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BY

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Abstract

This study assesses the economic and greenhouse gas emissions impacts of a proposed 400MW wind farm in Hawaii. Due to its island setting, this project is a hybrid between an onshore and offshore wind development. The turbines are planned for the island(s) of Lanai and, potentially, Molokai. The project includes building an undersea cable to bring the power to the population center of Oahu. It is motivated by 1) Hawaii's high electricity rates, which are nearly three times the national average, and 2) its Renewable Portfolio Standard mandating that 40% of electricity sales be met through renewable sources by the year 2030.

We use an economy-wide computable general equilibrium model of Hawaii's economy coupled with a detailed dynamic optimization model for the electric sector. We find that the 400MW wind project competes with imported biofuel as a least-cost means of meeting the RPS mandate. As such, the wind project serves as a "hedge" against potentially rising and volatile fuel prices, including biofuel. Though its net positive macroeconomic impacts are small, the estimated reduction by 9 million metric tons of CO_2 emissions makes the project a cost-effective approach to GHG reduction. Moreover, variability in imported fuel costs are found to be a much more dominant factor in determining cost-effectiveness than potential cost overruns in the wind project's construction.

Keywords

Wind Energy; Hawaii; Renewable Portfolio Standard; Computable General Equilibrium

I. Introduction

Wind energy is touted as being one of the most viable renewable sources for electricity based on its favorable cost and carbon neutrality [1] The U.S. produces 3.5% of its electricity from wind [2] and its market share is growing. Between 2007 and 2010, wind energy accounted for 36% of new electric generation capacity in the U.S. and, by the end of 2011, wind energy installations totaled 47 gigawatts [3]. It has been suggested that wind energy can provide 20% of U.S. electricity needs by the year 2030 [4].

Nonetheless, the cost of producing electricity from wind is more expensive than most fossil fuel-fed thermal generators [5]. Policies like the Federal Production Tax Credit of 2.1 cents per kWh, however, makes wind power more cost competitive [3]. In addition, wind energy continues to be a main resource to meet state Renewable Portfolio Standards (RPS) [6].

This study builds understanding of the economic and greenhouse gas emissions impact of a large-scale wind project, particularly relevant to islands. The wind farm of interest is planned for the rural islands of Lanai and Molokai (or some combination thereto) to bring power via an undersea cable to the urban island of Oahu, which is home to roughly three-quarters of the State's 1.3 million residents. The project is currently in the scoping and environmental review stage and is one of the Hawaiian Electric Company's (HECO) primary projects to meet its RPS [7,8]. Hawaii's RPS law specifies that: 1) 10% of net electricity sales be based on renewable energy sources by the end of 2010, 2) 15% by 2015, 3) 25% percent by 2020, and 4) 40% by 2030 [9].[1] Hawaii's electricity portfolio is currently overwhelmingly dominated by oil-burning.

Hawaii offers an illustrative case for understanding the systemic and temporal impacts of renewable energy projects. Its island geography makes for a tractable modeling framework because there is no opportunity for sharing power outside the State. The Hawaii Computable General Equilibrium Model (H-CGE) is a "top-down" representation of Hawaii's overall economy while the Hawaii Electricity Model (HELM) offers "bottom-up" detail of the electric sector. This dual approach provides a level of depth and breadth within a modeling platform that allows us to estimate the optimal mix of electricity generation over a suite of possible technologies, changes in electricity pries, and impacts to household welfare, gross state product and electric sector greenhouse gas emissions.

A number of scenarios are run to understand the impact of the proposed wind project. They are 1) a "No Policy" scenario where the RPS does not exist (this serves as a baseline for analysis of the subsequent scenarios); 2) an "RPS w/o BigWind" scenario that determines the least-cost mix of electricity generation to meet the State's RPS law – where the wind project is not built; and 3) an "RPS w/BigWind" scenario that requires the wind project be built in the year 2020 while selecting

[1] Renewable fuel/energy types include solar, wind, ocean, geothermal, biomass-based, landfill gas, hydroelectric, CHP/cogeneration, hydrogen, anaerobic digestion, and waste.

least-cost technologies relative to the wind project. The scenarios are each run under *low*, *reference*, and *high* fuel prices, based on the U.S. Energy Information Administration's (EIA) *Annual Energy Outlook 2012*.

We find that the "big wind" project, as it as come to be known in Hawaii, serves as a "hedge" against potentially rising and volatile fuel prices, including biofuel prices. Fuel costs are found to be a much more dominant factor in assessing the cost-effectiveness of the project than potential cost overruns in the wind project's construction. The proposed 400MW wind project offers a least-cost means of achieving the RPS for the electric sector under *reference* and *high* fuel prices, both fossil and bio-based. Even when fossil fuel and biofuel prices are expected to be *low*, the proposed wind project retains its net macroeconomic benefits. Though macroeconomic impacts are extremely small, the estimated reduction by 9 million metric tons of CO2 emissions make the project a cost-effective approach to GHG reduction.

We find that the 400MW wind project displaces importing biofuel as a least-cost means for the electric sector to meet the RPS. Moving forward with the proposed 400MW wind project, however, serves to dramatically reduce the amount of imported biofuel necessary to meet the RPS target (by over 50%) and benefits the overall economy because of a positive terms of trade effect.

The following section (Section II) discusses the relevant literature on assessing the cost of wind energy production, including the proposed Hawaii project. Section III presents HELM, H-CGE and their data. Section IV presents the scenarios and results, including sensitivity analysis. Section V discusses the results and offers concluding remarks.

2. Wind Energy Production

Wind energy is a rapidly expanding resource. The majority of wind development in the past decade has been onshore though there is increasing interest in development of offshore wind projects [10]. The cost of wind projects varies widely and often depends on location [10]. The cost-competitiveness of a wind project depends on both the physical characteristics of the proposed site (*e.g.*, wind resource and distance to demand center) as well as the other available resources for electricity. Wind energy would be much less cost-competitive, for example, in an electricity portfolio dominated by coal than oil. The range of available alternatives also greatly impacts the overall greenhouse gas emissions profile from the electric sector and as a result of wind energy projects. The reductions in greenhouse gas emissions that a wind project achieves depends on the resources it would displace. Greenhouse gas emission reductions will be considerably higher if wind-based electricity displaces coal, for example, rather than other renewable sources of electricity such as solar photovoltaic

2.1 Production Costs

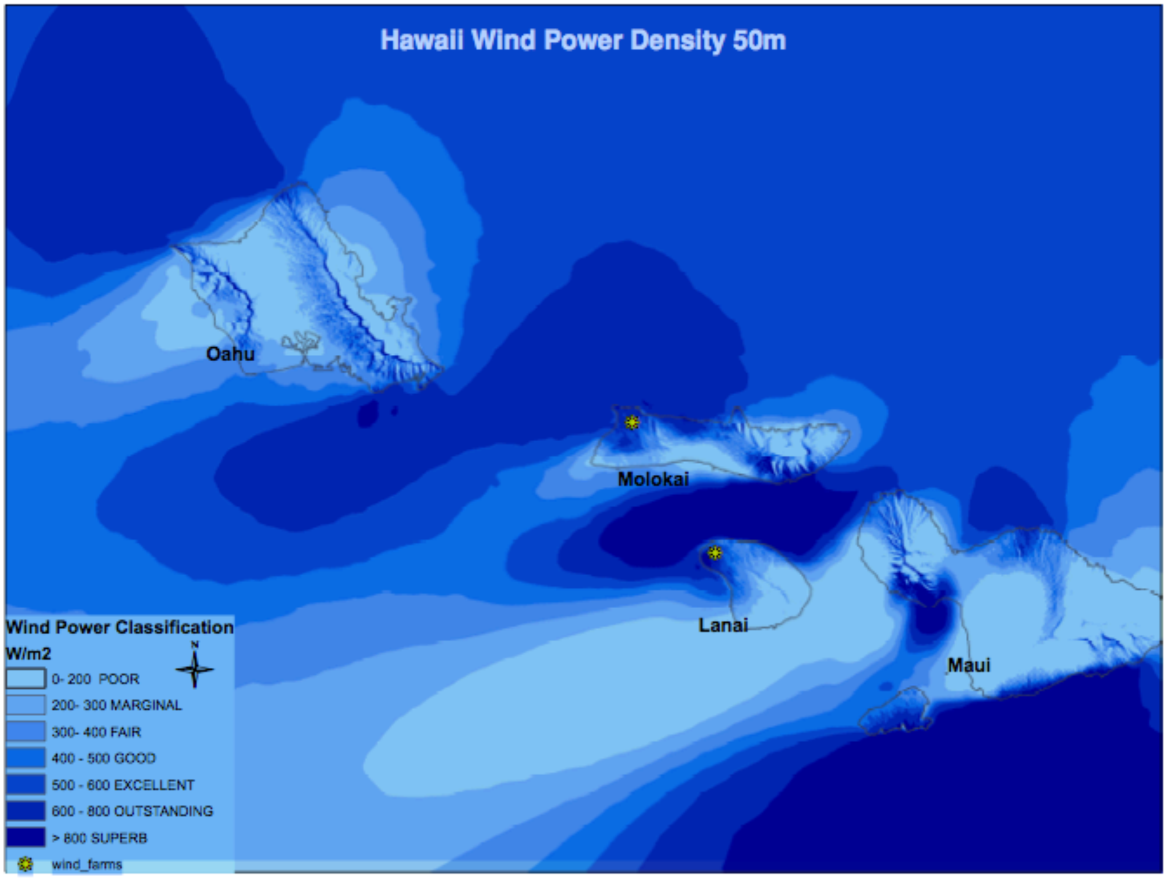
As detailed in Blanco [11], the major components of cost in relation to wind energy are capital and construction costs. Capital expenditures include the turbine, connection cables and the sub-station. Construction costs account for the cost of labor and civil work, including foundations, roads and buildings. Other variable costs include cost of operations and maintenance, insurance and taxes as well as other management-related expenditures. Land and sub-station rental fees are also a factor. The cost differences between onshore and offshore wind farms are substantial. Whereas Blanco [11] estimates that cost of the turbine accounts for 71% of onshore wind, it is only 33% of offshore wind. For offshore wind, the foundations add considerably to expenditures, as well as cable installation. The actual costs of wind projects vary widely, depending on location and size. For example, two offshore wind projects constructed in 2008 in the UK ranged from $6.6US million per MW and $4.3, respectively [10]. The more than 50% difference in cost is primarily driven by location, which includes factors such as water depth and distance from shore. Project size and wind turbine size are important factors as well [10]. Moreover, if capacity factors improve (i.e. by increasing ability of the grid to take intermittent power) and capital costs decrease as the industry matures, the cost-effectiveness of wind energy projects could change dramatically. Additionally, there is opportunity to decrease operations and maintenance costs, through technologies like remote-control devices [11].

2.2 Hawaii's Proposed "Big Wind" Project

The proposed 400 MW wind project that would bring power from Maui County to the City & County of Honolulu, from a cost perspective, is a hybrid between an onshore and offshore wind project. It is more similar to an onshore project in terms of turbine installation while, on the other hand, it resembles an offshore wind project in terms of the undersea cable.

Wind energy is an appealing means of reaching Hawaii's RPS because of the consistency of Hawaii's "tradewinds," though there is a geographic disconnect between quality wind types and electricity demand. Figure 1 shows the gradient of wind resources on Oahu and Maui County.

Figure 1. Hawaii Wind Map



Data Source: State of Hawaii GIS Wind Energy Resource Data

Oahu is home to three quarters of the State's population, but the State's best wind resources, shown in dark blue, are on Molokai and Lanai (both part of Maui County). On Molokai, the location of interest is the west end of Ilio Point (shown with an asterisk). For a further description about the potential for wind energy in Ilio Point, see Stockton [12]. On Lanai, the location of interest is the northwest area of Polihua Beach (also shown with an asterisk).

A recent study estimates that up to 25% of Oahu's electricity demand can be met with wind energy at an average capacity factor of 41% [13]. This study determined that up to 500 MW of wind energy (based on 400 MW off-island and 100 MW on-island) can be integrated into Oahu's grid while maintaining system reliability.

2.3 Analytical Approaches

In their most straightforward incarnation, studies assess the viability of wind energy based on its levelized cost (i.e. estimating fixed and variable costs over time; See for example Snyder and Kaiser, [10], and Hoppock and Patino-Echeverri, [6]). Valenzuela and Wang [1] assess the market value of wind power within central Europe using an autoregressive function. There is additionally a rich set of studies that assess the regional economic impacts of regional projects (see for example: Costanti [14]; Lantz [15]; Lantz and Tegan [16]; Slattery et al. [17]). Many take a top-down approach, mainly from Input-Output analysis (see discussion in Brown et al. [3]). Brown et al. [3] provides an ex-post econometric study using county-level data in the Great Plains region of the U.S.

This study similarly seeks to assess regional economic impacts of a proposed wind project, though it takes a methodologically different approach in combining a "top-down" computable general equilibrium model of Hawaii's economy with a "bottom-up" electric sector model. Top-down models, in this case based on computable general equilibrium, offer a representation of the entire economy and can be structured to focus on particular sectors, such as electricity. General equilibrium models are considered an improvement over their theoretical predecessors, Input-Output models, because they contain price feedbacks.

Bottom-up models are often dynamic optimization programs of an individual sector, in this case electricity, and allow for greater detail on capital costs, operating costs, technological constraints, and environmental factors [18]. Such electric sector optimization models simulate competition amongst electricity types by choosing the most cost-effective technology, or mix of technologies, to meet electricity demand within given load and other physical constraints [18].

A methodology to integrate top-down and bottom-up models is presented in Bohringer and Rutherford [19]. This application to wind energy provides an important contribution to the literature on the impacts of large-scale renewable energy projects because this modeling platform well-captures the tradeoff between the project's large capital investment coupled with decreased fuel (operating) costs over time. Understanding the impacts of the near-term costs and long-term benefits on the overall economy can help to inform decision-makers about the "big wind" project, particularly in terms of meeting the RPS and potential GHG reductions.[2]

3. Summary of Models and Data

HELM and H-CGE are solved using GAMS (General Algebraic Modeling System). HELM uses a non-linear programming solver and is formulated as a quadratic program. H-CGE uses MPSGE (Mathematical Programming for General Equilibrium Analysis) and is formulated as a mixed complementarity problem. For more information on these modeling platforms, refer to Brooke et al. [20], and Rutherford [21, 22].

3.1 HELM

HELM offers a detailed representation of Hawaii's electricity sector via a non-linear program model that is calibrated to the year 2007 and projects in five-year increments from 2010 to 2030. It solves

[2]Act 234 mandates that Hawaii achieve 1990 levels of GHG emissions by the year 2020, excluding aviation fuel. The State Department of Health is currently in the rule-making process.

for the least-cost mix of generation subject to satisfying demand, regulatory requirements, and system constraints. To fully account for the lifetime of the project's proposed wind turbines, which are assumed to be operational in the year 2020, HELM assumes that the electric sector remains in its last state (i.e. the 2030 outcome) until the year 2050. This assumption ensures accounting for the full lifecycle costs of all new units. HELM is calibrated to existing electricity units in the year 2007 for Hawaii's four counties: the City & County of Honolulu, Maui County, Kauai County, and Hawaii County.

3.1.1 Data and Model Structure

Electricity units are defined by several cost and operating characteristics. Existing unit costs include fuel, fixed and variable operating costs (FOM and VOM, respectively). Fuel costs are zero for renewable energy types such as geothermal, solar, and wind-based units. New units are also characterized by their capital costs to build (CAP). We assume that operations and capital costs are constant throughout the model horizon, although a distinction is made between existing and new units.

Important physical characteristics of the units are also represented such as heat rate and availability. Heat rates are included for fuel-burning plants and specify a unit's efficiency in terms of energy required per unit of electricity generated. Availability determines the amount of hours a unit will be off-line to undergo routine or emergency maintenance. "As available," or intermittent, units are subject to a capacity factor or utilization rate, which accounts for the fact that because of physical limitations of these units (e.g., the sun does not shine and the wind does not blow 24 hours a day). The average capacity factor for wind is 41% and, specifically for the "big wind" project, 42%. Rooftop solar photovoltaic units are subject to a capacity factor of 18% [13].

The initial and potential capacity of new technologies is based on a report by Booz, Allen, Hamilton [23], which was commissioned by the State to assess total available amounts of renewable electricity. Within the capacity for wind, both potential island-specific wind projects and the proposed 400-MW project are included. We assume the undersea cable is utilized solely by the "big wind" project.[3] In addition, we assume that a unit can be retired from use – reducing its capacity to zero – if it ceases to be cost-effective. Oil-burning units can be modified to burn bio-oil or biodiesel depending on the type of oil-burning unit. For diesel burning units, we assume biodiesel and conventional diesel are perfect substitutes. For fuel oil units, we assume the maximum share of bio-oil (or crude palm oil) that can be burned is 75%. This assumption is made based on utility testing of their units [24].[4]

[3] This is reasonable given the assumption that the cable solely links the islands of Lanai, Molokai and Oahu. Future analysis, however, will assess the impact of including an undersea cable to Maui Island, which may open up a larger range of renewable sources of electricity.

[4] Most recent tests indicate that existing oil-fired units may be able to burn 100% bio-oil.

The database for HELM is constructed from several publicly available sources – ranging from planning documents including the utilities' Integrated Resources Plans (IRPs), which are mandated by the Public Utilities Commission (PUC), submitted "rate case" approvals to the PUC, and the U.S. EIA's state energy database.

Table 1 shows the average cost (weighted by capacity) and unit characteristic data used for this analysis (HELM utilizes unit specific numbers). Electricity units are presented by Steam Turbine (ST), Combustion Turbine (CT), Combined Cycle (CC), Diesel Generator (DG), Coal, Geothermal (Geo), Wind, Rooftop Photovoltaic (PV), Solar Thermal (existing only), Biomass, Waste, and Hydro. We assume that ST, CT, CC and DG units are able to burn both conventional and bio-based oil.

Table 1. Costs and Physical Characteristics of Existing and New Units [24-36]

		Cap-acity GW (sum)	FOM 2007 $/kW (avg)	VOM 2007 $/MWh (avg)	Capital Cost 2007$/kW (avg)	Heat-rate MMBtu /MWh (avg)	Avail-ability [a] % (avg)	Cap-acity Credit	Cap-acity Factor
Existing	ST	1.18	140	1	-	11	88	1	-
	CT	0.38	73	14	-	17	87	1	-
	CC	0.47	76	6	-	9	89	1	-
	DG	0.03	13	14	-	10	88	1	-
	Coal	0.18	65	5	-	10	84	1	-
	Geo	0.03	150	19	-	1	95	1	-
	Wind	0.06	78	2	-	-	95	0	0.39
	Other *	0.11	-	-	-	-	-	-	-
	* (Solar Thermal, Biomass, Waste, Hydro)								
New	CT	No Lim	32	5	1200	12	88	1	-
	CC	No Lim	20	20	2400 [b]	8	86	1	-
	Geo	0.13	150	17	4000	1	95	1	-
	Rooftop PV [c]	1.50	0	-89 [d]	7100 [e]	-	95	0	0.18
	Biomass	0.13	230	5	3400	14	86	1	-
	Waste	0.08	390	17	8000	17	83	1	-
	OtherWind	0.26	42	3	3800	-	95	0	0.41
	BigWind	0.40	28	2	5000	-	95	0	0.42

a One minus the availability factor gives the percentage of time that a unit is off-line due to maintenance.

b This cost represents a dual train CC unit based on publicly available utility estimates for new units. Sensitivity analysis is conducted based on the cost of a single train unit ($1900/kW and a more prohibitive $3600/kW).

c For the purposes of this analysis we also considered utility-scale solar PV. The publicly available data, however, were inconsistent with current trends. Given the rapidly changing nature of the PV market, we decided to exclude utility-scale solar from analysis. The implications of our results, however, remain unchanged.

d To compare customer-sited generation on the same basis as utility-sited generation, the HELM model applies a negative VOM cost to the customer-sited generation to account for the fact that it incurs no transmission and distribution (T&D) operating expenses. The difference between household electricity and wholesale electricity (cost to generate electricity) is used as a proxy for T&D costs (based on the utilities Effective Rates Summary, average cost difference for 2011). These costs are then subtracted from the cost to generate electricity from customer-sited generation. This cost varies by island.

e This is the full cost before state and federal income tax credits (35% and 30%, respectively) are applied. Subsidies are accounted for with HELM.

Labor costs are apportioned from FOM costs, as they are typically aggregated as one cost item within public data sources. We estimated annual labor costs per unit type by taking the average electric sector salary, as detailed in the 2007 State Input-Output Table, and multiplying by the number of employees, as found on the Unit Information Forms filed with the PUC. Labor costs vary widely by technology. For example, we estimate labor costs for wind energy as $9.30/kw, in comparison to between $25 and $30/kw for a current oil-burning unit.

There is tremendous uncertainty in regards to the capital costs of the wind project – mainly around the cable and conversion stations. There are two major studies, commissioned by the State, that attempt to estimate components of cost. Electranix [37] estimates that the cable and conversion stations will cost anywhere between $834 and $1,679 per kw (adjusted for $2005). Navigant [38] estimates a range of $1,320 to $1,522/kw. Including the cost of the wind turbines themselves, $3,000/kw (taking a direct average cost of prior on-island wind projects across the State), leads to an all-in cost ranging between $3,800 and $4,665/kw. Both studies and, in particular Electranix, state the uncertainty in their estimates. For the purposes of this study, we take a range of estimates: $4,000, $5,000 and $6,000/kw. We use $5,000/kw as the baseline estimate, as this is most in line with both Navigant and Electranix estimates. The higher estimate, $6,000/kw is used to assess the impacts of any potential cost overruns.

The operating costs, however, are expected to be less than the average (smaller-scale) wind project within the State (for example, by $14/kW FOM and $1/MWh VOM) due to economies of scale.

HELM additionally accounts for lifecycle CO2 emissions, where the emissions factors are shown in Table 2.

Table 2. Lifecycle GHG Emissions Factors (kg CO2/kWh and MTCO2/MMBtu) [39,40]

	Total (kg CO2/ kWh)	Total (MTCO2/ MMBtu)
Oil	-	0.098
Coal	-	0.11
Bio	-	0.024
Geo	0.017	-
Wind	0.007	-
Solar	0.076	-
Other	0.53	-

The emissions factors for all sources except crude palm oil and biodiesel are estimated using the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET) version 1.8d.1. This is a publically available model developed by the Argonne National Laboratory [39]. The emissions associated with crude palm oil and biodiesel are based on analysis from Wicke et al. [40] and, as the local utility has committed that biofuel sources will be certified by the Roundtable on Sustainable Biofuels, factors are chosen at the low end of Wicke et al.[40]. We assume the biofuel emissions factor is a 75% improvement over conventional oil.

For a full description of HELM refer to Coffman, Griffin and Bernstein [41].

3.2 H-CGE

H-CGE is a recursive dynamic general equilibrium model, calibrated to the year 2007 and projecting from 2010 to 2030 in five-year increments. It is based on a Social Accounting Matrix developed in the 2007 State of Hawaii Input-Output (I-O) Study [42]. The benefit of a general equilibrium framework is that it shows interaction between consumers and producers, including price feedbacks (i.e. capturing "rebound effects") and capital accumulation over time. H-CGE represents sector-level production for all sectors except electricity, which is represented in HELM.

3.2.1 Data and Model Structure

H-CGE represents a classical Walrasian system where goods are produced under perfect competition and constant returns to scale using intermediate commodities, imports, labor (provided by households) and capital. Hawaii's economy is depicted as a small open economy. Hawaii producers are assumed to be world price takers, including the world price of oil. The oil price projections provided in EIA's *Annual Energy Outlook 2012* (*low*, *reference*, and *high*) [43] are used to provide baseline scenarios. It is calibrated to the year 2007 and solves as a recursive dynamic model (i.e. representing endogenous capital accumulation) for the years 2010, 2015, 2020, 2025 and 2030. Five-year intervals are chosen (rather than year-to-year) because of the large capital investments required in the electricity sector, thus negating smooth transitions on an annual basis. For a full description of H-CGE's model structure, including detail on the electricity and petroleum sectors and the dynamic capital accumulation mechanism, see Appendix I.

A total of sixty-eight sectors are represented in the 2007 I-O table including electricity and petroleum manufacturing, as well as other energy-related sectors such as ground transportation, water transportation, and aviation. For the purposes of tractability in presentation, the sectors are aggregated to four sectors: electricity, petroleum manufacturing, other, and state government. Important agents of final demand include households, visitors, and federal and state governments.

On the production side, the 2007 State of Hawaii I-O Table provides the value of sector-level and value-added activity. In addition, it details the value of imports to each sector and the number of jobs. The following table, Table 3, provides a summary of the aggregate data used to calibrate H-CGE.

Table 3. Overview of Hawaii's Electric Sector in Relation to the Rest of the Economy [43]

	Total Output [a]	Inter-Industry Demand	Imports	Labor Income	Proprietor Income	Other Value-Added	Jobs [b]
	$ 2007 Billion						#
Total	**$105.90**	**$28.60**	**$19.70**	**$36.70**	**$3.70**	**$17.10**	**868,000**
Electricity	2.10%	3.80%	2.10%	0.80%	0.00%	3.80%	0.30%
Petroleum Manufacturing	4.40%	10.60%	19.90%	0.20%	0.40%	1.10%	0.10%
Other Sectors	87.20%	83.70%	75.70%	85.30%	99.50%	93.10%	89.20%
State & Local Government	6.10%	1.80%	2.20%	13.70%	0.00%	1.90%	10.40%

[a] The value of total output is equal to the summed value of inter-industry demand, imports, labor income, proprietor income and other value-added. These components provide a "production function" for each sector detailed within the I-O Table.

[b] "Jobs" represents both the quantity of employee labor and proprietor labor.

May not add to 100% due to rounding.

Hawaii's economy produces $106 billion of output annually. There are 868,000 jobs, over half within service-related sectors. The state and local government is also a large employer, with 10% of jobs and 14% of wages paid. The electric sector accounts for 2% of overall economic activity and 0.3% of jobs. Petroleum manufacturing accounts for 4% of economic activity, where petroleum is the largest input into the electric sector (roughly 12 million barrels and equivalent to 693 million dollars [44]. In 2007, $3.9 billion was spent on imports into the petroleum manufacturing sector (i.e. the value of crude oil). This is 3.6% of the value of total economic activity.[5] Residents spend $840 million on electricity annually and, due to the high dependence on oil, pay the highest rates in the country at an average of 28 cents per kilowatt-hour [45,46].

Goods and services are consumed as intermediate inputs into the production of other industries, as well as by agents of final demand. Table 4 shows consumption of goods and services within Hawaii's economy by residents (households), visitors, state and local government, federal government, as well as the value that is put into investment and exported from the State.

Table 4. Overview of Hawaii's Final Consumption [42]

	Household Demand	Visitor Demand	State and Local Gov [a]	Federal Gov [b]	Investment	Exports
	$ 2007 Billion					
Total	**$42.20**	**$14.60**	**$7.70**	**$9.80**	**$12.60**	**$4.70**
Electricity	1.80%	0.00%	4.20%	0.40%	0.00%	0.00%
Petroleum Manufacturing	2.10%	0.10%	1.10%	0.90%	0.10%	11.60%
Other Sectors	79.90%	84.30%	19.90%	90.50%	70.30%	71.10%
State & Local Government	1.70%	0.00%	68.00%	0.00%	0.00%	0.00%
Imports	14.60%	15.50%	7.00%	8.10%	29.60%	17.40%

[a] State and Local Government includes both investment and consumption

[b] Federal Government includes both civilian and military, investment and consumption.

[5] Note that the value of total economic activity, $105.9 billion in 2007, is not the same as gross state product. Gross state product measures the value of total output net the value of imports. It is more appropriate to assess the value of crude oil imports in relationship to total output, rather than gross state product, because crude oil is an import activity. Thus it is being "double-counted" if estimated in comparison to gross state product.

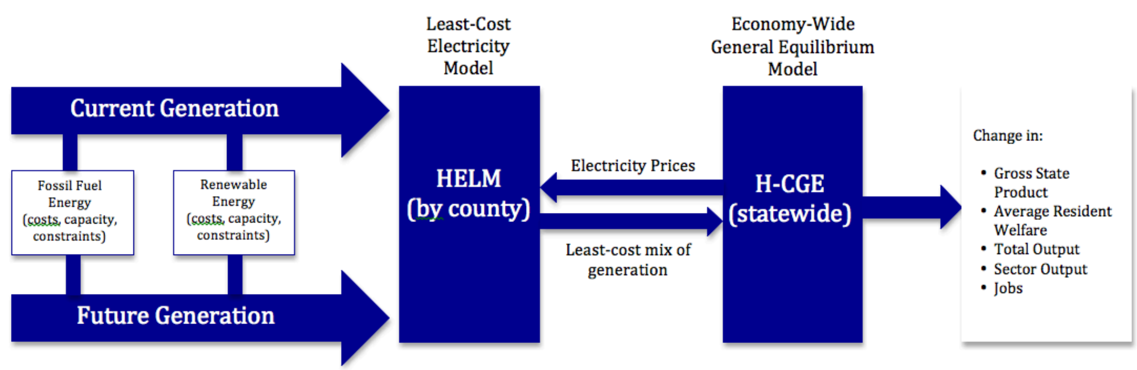
In the base year, residents consume $42 billion of goods and services annually, the largest portions being services (38%), real estate (20%) and imported products (15%). Residents spend $753 million on electricity and $891 million on petroleum products (primarily gasoline). Visitors, on the other hand, do not consume electricity "directly" (i.e. they are not customers of the electric utilities) but rather "indirectly" through hotel services and other amenities.

Electricity is a large expense for State and Local government, at $320 million annually and equivalent to 4% of all expenditures.

3.3 Model Integration

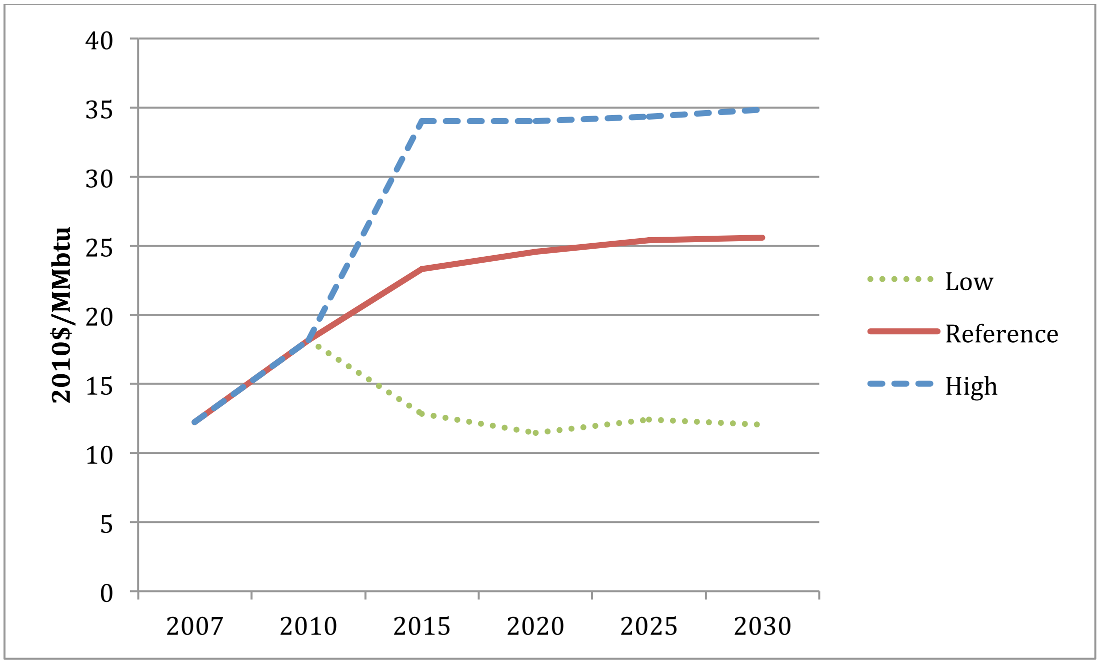
HELM requires that generation meet overall electricity demand, where the electricity demand forecast is provided by H-CGE, based on underlying economic conditions. Economic conditions are determined based on a projection of Hawaii's historic growth rate [47] and the fuel price forecast [43]. HELM assesses the least-cost approach to meeting electricity demand, which changes the cost profile for electricity and affects the overall economy. Figure 2 provides a conceptual framework for the way in which the two models, HELM and H-CGE, are integrated.

Figure 2. H-CGE and HELM Interaction



Both models are informed by fuel price forecasts provided by the *Annual Energy Outlook 2012* [43]. For illustrative purposes, Figure 3 shows the world oil price forecast. The reference case is used to establish a baseline scenario analysis while the high and low cases are used for the purpose of sensitivity analysis.

Figure 3. Oil Price Forecast [43, 48-50]



Coal and biofuel price forecasts are also used. While the projected price of oil and coal are rather straightforward, we make additional assumptions about the future price of bio-oil. As there are no (known) price forecasts that would behave consistently with the EIA NEMS model, we take a two-tier approach. First, we assume that bio-oil follows similar market trends as ethanol (E85) [43]. Because oil and bio-oil are near perfect substitutes, we additionally assume that the price of bio-oil tracks that of oil. If the projected price of oil exceeds that of the projected price of bio-oil, we assume that bio-oil adopts the same price level as oil. On the other hand, if the price of bio-oil is projected to be higher than that of oil, we take the projected price of bio-oil. We make this "minimum cost" assumption to reflect the substitutability between oil and bio-oil and to better reflect the price that Hawaii-based buyers are likely to face in a globally competitive market.

4. Scenarios and Results

4.1 Description of Scenarios and Sensitivity Analyses

To assess the economic and GHG impacts of the proposed "big wind" project, we run three scenarios: 1) No-Policy, 2) RPS w/o BigWind, and 3) RPS w/BigWind under *low*, *reference* and *high* fuel price forecasts. The No-Policy scenario serves as a baseline where no RPS policy or "big wind" project exists. The RPS w/o BigWind scenario solves for the least-cost means of achieving the RPS given available technologies, excluding "big wind" (i.e. the 400 MW wind project is assumed to not be built). The RPS w/BigWind scenario requires compliance with the RPS target and, conversely, forces "big wind" to come on-line in the year 2020. While the No-Policy scenario serves as a baseline, particularly in understanding the RPS's contribution to GHG abatement, it is the RPS w/o

BigWind and RPS w/BigWind that provide the most fruitful comparison. We use the *reference* fuel price case for baseline analysis and *low* and *high* fuel prices for sensitivity analyses.

We assume that all technologies are able to come on-line based on current policies and technological constraints. In addition, we assume that further use of coal is limited in Hawaii because, in 2008, the Hawaiian Electric Company signed an agreement (HCEI) [9] that committed itself to not use more coal for electricity generation. Coal seldom enters the energy planning dialogue in Hawaii – evidenced by the fact it is entirely omitted from the current utility Integrated Resource Plan. As part of our sensitivity analyses, however, we ran additional scenarios that allowed the development of further coal units. Because the RPS constraint targets renewable energy sources, the "additional coal" scenarios did not markedly change our results from the perspective of the cost effectiveness of the wind project. For tractability, we will thus discuss our "no more coal" results, as these better reflect the impacts of the wind farm against the status quo, or business-as-usual.

Indicators of interest include 1) the least-cost choice of electricity technologies, 2) electric-sector GHG emissions, 3) electricity cost, 4) average household expenditures, and 5) gross state product (GSP).

4.2 Scenario Results: Reference Fuel Prices

This section describes the results of the three scenarios assuming reference fuel prices, focusing on the impacts between the RPS w/o and RPS w/BigWind. The No-Policy scenario provides a baseline assessment of GHG emissions and thus implicit abatement caused by the policy.

4.2.1 Electric Sector Impacts

Under a *reference* fuel price forecast, we find that the wind project is cost effective even without RPS policy and would provide nearly 10% of the State's electricity.[6] Figure 4 shows a summary of electricity generation in the year 2030 for the reference fuel price scenarios (No-Policy, RPS w/o BigWind and RPS w/BigWind).

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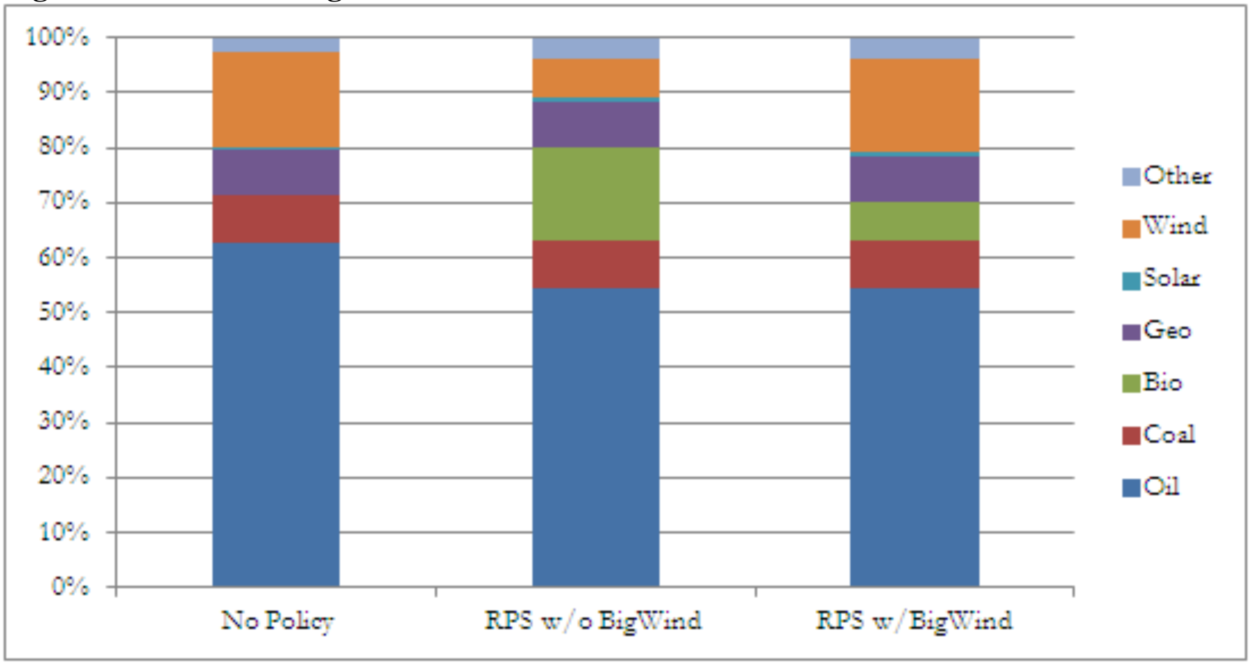
[6] The HELM model assumes that the electricity system can operate without incident if up to 20% of its generation derives from non-firm resources (e.g., wind and solar).

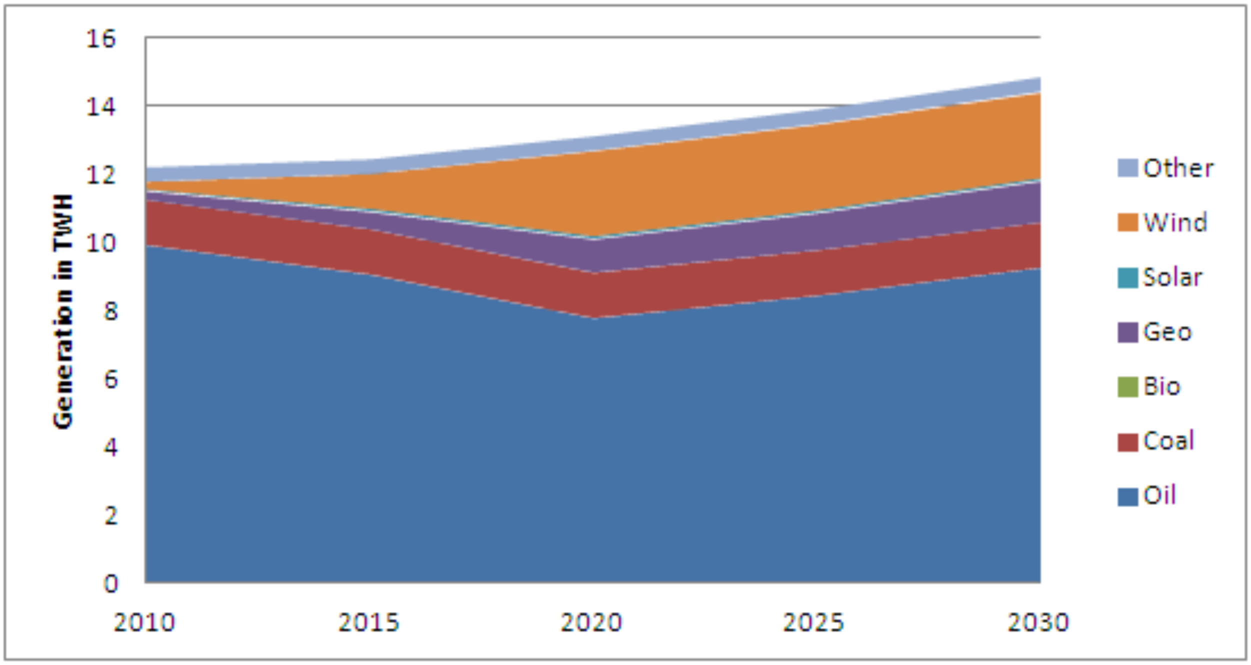
Figure 4. Generation Mix in 2030 under Reference Fuel Prices: No Policy, RPS w/o BigWind and RPS w/BigWind



In the "No Policy" case, the 400 MW wind project is endogenously selected to come online in its first year of availability, 2020. Island-specific wind projects, such as the total of 100MW on Oahu, are also cost-effective even under the No Policy scenario. Within the RPS w/BigWind scenario, wind energy is estimated to meet a total of 17% of the State's electricity needs in 2030 and account for 42% of the RPS mandate. If the wind project is not built (RPS w/o BigWind), the RPS is predominantly met through fuel-switching to biofuel.

Figure 5 shows the least-cost mix of electricity generation over time, under the *reference* fuel price and "No Policy" assumption.

Figure 5. 2010 to 2030 Electricity Generation by Source, "No Policy" and *Reference* Fuel Prices



The wind project largely serves to displace oil. Geothermal, solar and the "other" category, which includes hydroelectric and waste-to-energy resources, remain nearly identical throughout the scenarios and therefore will not be further discussed.

With the introduction of the RPS law, bio-oil becomes an important part of the generation mix. Figures 6 and 7 show the least-cost mix of generation assuming the RPS is met without and with the 400MW wind project (RPS w/o BigWind and RPS w/BigWind, respectively).

Figure 6. 2010 to 2030 Electricity Generation by Source, "RPS w/o BigWind" and *Reference* Fuel Prices

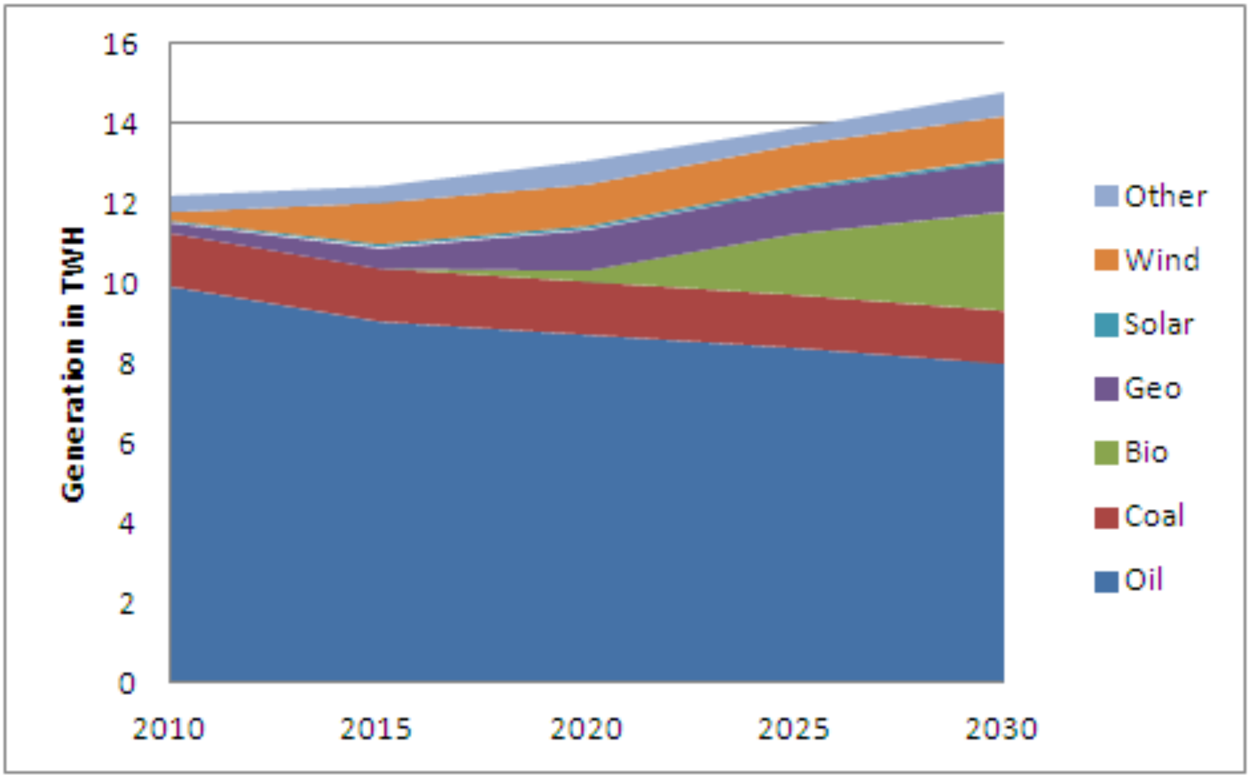
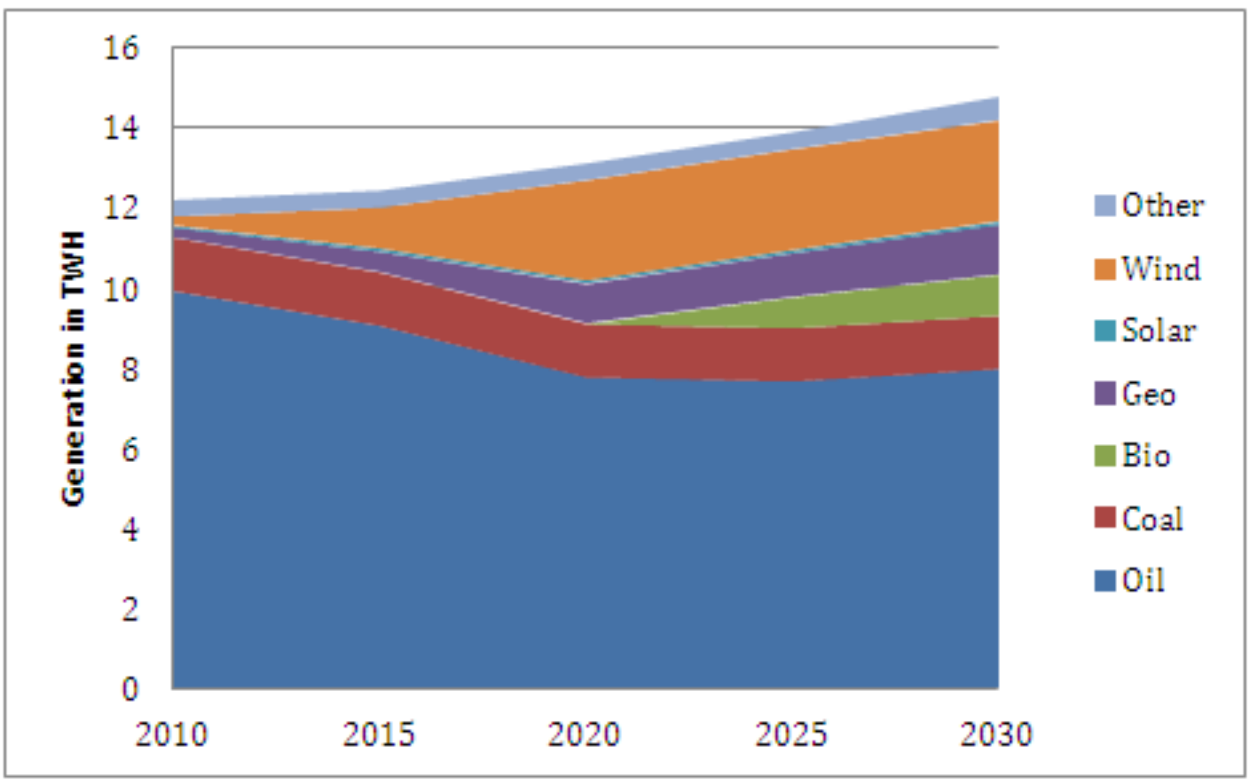


Figure 7. 2010 to 2030 Electricity Generation by Source, "RPS w/BigWind" and *Reference* Fuel Prices



What is most readily apparent in the RPS scenarios is that the wind project serves to displace biofuel. Biofuel provides a relatively inexpensive means to achieve the RPS because of the straightforward substitution with oil and thus minimal capital cost. The proposed wind project dramatically reduces the use of biofuel to meet the RPS requirement; for example, from 17% of the State's electricity demand met through biofuel generation to 7% in 2030. This is important because, from a GHG perspective, wind and bio-based energy are quite distinct.

Table 5 provides a summary of impacts to the electric sector for the reference fuel price scenarios (No-Policy, RPS w/o BigWind and RPS w/BigWind).

Table 5. Electric Sector Impacts
Summary for 2030, Reference Fuel Price

	2030 Results		
	No Policy	**RPS w/o BigWind**	**RPS w/ BigWind**
	No New Coal		
Total Renewable Electricity as a % of Sales [a,b]	31%	40%	40%
Relative Cost of Policy to Electric Sector	1.00	1.00	1.00
Cumulative (20 Year) GHG Emissions (MMTCO2)	231	235	226

a Does not add to 100% due to rounding.
b The RPS policy is defined as a percent of sales. The difference between sales and generation is line losses, which are assumed to be 8%. Therefore, a generation mix of 37% renewable sources as in Table 7 corresponds to a 40% RPS level (37%/(1-8%) = 40%).

While the relative cost of the RPS w/o BigWind and RPS w/BigWind are nearly identical, GHG emissions decrease by 9 $MMTCO_2$ (about 4%) when the "big wind" project is built. We assume that biofuel emissions offer a 75% improvement over that of oil. However, if biofuel-based emissions were to be considerably worse – for example, because the lands are being degraded to grow the biofuel – then the finding that the wind project provides cost-effective GHG emissions abatement relative to the status quo would be considerably stronger.

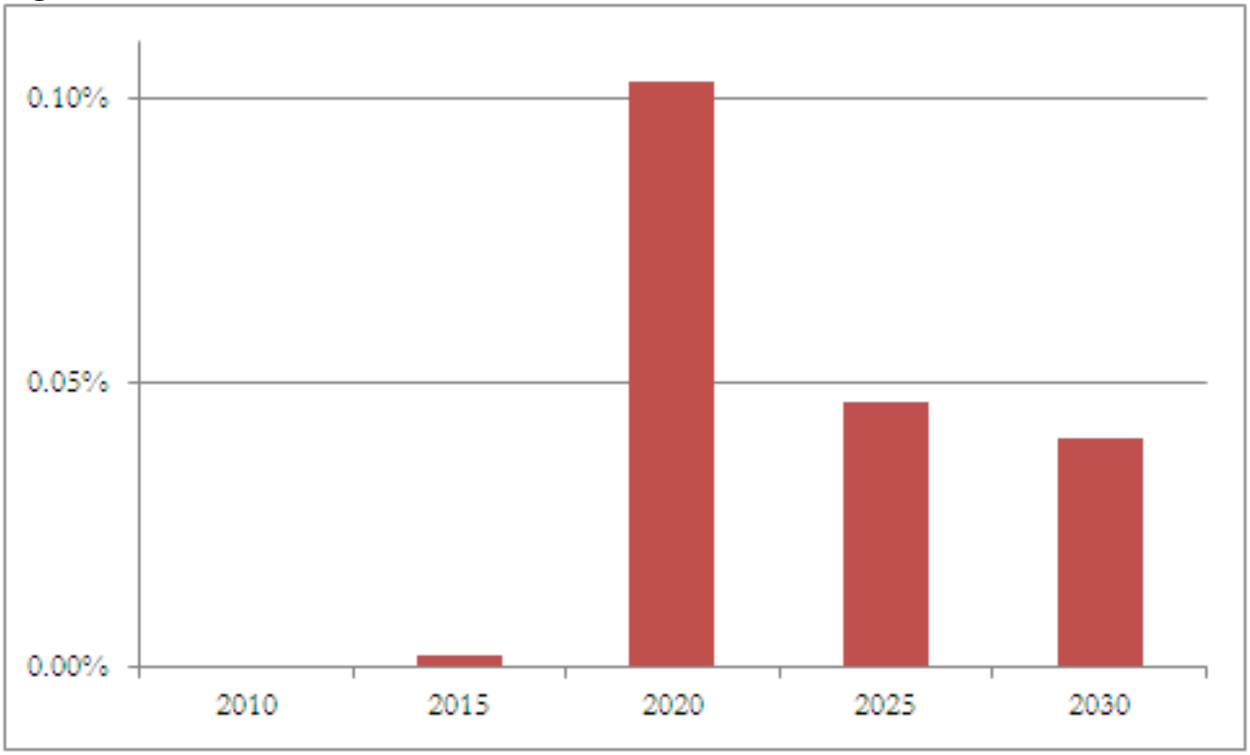
We interestingly find that, under *reference* fuel prices, the RPS (with and without BigWind) does not substantively raise the cost of electricity provision. While the literature on RPSs generally finds that the policy raises the cost of electricity provision [51], this finding to the contrary simply highlights the uniqueness of Hawaii as an oil-burning State with extremely high baseline electricity costs.

4.3 Macroeconomic Impacts

As expected, the macroeconomic impacts of the proposed wind project are quite small. This is a nearly $2 billion project in comparison to a $105 billion economy. That said, the model runs clearly show that it provides benefit to the economy within the overall time horizon.

Figure 8 shows the relative benefit in terms of Real Gross State Product of the proposed wind project (RPS w/BigWind) in comparison to the RPS without the wind project (RPS w/o BigWind).

Figure 8. Change in Real Gross State Product, RPS w/BigWind Relative to RPS w/o BigWind 2010 to 2030



The overall impacts are extremely small, only a fraction of a percentage difference. Nonetheless, they are clearly positive through the model time horizon. The benefits are most evident in the period the project is built, 2020 time frame, and dissipate into the future. In total, the proposed wind project is estimated to increase Real Gross State Product by $167 million. This translates into a welfare benefit (in net present value) of $69 million over the 20-year time horizon – only $0.34 per year per worker. The welfare effect is so small as to be negligible.

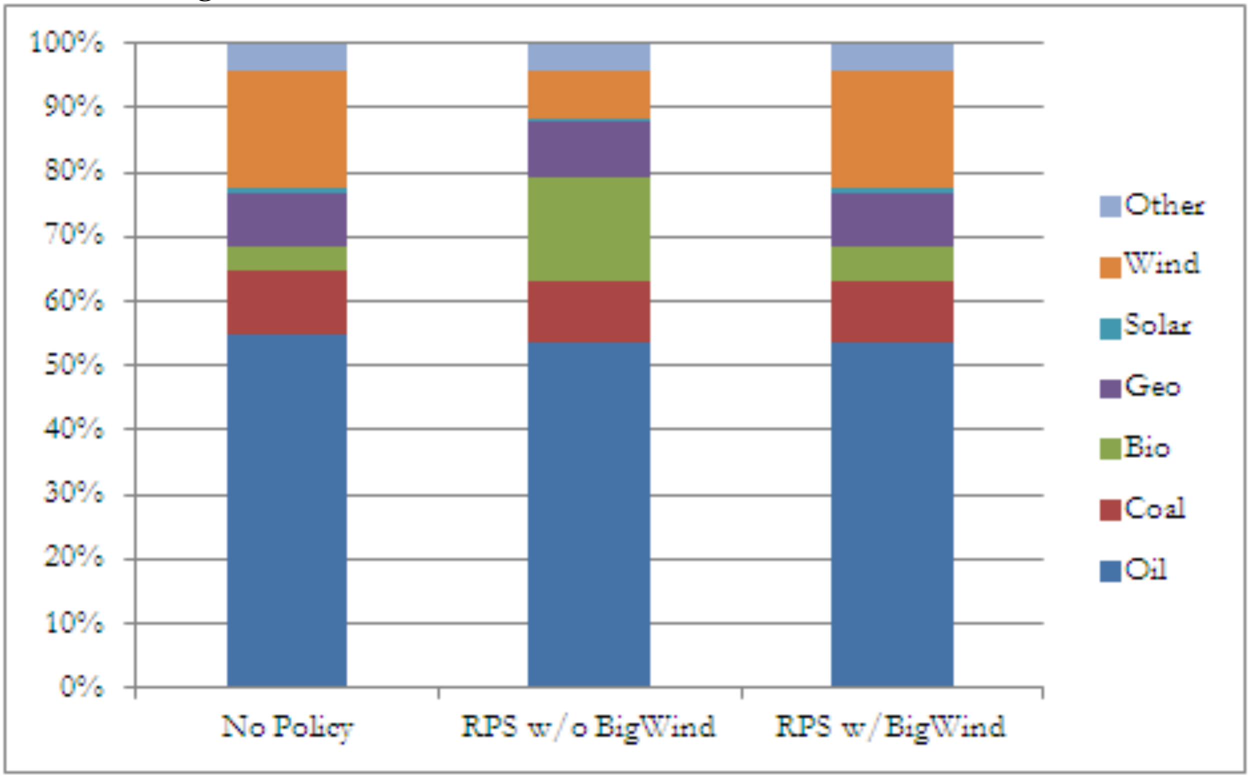
Additionally, because the macroeconomic model, H-CGE, captures economy wide costs and benefits, it is a better tool than HELM, which only accounts for the electricity sector, to assess the cost of GHG abatement to Hawaii's economy. H-CGE shows that the wind project makes tremendous sense from a GHG mitigation standpoint – as GHGs are reduced in a circumstance where net benefits are slightly positive.

4.4 Sensitivity Analysis: Fuel Price Variability

The proposed wind project provides a "hedge" against rising fossil fuel prices. When fuel prices are expected to be *high*, the net macroeconomic benefit of the wind project is $1.4 billion (in comparison to $167 million in the *reference* fuel price case).

Figure 9 shows the mix of electricity generation in the year 2030 for the high fuel price case for the three scenarios (No-Policy, RPS w/o BigWind and RPS w/BigWind).

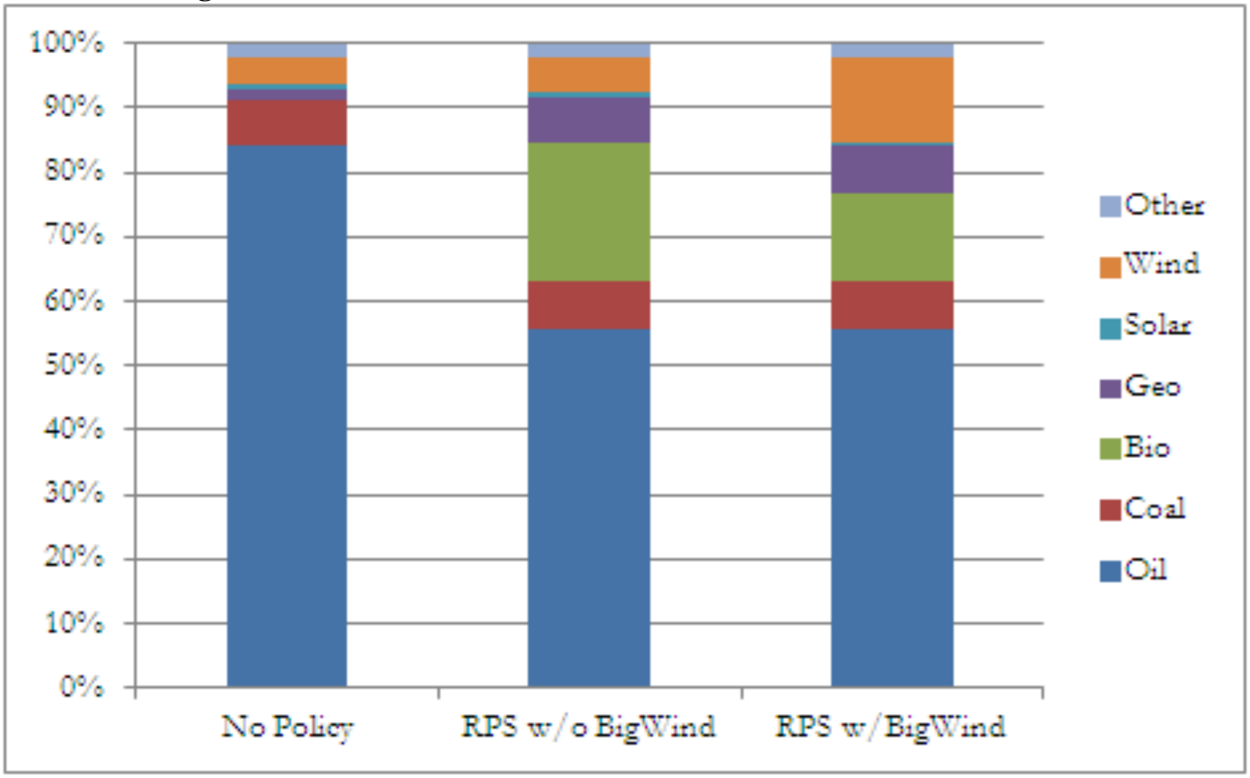
Figure 9. Generation Mix in 2030 under High Fuel Prices: No Policy, RPS w/o BigWind and RPS w/BigWind



The wind project is once again cost effective, even under "no policy." The overall mix looks very similar to the *reference* fuel price case – though there are greater macroeconomic benefits because of the larger terms of trade effect (from avoiding importation of high-priced fossil fuels and biofuels).

Figure 10 shows the mix of electricity generation in the year 2030 for the low fuel price case.

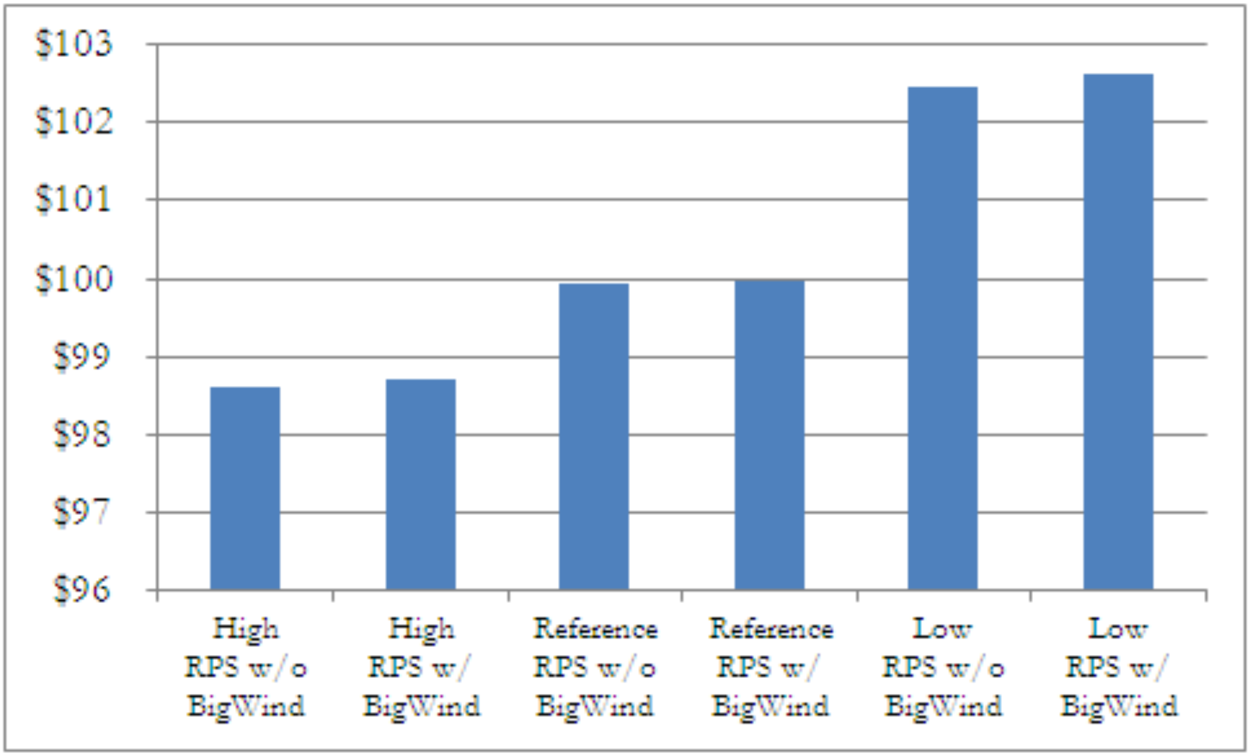
Figure 10. Generation Mix in 2030 under Low Fuel Prices: No Policy, RPS w/o BigWind and RPS w/BigWind



When fossil fuel prices are low, the wind project is not a least-cost means of producing electricity. Nonetheless, in meeting the RPS, the wind project still serves to displace biofuel. The overall penetration of wind energy is also not as high. In this scenario, bio-oil remains an important fuel in meeting the RPS mandate.

Figure 11 summarizes impacts to real gross state product. It shows real gross state product in the RPS scenarios, with and without the 400 MW wind project in the year 2030.

Figure 11. 2030 Real Gross State Product $ Billion, RPS w/o BigWind and RPS w/BigWind



Fuel prices, particularly that of oil, are extremely impactful to Hawaii's economy (see Coffman [52] and Coffman et al. [53] for further discussion). The wind project does serve to moderately offset the economic effects of rising fuel prices.

4.5 Sensitivity Analysis: Wind Project Capital Costs

While the cost-effectiveness of the 400MW wind project is, as expected, sensitive to assumptions about its' capital cost, we find that fuel prices are a much more dominant factor. Table 6 shows the net savings to the electric sector of the "big wind" project in meeting the RPS (i.e. the net present value cost of the RPS w/o BigWind minus the net present value cost of the RPS w/BigWind).

Table 6. Net Savings to the Electric Sector of the "Big Wind" Project in Meeting the RPS

		Fuel Price Forecast		
		Low	*Reference*	*High*
Capital Cost	*$4000/kw*	-$90	$850	$1,530
	$5000/kw	-$530	$470	$1,110
	$6000/kw	-$970	$40	$700

The proposed 400MW wind project is systematically relatively cost-effective under the *reference* and *high* fuel price forecasts, but not the *low* – regardless of capital cost. Moreover, at $6,000/kw (assuming 20% cost overrun from the baseline $5,000/kw assumption), the wind project ceases to be a least-cost means to generate electricity regardless of policy (i.e. the project is no longer selected in the No Policy scenario) under reference fuel prices. It does, however, get built in the No Policy scenario when fuel prices are high. Only at capital expenditures upwards of $8000/kw (i.e. almost twice Navigant and Electranix 2011 estimates) does the wind project cease to be a cost-effective means of attaining the RPS under *reference* fuel price projections.

5. Discussion and Conclusions

This study assesses the electric-sector and economy-wide impacts of a proposed 400 MW wind farm and undersea cable to provide electricity to Oahu, Hawaii. The analysis takes a bottom-up and top-down approach to assess the project through an integrated modeling platform – to better understand overall economic costs and benefits of the project.

In sum, assuming that the wind project operates effectively and as expected from previous studies, we find that the "big wind" project provides net benefit – it is a least-cost means to achieve the RPS under reference fuel prices and has positive impacts to the overall economy (albeit very small).

The juxtaposition between the greenhouse gas emissions reductions benefit and least-cost means to achieve the RPS under all but potentially *low* fuel prices against the small macroeconomic impacts demonstrates the complexity of planning for renewable energy – where any one project is economically negligible in and of itself, though many projects together may have additive effects.

At its core, we find that the 400MW wind project competes with imported biofuel as a least-cost means of meeting the RPS mandate (which offers a critique to the RPS as a policy mechanism to foster development of indigenous or relatively GHG-favorable sources of energy). The proposed 400 MW wind project serves to reduce the amount of biofuel necessary to meet the RPS target. Fundamentally, the wind project serves as a "hedge" against potentially rising and volatile fuel prices. Moreover, even when fossil fuel and biofuel prices are expected to be low, the proposed wind project retains macroeconomic benefits over the expected economic life of the project.

This analysis can be considered as a first step in investigating the full impacts of the proposed 400MW wind project. Since this analysis finds that this project would be economical, the next step would be to incorporate system integration issues. In particular, since wind is a non-firm resource, it requires some back-up generation to handle the fluctuations in the wind's output and sensitivity analysis should be performed to understand the effectiveness of the wind project under different assumptions about the maximum amount of non-firm resources the system can handle at any one instant in time. This analysis assumed a maximum of 20%, but lower levels should additionally be considered at a level of disaggregation for utility system planning.

In addition, the siting of wind turbines is of tremendous concern [54,55]. On Lanai, for example, the planned footprint for a 400 MW project is 22,000 acres, which is nearly a quarter of the island's 90,000 acres. Similar to other communities, Lanai residents are concerned that the wind farms will be noisy, decrease property values, harm birds and other wildlife, as well as spoil the landscape [5].

Lanai residents have voiced concern over disruption to traditional hunting and fishing practices and damage to cultural and archaeological sites [56].

5.1 Limitations of the Analysis and Areas of Uncertainty

5.1.1 Cable and Smart Grid Upgrades

The wind project is characterized by a number of uncertainties, not solely limited to capital cost. There is also uncertainty around the reliability of the cable. Given the difficulty in understanding the probability for malfunction, however, this uncertainty is outside the scope of our analysis.

While the proposed "big wind" project reduces risk in terms of sensitivity to fuel prices, there is certainly a tradeoff in terms of risk reduction from system reliability. While it is outside the scope of this analysis, there is clearly risk in regards to whether the proposed wind project and grid system would perform such that a capacity factor of 42% could actually be achieved. For example, the impacts of the project will be dramatically different if the capacity factor for wind in the sites of interest proves to be substantially different from the documented estimates. Moreover, the HNEI [13] study cited a number of physical and system upgrades that would additionally have to occur to maintain system reliability with 25% renewables (wind/solar) on Oahu's grid.

5.1.2 Biofuels

In addition, the immaturity of bio-oil markets is another point of major uncertainty. We concede that using a bio-oil price forecast based on projected ethanol trends is quite limiting – and we suspect that it biases estimates downward. This is largely why we make the assumption that bio-oil prices cannot drop below that of projected oil prices. It seems likely that the gap between bio-oil and oil prices should be somewhat larger than what is represented in the model, particularly given a change in policies away from bio-based fuels [57]. Nonetheless, we believe the study's findings are robust to this shortcoming because it would solely reinforce the finding that the wind project serves as insurance against rising fuel prices.

Similarly, the way in which biofuels are produced matters. We assume that bio-oil is produced on previously degraded lands and thus provide a 75% improvement over lifecycle GHG estimates for oil. We make this assumption because the local utility has committed itself to working with the Roundtable on Sustainable Biofuels. If biofuels are produced in a less-responsible manner, this would make the proposed wind project yet more cost-effective in terms of a GHG reduction tool.

5.1.3 New Technologies and Data Limitations

The model itself has a number of associated uncertainties. The first is that neither technological improvement nor technologies that are not currently commercially available are represented. This could clearly disadvantage technologies that are experiencing rapid market change, such as solar photovoltaic, and potentially newly commercially available technologies, like Ocean Thermal Energy Conversion. Nonetheless, data limitations prohibit us from including technological innovations – particularly as large assumptions about technologies might confound model results with further uncertainty while failing to provide insight on the question at hand, the current decision about wind energy.

We additionally limit potentially important fossil fuels in Hawaii's electricity generation mix: liquefied natural gas (LNG) and new coal. We believe that a conversion to LNG merits a study in and of itself, while new coal is limited for reasons discussed in the paper. We do believe that the current model well-represents a business-as-usual projection and, moreover, neither of these fuels contribute toward the 40% RPS mandate.

The data limitations on labor make it difficult to estimate labor impacts with tremendous confidence. Within public documents, labor costs are combined with FOM and thus we underwent a process to untwine the two. We made assumptions about average labor costs for each unit, which is clearly a very aggregate way in which to view unit-by-unit labor costs. Nonetheless, it is well-documented that wind energy is not particularly labor intensive (reflected in our estimates) and thus labor is not a large component of this analysis. This would be different for a labor-intensive energy type, like biofuel.

In addition, the models are linked through a partial equilibrium framework. Although the economy-wide impacts are in general equilibrium, there are no "rebound" effects from the economy-wide activity to the electric sector. Making this full general equilibrium link is an area of future work – and requires more detailed data for the electric sector consistent with the Input-Output framework. This modeling technique would give insight into changes in electricity demand as a result of proposed policy and projects.

5.2 In Sum

In this study we build understanding of the economic and GHG emissions impacts of the proposed wind project. The results can help within the planning process to gain better understanding of the overall impacts of "big wind," as it is been dubbed in Hawaii, in contrast to the community-specific challenges, and, ultimately, help inform in what manner this project should move forward.

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Appendix A. H-CGE and Integration with HELM

The Hawaii Computable General Equilibrium Model (H-CGE) is an economy-wide computable general equilibrium (CGE) model of Hawaii's economy. It reflects activity in 68 sectors and 11 agents of final demand including households, visitors, state and local government, as well as federal government. It is integrated with HELM in respect to the electric sector, as described in Bohringer and Rutherford [19].

Production of Non-Energy Sectors

Production in the economy is represented through a nested-Leontief function. At the first level, a Leontief production function represents final output (Y_j) in sector j=1,..n as made up of intermediate inputs (Z_{ij}) of commodity i=1,..n, and energy/value-added (EV_j). Final output of sector j and intermediate input of commodity i include all sectors with the exception of energy (petroleum manufacturing and electricity):

$$Y_j = \min[Z_{1j} / \alpha_{1j}, ...Z_{nj} / \alpha_{nj}, EV_j / \alpha_{vj}] \qquad \text{(A.1)}$$

where α_{ij}, α_{vj} are unit input coefficients for intermediates and energy/value-added respectively. At the second level, intermediate inputs consist of flexible domestically-produced and importable commodities represented through an Armington[7] constant elasticity of substitution (CES) production nest:

$$Z_{ij} = [\theta_{Dij} D_{ij}^{(\varepsilon_{ijm}-1)/\varepsilon_{ijm}} + \theta_{Mj} M_j^{(\varepsilon_{ijm}-1)/\varepsilon_{ijm}}]^{\varepsilon_{ijm}/(\varepsilon_{ijm}-1)} \qquad \text{(A.2)}$$

where ε_{ijm} is the CES substitution between domestically-produced good i and imports by producer j. ε_{ijm} takes the value 1.0. D_{ij} is what producer j demands of sector i for domestically-produced goods and M_j is the composite import good demanded by sector j. The parameter shares are represented by θ_{Dij} and θ_{Mj}, respectively.

For the energy/value-added (EV_j) nest, energy sectors (E_j) are represented as substitutable with value-added (V_j):

$$EV_j = [\alpha_{Ej} E_j^{(\sigma_{EVj}-1)/\sigma_{EVj}} + \alpha_{Vj} V_j^{(\sigma_{EVj}-1)/\sigma_{EVj}}]^{\sigma_{EVj}/(\sigma_{EVj}-1)} \qquad \text{(A.3)}$$

where σ_{EVj} is the CES among energy and value-added variables and α_{Ej}, α_{Vj} are the respective parameter shares. σ_{EVj} takes the value 0.5.

[7] The "Armington assumption" states that goods are differentiated by country of origin and is often used in regional CGE models to account for cross-hauling in trade data and to preclude unrealistic extreme specialization within countries. See Armington (1969).

Value-added consists of capital (K_j) and labor (L_j), where labor is a composite of wage labor and proprietor income:

$$V_j = [\alpha_{Lj} L_j^{(\sigma_{Vj}-1)/\sigma_{Vj}} + \alpha_{Kj} K_j^{(\sigma_{Vj}-1)/\sigma_{Vj}}]^{\sigma_{Vj}/(\sigma_{Vj}-1)} \tag{A.4}$$

where σ_{Vj} is the CES among value-added variables and α_{Lj}, α_{Kj} are the respective parameter shares. σ_{Vj} takes the value 1.0.

Labor (L_j) is a composite between wage labor (W_j) and proprietor income (R_j), which are, represented in a Leontief relationship:

$$L_j = \min[W_j / \alpha_{Wj}, R_j / \alpha_{Rj}] \tag{A.5}$$

where α_{Wj}, α_{Rj} are unit input coefficients for wage labor and proprietor income respectively.

Energy sectors include electricity (EL_j) and petroleum manufacturing (PM_j) such that:

$$E_j = [\alpha_{ELj} EL_j^{(\sigma_{Ej}-1)/\sigma_{Ej}} + \alpha_{PMj} PM_j^{(\sigma_{Ej}-1)/\sigma_{Ej}}]^{\sigma_{Ej}/(\sigma_{Ej}-1)} \tag{A.6}$$

where σ_{Ej} is the CES among energy sector variables and α_{ELj}, α_{PMj}, are the respective parameter shares. σ_{Ej} takes the value 0.2.

The initial endowment of wage labor, proprietor income, and capital ($\overline{W}_0, \overline{R}_0, \overline{K}_0$) are given within the baseline dataset. In calibration, the value of the initial endowment of wage labor, proprietor income and other value-added must equal the sum of each factor over all *j* industries

$$W = \overline{W}_0 = \sum_j W_j \tag{A.7}$$

$$R = \overline{R}_0 = \sum_j R_j \tag{A.8}$$

$$K \equiv \overline{K}_0 = \sum_j K_j \tag{A.9}$$

Output commodity Y_j 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_j) sales and exports (X_j):

$$Y_j = [\beta_{Dj} D_j^{(\varepsilon_j-1)/\varepsilon_j} + \beta_{Xj} X_j^{(\varepsilon_j-1)/\varepsilon_j}]^{\varepsilon_j/(\varepsilon_j-1)} \tag{A.10}$$

where ε_j is the elasticity of transformation and β_{Dj}, β_{Xj} are parameter shares. ε_j equals 5.0.

Production of Petroleum Manufacturing

The production of the petroleum manufacturing sector is assumed to be somewhat more "rigid" than other sectors. Specifically, the production of petroleum manufacturing output (i.e. refined petroleum products) is assumed to be a nested Leontief structure, with the exception of the value-added nest (which takes the form of Cobb-Douglas). This means that there is ability to upgrade capital stocks to alter sector output. Otherwise, without capital upgrades, refinery technology is such that inputs are taken in fixed proportions. In addition, for the purpose of the EIA oil price scenarios, the value of imports into the petroleum manufacturing sector is assumed to be crude oil.

Production of Electricity

The electric sector is defined in detail within HELM. Thus the electric sector within H-CGE acts as a "placeholder" (within the representative agent endowment block) in which results from HELM are used as inputs to produce new equilibrium conditions.

In terms of H-CGE's output being used as input into HELM, H-CGE provides the dynamic projection of baseline electricity demand for the State under the three EIA oil price scenarios. To more accurately represent demand over time, an exogenous electricity efficiency parameter is used to represent gains in both technology and federal programs (which are not endogenous to H-CGE). The parameter is estimated using EIA data on residential energy intensities and economy-wide efficiency parameters (energy per GDP) over time [58]. The figure is taken to be a 0.8% annual efficiency gain.

The production function for electricity represented in H-CGE is distinct from other models. It is modified from Ross [59] in the way that energy and value-added are treated. It did not seem appropriate to assume a substitution between capital and labor (as is common practice) for this sector because the tradeoff is really between existing electricity generation and new electricity generation (i.e. oil and capital).

Household Consumption

Household consumption, at the first level, is represented by a Cobb-Douglas utility function between transportation (*TC*) and other consumption (*OC*):

$$U = [\rho_{TC} TC^{(\sigma-1)/\sigma} + \rho_{OC} OC^{(\sigma-1)/\sigma}]^{\sigma/(\sigma-1)} \tag{A.11}$$

where U is the utility level, TC is consumption of transportation, and OC is the consumption of other goods; ρ_{TC}, ρ_{OC} are the resident income expenditure share on transportation and other consumption, respectively; and σ is the CES parameter, taking a Cobb-Douglas form (value of 1). Within other consumption (*OC*), households consume both energy goods (*EH*) and non-energy goods (*C*):

$$OC = [\theta_{EH} EH^{(\sigma_{OC}-1)/\sigma_{OC}} + \theta_C C^{(\sigma_{OC}-1)/\sigma_{OC}}]^{\sigma_{OC}/(\sigma_{OC}-1)} \qquad \text{(A.12)}$$

where EH is the energy consumption of households, and C is the consumption of other goods; θ_{EH}, θ_C are the parameter shares, respectively; and σ_{OC} is the CES parameter, taking the value of 0.25.

Households consume energy goods in the form of electricity (EL) and gas (GS):

$$EH = [\theta_{EL} EL^{(\sigma_{EH}-1)/\sigma_{EH}} + \theta_{GS} GS^{(\sigma_{EH}-1)/\sigma_{EH}}]^{\sigma_{EH}/(\sigma_{EH}-1)} \qquad \text{(A.13)}$$

where EL is the electricity consumption of households, and GS is the gas consumption of households; θ_{EL}, θ_{GS} are the parameter shares, respectively; and σ_{EH} is the CES parameter, taking the value of 0.1.

Residents flexibly consume both domestically-produced goods (i=1,…,n) and an imported composite good (m):

$$C_i = [\theta_{Di} D_i^{(\varepsilon_M-1)/\varepsilon_M} + \theta_M M^{(\varepsilon_M-1)/\varepsilon_M}]^{\varepsilon_M/(\varepsilon_M-1)} \qquad \text{(A.14)}$$

where ε_M is the Armington CES between domestically-produced good i and imports m, taking the value of 1.0. D_i is resident demand for domestically-produced good i and M is imported demand. The parameter shares are represented by θ_{Di} and θ_M, respectively.

For transportation consumption, households consume purchased transportation (PT) and private transportation (i.e. private vehicles, "cars," represented through the purchase of gasoline) (CR):

$$TC = [\theta_{PT} PT^{(\sigma_{TC}-1)/\sigma_{TC}} + \theta_{CR} CR^{(\sigma_{TC}-1)/\sigma_{TC}}]^{\sigma_{TC}/(\sigma_{TC}-1)} \qquad \text{(A.15)}$$

where PT is the consumption of purchased transportation by households,[8] and CR is the consumption of gasoline (and diesel) for ground transportation; θ_{PT}, θ_{CR} are the parameter shares, respectively; and σ_{TC} is the CES parameter, taking the value of 0.1. This level of detail is provided within the household sector because the oil price scenarios will greatly impact household transportation patterns.

Household Budget Constraint

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

$$\sum_i p_i C_{ri} + p_m C_{rm} = p_w W + p_R R + p_K K + \overline{p}_{fx} BP - T_r \qquad \text{(A.16)}$$

[8] Including air transportation, water transportation, trucking, bus transit, and sightseeing transportation.

where prices p_i represent the market prices for commodities $i = 1,..n$ and p_m is the price of imports. C_{ri} is resident consumption of good i and C_{rm} is the consumption of imported goods. The resident derives income from factors of production including wage labor (W), proprietor income (P), and capital (K), where p_W, p_R, and p_K are the market price of the respective factors. The resident pays a lump-sum tax (T_r), net of transfer payments, to the State and Local Government. The resident also receives foreign exchange ($\overline{p}_{fx}BP$) from a balance of payment deficit, described below.

Visitors

Visitor consumption is represented through a simple Cobb-Douglas utility function:

$$U_v = [\sum_i \rho_{vi} C_{vi}^{(\sigma_{vi}-1)/\sigma_{vi}} + \rho_m C_{vm}]^{\sigma_{vi}/(\sigma_{vi}-1)} \tag{A.17}$$

where U_v is the visitor utility level, C_{vi} is consumption of domestic goods and services, C_{vm} is the consumption of imported goods, and ρ_{vi} and ρ_{vm} are the visitor income expenditure share on commodities $i = 1,..n$ and imports, respectively. σ_{vi} is the CES parameter, taking a Cobb-Douglas form (value of 1).

Because visitors do not provide labor or earn income within Hawaii, a representative visitor's income (I_v) is taken to be exogenous:

$$I_v \equiv I_{v0} = \sum_i p_i C_{vi} + p_m C_{vm} \tag{A.18}$$

where I_{v0} is the initial visitor expenditure.

Government

Government activity is represented through the State and Local Government (SG) and the Federal Government (FG). 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:

$$U_g = \min[G_{g1},..,G_{gn},G_{gm}] \tag{A.19}$$

where $g = SG, FG$.

The State and Local Government depends entirely on the economy for the tax base:

$$\sum_i p_i G_{SLi} + p_m G_{SLm} = \sum_i p_i Y_i \tau_i + T_r \tag{A.20}$$

where p_i and p_m are the price of commodities i=1,..,n and imports, respectively. Thus the left-hand side represents the cost of public expenditures. These expenditures are funded primarily through the State's general excise tax (τ_i) on producer output (Y_i) of commodity i. The State and Local Government also impose a variety of taxes (T_r), such as property and income taxes on residents.

The market clearing conditions must hold such that the cost of public expenditures balances government income.

$$\sum_i p_i G_{gi} + p_m G_{gm} = I_{g0} \equiv I_g \tag{A.21}$$

Balance of Payments

A balance of external payments (BP) is maintained under the assumption of a fixed exchange rate ($\bar{p}_{fx}$), where $\bar{p}_{fx}$ is the exchange rate with the "rest of the world." This assumption is made because Hawaii uses the U.S. dollar as a means of currency and, as a small economy, has no effect on the exchange rate. The quantity of imports (M) is constrained by the inflow of dollars obtained from visitor expenditures (I_v), Federal Government expenditures (I_{FG}), and Hawaii exports (X_j). Because Hawaii is a price taker, import and export prices are exogenous.

$$\bar{p}_{fx} BP = \bar{p}_m M - I_v - I_{FG} - \sum_j \bar{p}_{xj} X_j \tag{A.22}$$

Market Clearing

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_W, p_R, and p_K equal the market price of labor, proprietor income, and capital respectively.

$$p_j Y_j (1 + \tau_j) = \sum_{i=1,..n} p_i Z_{ij} + p_W W_j + p_R R_j + p_m M_j \tag{A.23}$$

In addition, sector j output, which supplies to the domestic market (D_j), is demanded by households and visitors $a \in \{h, v\}$, and government $g \in \{SG, FG\}$, and industries Z_i = 1,..,n.

$$D_j = \sum_a C_{aj} + \sum_g G_{gj} + \sum_i Z_i \tag{A.24}$$

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

Elasticity Values

Table A.1. provides the elasticity values used within H-CGE, provided above, and documented with a source where available.

Table A.1. Model Elasticity Values and Source

Elasticity Between:	**Value**	**Source**
Domestic Consumption & Exports	5	Konan & Kim [60]; Ross [59] uses 3.0
Non-Energy Sector Production		
Energy/Value-Added & Intermediate Inputs	0	Ross [59], standard assumption
Energy & Value-Added	0.5	Ross [59]
Electricity & Oil	0.2	Ross [59] uses 0.5, adjusted downwards
Capital & Income	1	Ross [59], standard assumption
Wage Income & Proprietor Income	0	Assumes fixed relationship between proprietors and labor
Domestic Goods & Imported Goods	1	Armington Assumption, Cobb-Douglas
Petroleum Manufacturing Sector		
Value-Added & Intermediate Inputs	0	Leontief Production, standard assumption
Capital & Income	1	Ross [59], standard assumption
Wage Income & Proprietor Income	0	Assumes fixed relationship between proprietors and labor
Domestic Goods & Imported Goods	0	Armington Assumption, Leontief due to rigid technology
Electricity Sector		
Value-Added & Intermediate Inputs	0	Leontief Production, standard assumption
Domestic Goods & Imported Goods	0.3	Ross [59]
Wage Income & Proprietor Income	0	Assumes fixed relationship between proprietors and labor
Capital & Oil	0.5	Assumed flexibility to allow for investment [a]
Household Consumption		
Transportation & Other Consumption	1	Ross [59]
Energy Goods & Non-Energy Goods	0.25	Ross [59]
Electricity & Gas	0.1	Ross [59] uses 0.4 for general "energy", adjusted down
Purchased & Private Transportation	0.1	Ross [59] uses 0.2, but HI has few public transit options
Other Goods and Services	0.5	Ross [59]
Domestic Goods & Imported Goods	1	Konan & Kim [60]
Visitor Consumption		
Consumption Goods	1	Konan & Kim [60]
Government		
Public Expenditures	0	Konan & Kim [60]

[a] This elasticity is not (known to be) cited within the literature because it represents a new structure presented in H-CGE that is adopted to better capture the tradeoff between current oil-burning electricity generators and investment in new units.

Elasticity values primarily follow the ADAGE model, a global (multi-country, multi-region) energy-CGE model developed by Martin Ross and documented in Ross [59]. In addition, figures are adopted from previous Hawaii-specific CGE modeling platforms, documented in Konan and Kim [60]. Leontief production functions (CES=0) and Cobb-Douglas preferences (CES=1) are generally standard CGE assumptions, as special cases of CES production and utility functions.

Dynamic Calibration

H-CGE is a recursive-dynamic model, based in the year 2007 and projecting in five-year intervals between the year 2010 and 2030. The primary driver of overall economic growth is an exogenous parameter based on Hawaii's historic growth rate, *g*, of 2.2% annually (11.6% growth rate over five years). This is calculated from historic estimates of real Gross State Product, 1977 to 2008 (DBEDT, 2009). Capital accumulation is endogenous within the model, meaning that investment in one period leads to new capital stock in the next:

$$p_K K_{t+1} = (1-\delta)(p_K K_{t-1} + p_K K_t) \tag{A.25}$$
$$p_K K_t = (r+\delta)(p_{INV} INV_{t-1}) \tag{A.26}$$

where δ is the capital depreciation rate and *r* is the rate of return on investment. The rate of return, *r*, is assumed to take the value of 5% annually (27.6% over five years) and δ is calibrated such that it is consistent with the overall growth rate, *g*, and *r*, given initial values of capital and investment provided in the benchmark dataset:

$$INV_0 = {(\delta + g) p_K K_0} \big/ {(\delta + r)} \tag{A.27}$$

where δ is calculated to take the value of 1.0% annually (5.1% over a five-year time period).[9,10] Other drivers of economic growth, such as labor, visitor expenditures, and the balance of payments, are assumed to grow exogenously at the steady-state growth rate *g*:

$$p_W W_{t+1} = (1+g) p_W W_t \tag{A.28}$$
$$p_R R_{t+1} = (1+g) p_R R_t \tag{A.29}$$
$$\overline{p}_{fx} BP_{t+1} = (1+g) \overline{p}_{fx} BP_t \tag{A.30}$$

Model Linking

Figure A.1. highlights the linkage between the H-CGE and HELM models. This section describes the three points in the solution process in which the two models communicate with each other.

In the first instance, the H-CGE model passes the baseline level of electricity demand to the HELM model. The H-CGE model reads in an exogenously specified oil price forecast, and then solves for a baseline solution without any input from the electricity sector and hence with the electricity sector treated like all other industrial sectors in the model. After H-CGE finds an equilibrium solution, it passes the resulting level of electricity demand for Hawaii to the HELM model.

HELM reads in this equilibrium level of electricity demand and uses this time series to define statewide electricity demand. Since HELM solves for generation for the four major islands, Hawaii,

[9] See Paltsev (2004) for documentation. This assumes an investment on a steady-state.

[10] In future iterations of H-CGE, this assumption will be checked for sensitivities to model outcomes.

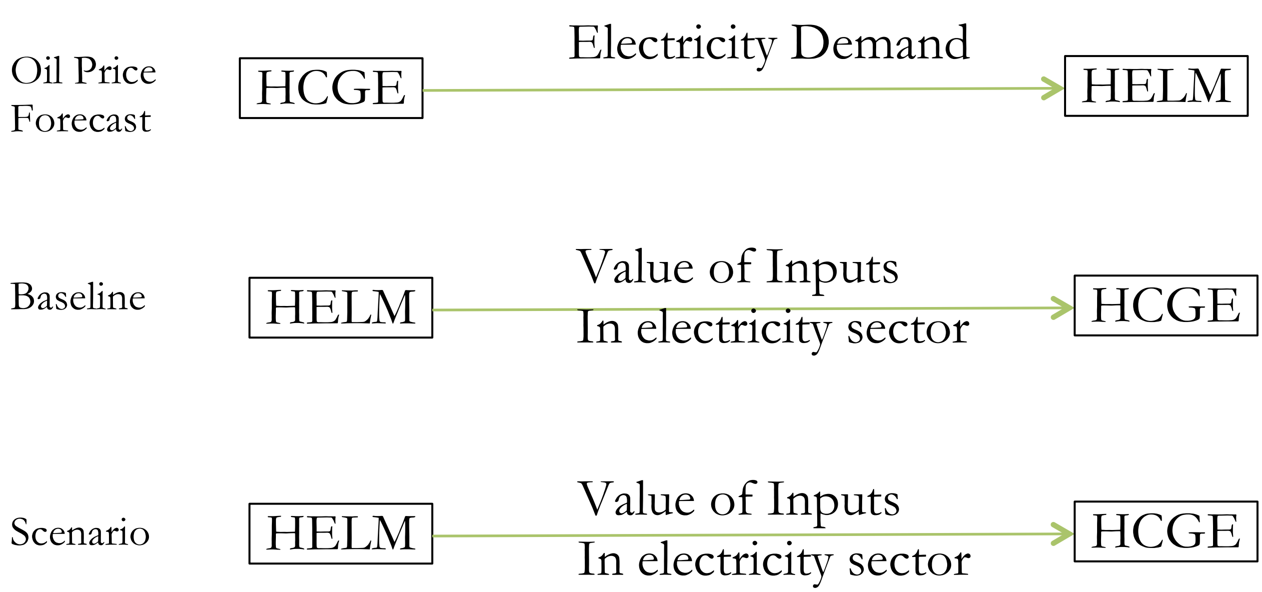
Kauai, Maui, and Oahu, the statewide demand is divided into four demands based on each island's historical share of statewide electricity demand.

HELM then solves for the least cost mix of generation given this level of demand for each island. HELM then passes back to the macro model the statewide quantity of resources used to produce electricity. These include labor, capital, materials, and energy (biofuels, coal, and oil).

H-CGE reads in these results and fixes the level of inputs into the electricity sector at these levels. H-CGE is then resolved for the baseline assuming this level of resources are used in electricity production. In finding the new baseline equilibrium, the model solves for the new prices for all goods and services including those for the electricity sector. This concludes the baseline solve.

Next, the models solve under the described scenarios. First HELM is solved to determine the least-cost generation mix while complying with the RPS policy. In the scenario solve, HELM is solved as a quadratic program. The non-linearity accommodates the linear demand function for electricity and thus electricity demand within HELM is allowed to respond to the RPS policy. The values of the inputs into the electricity sector are summed across the four islands to provide the level of inputs at for the entire state. H-CGE reads in these inputs and solves in similar fashion to how it solves its baseline. Figure A.1 graphically describes this process.

Figure A.1: Linkage between HCGE and HELM



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