q_W = \frac{B_1 b_H - C_1 - E(\theta_c)}{C_2 - B_2 b_H}. \tag{IV.15}$$

U.S. Climate Policy

Assuming the same set of assumptions on marginal cost and benefit functions as in section 3.6, except for the multiplicative uncertainty assumption for MB function, Figure 3.20 presents the cost-benefit model for the U.S. in 2010.

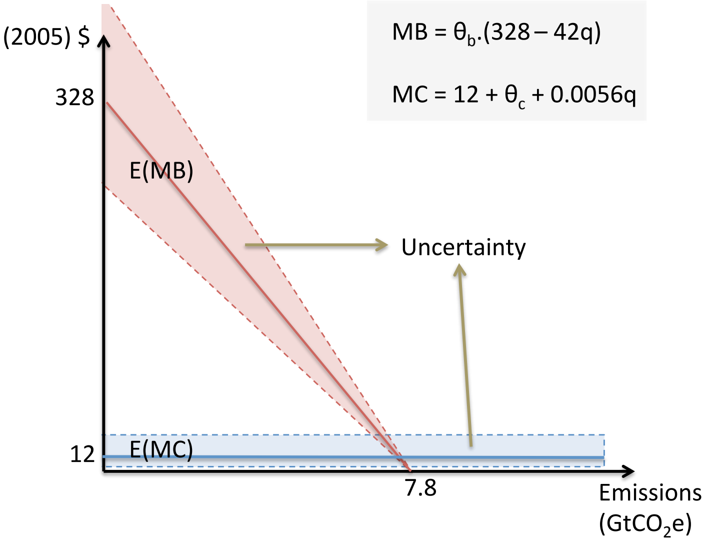

Figure 3.20. Marginal cost and benefit functions for U.S., 2010.

Similar to our original model, I first arbitrarily choose a 20% uncertainty range for MB (i.e., 1 ± 0.1, which implies an uncertainty multiplier between 0.9 and 1.1) and then test the assumption in a sensitivity analysis.

Optimal design for two-step tax policy:

$$\theta_c = \begin{cases} -10.64 & \pi = 1/2 \\ +16.33 & \pi = 1/2 \end{cases} \cdots, \theta_b = \begin{cases} 0.9 & \pi = 1/3 \\ 1 & \pi = 1/3 \\ 1.1 & \pi = 1/3 \end{cases} \cdots \Rightarrow \begin{cases} t_1 = \$12.042 \\ Q = 7.52 \text{ GtCO}_2\text{e} \\ t_2 = \$12.042 \end{cases} \quad \text{(IV.16)}$$

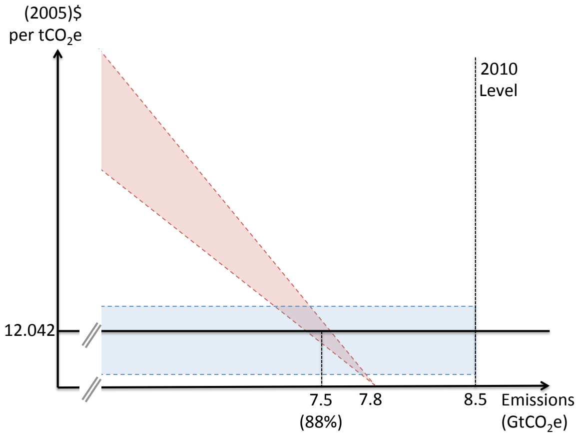

Figure 3.21. Optimal two-step tax policy design for the U.S.; with multiplicative uncertainty in MB

Optimal design for a cap-and-trade system with allowance reserve:

$$\theta_c = \begin{cases} -10.64 & \pi = 1/2 \\ +16.33 & \pi = 1/2 \end{cases} .., \theta_b = \begin{cases} 0.90 & \pi = 1/4 \\ 0.97 & \pi = 1/4 \\ 1.03 & \pi = 1/4 \\ 1.10 & \pi = 1/4 \end{cases} .. \Rightarrow \begin{cases} t_1 = \$12.042 \\ Q = 7.51 \text{ GtCO}_2\text{e} \\ t_2 = \$12.042 \\ \text{Reserve} = 0.04 \text{ GtCO}_2\text{e} \end{cases} \quad \text{(IV.17)}$$

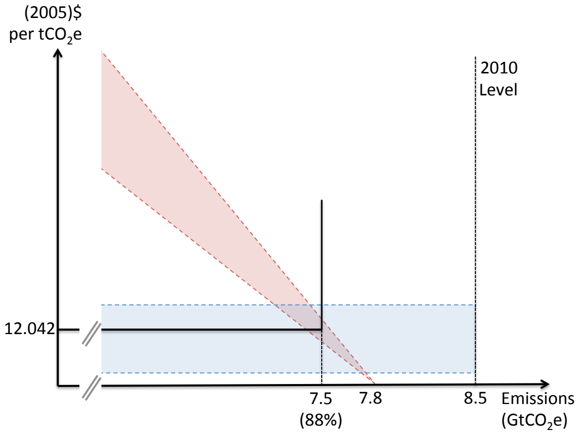

Figure 3.22. Optimal cap-and-trade with allowance reserve policy design for the U.S.; with multiplicative uncertainty in MB

Discussion

The effect of multiplicative uncertainty modeling for MB function in this exercise is very similar to the case of tightening the uncertainty range in original model. This is mainly due to the relatively low marginal (damage) cost of emissions *flow* at current GHG emissions *stock* level. Therefore, as described in discussions of section 3.5, the tax level differential and allowance reserve shrank accordingly. As a combined effect of almost flat marginal (damage) cost curve and tight variation in marginal abatement cost (in our interval of interest for the US climate model), the two tax levels become identical, similar to the case of absolute flat marginal cost curve. Therefore, the results present a carbon tax and a cap-and-trade with price floor. The expected welfare losses of the two policies echo our conclusion from original model about superiority of a price-based mechanism over a quantity-based hybrid policy.

I also ran similar set of sensitivity analysis scenarios to check for impacts of our choice of values for model parameters on policy design parameters, as well as the ranking of the two policies with regard to their expected welfare loss. The former impact found to be similar to the original model, i.e., the policy design parameters are fairly robust within a reasonable change in model parameter values. The policy ranking, however, revealed one difference from original results: when multiplicative uncertainty in MB becomes large enough (i.e., ± 50% in that specific scenario, as opposed to the ± 10% in benchmark model), the quantity-based policy (i.e., Policy 2) offered a 2.5% advantage over the price-based policy (i.e., Policy 1).

3.12 Appendix 3.V. Sensitivity Analyses

A number of scenarios have been ran to test the robustness of my results, especially in terms of ranking the two hybrid policies with respect to their expected welfare loss.

Tables 3.V-1 and 3.V-2 compare the results from baseline model with alternative scenarios for both original model (i.e., additive uncertainty for MB) and alternative model (i.e., multiplicative uncertainty for MB). In both tables, columns 1 and 2 list the parameter choice for each scenario, column 3 shows the expected loss under both policies and their differences, and columns 4 and 5 present the change in both policies' design parameters under corresponding scenarios.

Table 3.V-1. Sensitivity analysis – results for original model (additive uncertainty for MB)

	1			2			3			4			5				
							$ million			P1			P2				
	B1	Uncertainty	B2	C1	Uncertainty	C2	EL(P1)	EL(P2)	Diff	t1	t2	Q	t1	t2	Q1	Q2	A.R.
Baseline (value)	328	10%	-42	12	10%	0.0056	2238	2261	23	12.038	12.047	7.523	12.038	12.044	7.263	8.304	1.041
Senarios (%change)	-25%						2238	2261	23	-0.1%	-0.1%	-25.9%	-0.1%	-0.1%	-26.9%	-23.5%	0%
	25%						2238	2261	23	0.1%	0.1%	25.9%	0.1%	0.1%	26.9%	23.5%	0%
		5%					2238	2261	23	0%	0%	0%	0%	0%	0.0%	-4.7%	-37.5%
		20%					2238	2261	23	0%	0%	0%	0%	0%	-10.8%	9.4%	150%
		40%					2238	2261	23	-0.1%	0.1%	0%	-0.1%	0.1%	-25.1%	28.2%	400%
			-50%				4476	4521	45	0.3%	0.4%	100.0%	0.3%	0.4%	100%	100%	100%
			-10%				2487	2512	25	0%	0%	11.1%	0%	0%	11.1%	11.1%	11.1%
			10%				2035	2055	21	0%	0%	-9.1%	0%	0%	-9.1%	-9.1%	-9.1%
			50%				1492	1507	15	-0.1%	-0.1%	-33.3%	-0.1%	-0.1%	-33.3%	-33.3%	-33.3%
				-50%			2238	2261	23	-49.8%	-49.8%	1.9%	-49.8%	-49.8%	2.0%	1.7%	0%
				50%			2238	2261	23	49.8%	49.8%	-1.9%	49.8%	49.8%	-2.0%	-1.7%	0%
					-50%		334	337	3	0%	0%	0%	0%	0%	0%	0%	0%
					100%		5336	5390	54	0%	0%	0%	0%	0%	0%	0%	0%
						0	2239	2261	23	-0.3%	-0.4%	0%	-0.3%	-0.4%	0%	0%	0%
						-50%	2238	2261	23	-0.2%	-0.2%	0%	-0.2%	-0.2%	0%	0%	0%
						100%	2238	2261	23	0.3%	0.4%	0%	0.3%	0.4%	0%	0%	0%
						0.1	2233	2256	23	5.3%	6.5%	-0.2%	5.3%	6.1%	-0.2%	-0.2%	-0.2%
						1	2187	2209	22	54.4%	66.9%	-2.3%	54.4%	62.8%	-2.3%	-2.3%	-2.3%
4-pt PDF for both							2238	2261	23	0%	0%	+/- 3%	0%	0%	0%	0%	0%

Table 3.V-2. Sensitivity analysis – results for alternative model (multiplicative uncertainty for MB)

	1			2			3			4			5				
							$ million			P1			P2				
	B1	Uncertainty	B2	C1	Uncertainty	C2	EL(P1)	EL(P2)	Diff	t1	t2	Q	t1	t2	Q1	Q2	A.R.
Baseline (value)	328	10%	-42	12	10%	0.0056	2253	2274	20	12.042	12.042	7.523	12.042	12.042	7.513	7.549	0.036
Senarios (%change)	-25%						2253	2274	20	-0.1%	-0.1%	-25.9%	-0.1%	-0.1%	-26.0%	-25.9%	-0.1%
	25%						2253	2274	20	0.1%	0.1%	25.9%	0.1%	0.1%	26.0%	25.9%	0.1%
		5%					2242	2264	22	0%	0%	0%	0%	0%	0.1%	-0.2%	-48.5%
		30%					2273	2290	17	0%	0%	0%	0%	0%	-0.1%	0.2%	46.0%
		40%					2735	2670	-66	0%	0%	0%	0%	0%	-0.6%	0.9%	325.3%
			-50%				4506	4546	40	0.3%	0.4%	100.0%	0.3%	0.4%	100.0%	100.0%	100.7%
			-10%				2504	2526	22	0.0%	0.0%	11.1%	0%	0%	11.1%	11.1%	11.2%
			10%				2049	2067	18	0.0%	0.0%	-9.1%	0%	0%	-9.1%	-9.1%	-9.1%
			50%				1502	1516	13	-0.1%	-0.1%	-33.3%	-0.1%	-0.1%	-33.3%	-33.3%	-33.4%
				-50%			2253	2274	20	-49.8%	-49.8%	1.9%	-49.8%	-49.8%	2.0%	1.7%	-49.8%
				50%			2253	2274	20	49.8%	49.8%	-1.9%	49.8%	49.8%	-2.0%	-1.7%	49.8%
					-50%		336	339	3	0%	0%	0%	0%	0%	0%	0%	0%
					100%		5372	5420	48	0%	0%	0%	0%	0%	0%	0%	0%
						0	2254	2274	20	-0.3%	-0.4%	0%	-0.3%	-0.4%	0%	0%	-0.3%
						-50%	2253	2274	20	-0.2%	-0.2%	0%	-0.2%	-0.2%	0%	0%	-0.2%
						100%	2253	2273	20	0.3%	0.4%	0%	0.3%	0.4%	0%	0%	0.3%
						0.1	2248	2268	20	5.9%	5.9%	-0.2%	5.9%	5.9%	-0.2%	-0.2%	5.7%
						1	2201	2220	20	60.3%	61.0%	-2.3%	60.3%	60.8%	-2.4%	-2.1%	57.2%
4-pt PDF for both							2238	2261	23	0%	0%	+/- 0.1%	0%	0%	0%	0%	0%

Tables 3.V-3 presents the results of comparison between the two policies together and with the most preferred climate policy (i.e., carbon tax).

Table 3.V-3. Sensitivity analysis – welfare loss comparison across policies

							Original Model				Alternative Model			
	B1	Uncertainty	B2	C1	Uncertainty	C2	Tax / C&T	P1 / Tax	P2 / Tax	P1 / P2	Tax / C&T	P1 / Tax	P2 / Tax	P1 / P2
Baseline	328	10%	-42	12	10%	0.0056	23%	103%	104%	99%	98%	104%	104%	99%
Senarios	-25%						23%	103%	104%	99%	98%	104%	104%	99%
	25%						23%	103%	104%	99%	98%	104%	104%	99%
		5%					49%	103%	104%	99%	99.5%	103%	104%	99%
		20%					5%	103%	104%	99%	96%	104%	104%	99%
		40%					1%	103%	104%	99%	48%	107%	104%	102%
			-50%				23%	103%	104%	99%	98%	104%	104%	99%
			-10%				23%	103%	104%	99%	98%	104%	105%	99%
			10%				23%	103%	104%	99%	98%	103%	104%	99%
			50%				23%	103%	104%	99%	98%	104%	104%	99%
				-50%			23%	103%	104%	99%	99%	104%	104%	99%
				50%			23%	103%	104%	99%	97%	104%	104%	99%
					-50%		5%	99%	100%	99%	96%	99%	100%	99%
					100%		43%	99%	100%	99%	99%	99%	100%	99%
						0	23%	103%	104%	99%	98%	104%	104%	99%
						-50%	23%	103%	104%	99%	98%	104%	104%	99%
						100%	23%	103%	104%	99%	98%	104%	104%	99%
						0.1	23%	103%	104%	99%	98%	104%	104%	99%
						1	23%	103%	104%	99%	97%	104%	104%	99%

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