THE WELFARE ECONOMICS OF

RENEWABLE ELECTRICITY POLICIES IN CALIFORNIA

A Thesis

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ABSTRACT

With one of the most complicated and ambitious renewable energy policies in the country, California's wholesale electricity market is severely understudied in terms of the interaction effects between different policies. We focus on two key policy measures: production and investment tax benefits received by renewable electricity producers, and the blend mandate, Renewable Portfolio Standard (RPS). The impact of each policy set on market distortions and GHG emissions and their interactions are analyzed. We simulate alternative policy scenarios in the market using a partial equilibrium model, and see how changing each policy affects the equilibrium prices and quantities. Furthermore, using standard welfare measures, we compute the welfare gains and losses of the scenarios and show how different groups are affected by them.

We find that the existence of both policies are mutually detrimental relative to having a sole policy of either a blend mandate or a renewable production subsidy, as the mandate exacerbates the negative effect a subsidy has on the market and the subsidy mitigates the positive effect blend mandate has on reducing GHG emissions. Total social welfare declines with either the observed blend mandate alone or production subsidies alone, but the reductions accelerate when the two policies are combined. We conclude that having RPS by itself is best if our policy goal is to decrease GHG emissions to an efficient level, and that pricing carbon is best if our policy goal is to maximize social welfare in reducing GHG emissions, regardless of the amount.

BIOLOGICAL SKETCH

The author received her B.A. in Mathematical Economic Analysis at Rice University in 2013. She is currently pursuing her MS in Applied Economics and Management at Cornell University with expected degree conferral in August, 2016. She will start her doctoral studies in Public Policy beginning September, 2016 at Harvard University.

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1. Introduction

Federal and state governments have aggressively promoted renewable energy since the 1980s as a solution to a host of economic and environmental problems including rising energy prices, dwindling supply of fossil fuels, energy security, and GHG emissions. With the help of government intervention, U.S. renewable electricity experienced a rapid growth in the past decade and a half: From 2000 to 2015, electricity net generation from renewable energy excluding hydroelectric jumped from 80,905 to 298,358 thousand MWh, where wind jumped from 5,593 to 190,927 thousand MWh and solar from 493 to 26,473 thousand MWh.[1] Globally, U.S. now comes in second in both the annual investment and total generation following China.[2] Table 1.1 shows net renewable electricity generation for all sectors in the United States for years 2010-2015 and in California for years 2002-2014.

Table 1.1 Net Renewable Generation in USA and in CA

	National (Thousand MWh)		California (GWh)	
Technology/Year	2000	2015	2002	2014
Wind	5,593	190,927	3,546	23,913
Solar	493	26,473	863	12,566
Biomass	60,726	64,191	7,140	7,507
Total	80,905	298,358	29,879	59,803

Enabling such fast growth were unprecedented financial support for the industry. The U.S wind production currently receives a $23/MWh production tax credit (PTC), solar production a 30% investment tax credit (ITC), and on top of that, both benefit from accelerated tax depreciation. Electricity related federal subsidies and

[1]EIA, 2015 http://www.eia.gov/totalenergy/data/monthly/pdf/sec7_5.pdf
[2]Renewable Energy Policy Network for the 21st Century, 2014 http://www.ren21.net/Portals/0/documents/Resources/GSR/2014/GSR2014_full%20report_low%20res.pdf

support totaled $16.1 billion dollars in fiscal year 2013, a 38% increase from $11.7 billion dollars in 2010. Renewable electricity received 72% of such support. Amongst all renewables, wind electricity received the largest share of direct federal subsidies of $5.9 billion, accounting for 37% of total electricity related subsidies in 2013, and a 5% increase compared to a $5.1 billion subsidy in 2010. Solar power received $4.4 billion in 2013, a 27% of the total electric power related subsidies, and a 5 fold increase from 2010 (EIA, 2015).[3] These two sources both benefited from substantial increases in federal subsidies, especially compared to other renewable sources such as biomass, which experienced a 40% decrease in subsidies from $1,030 million to $629 million during the same time period. The different levels of subsidy depending on energy sources are due to difference in per unit subsidy offered by the federal government, the amount of net electricity generated by different plant types, and the size of investment/property of each projects. The reason for different per unit subsidies are largely political which is beyond the scope of this paper.

In addition to federal tax benefits, states have increasingly adopted regulatory policies and public financing mechanisms. Most commonly used one is a blend mandate, also known as renewable portfolio standard (RPS), which requires energy suppliers to source a certain minimum quantity from renewable energy sources. Because mandate seems to not influence taxpayers, it is commonly assumed that consumers (ratepayers) face higher overall electricity prices, which is calculated as a weighted average of the market prices for renewable and non-renewable electricity. Though with an assumption of competitive market, renewable electricity should have the same market price, we see that this isn't the case in real life. This can be explained

[3] EIA, 2015 http://www.eia.gov/analysis/requests/subsidy/

by several factors including the imperfect competition of the California renewable electricity market, different time/location value of the resources, and the lack of price competition among the load serving entities, because the consumers are limited in their choice of utilities given the physical boundaries of electric service areas.

Another reason for the fast growth of the renewable energy is the decreasing cost. Since renewable electricity has no fuel costs, most of this cost reductions came from technological advances, which decreased installation costs of solar panels or wind turbines. Hardware costs, which include the cost of modules, inverters, and racking, etc., comprise about 65% of the total cost associated with solar power, and have fallen more than 50% since 2009 to today. Median project costs dropped to $3.1/W in 2014, compared to $6.3/W in 2009.[4] As for wind, the turbine costs and installation costs, which is about 57% of the total cost, have fallen 20%-40% from 2008. Wind projects built in 2014 had an average installed cost of 1,710/kW, compared to projects in 2009 and 2010 which costed around 2,300/kW.[5]

Despite the fiscal incentives far larger than that enjoyed by conventional electric generation technologies such as coal, natural gas, or nuclear fuels, and despite consistently decreasing costs, renewable electricity — particularly wind and solar — remain to have high costs compared to conventional fuels. Even worse, factors specifically relate to renewable electricity, such as low capacity factor, decreasing number of prime sites, transmission costs, and intermittency costs, are often left out in the cost studies. As a result, these sources remain at relatively small market shares. U.S. renewable electricity generation after excluding hydroelectric accounted for 6% of total

[4] https://emp.lbl.gov/sites/all/files/lbnl-1000917_0.pdf
[5] http://energy.gov/sites/prod/files/2015/08/f25/2014-Wind-Technologies-Market-Report-8.7.pdf

generation in 2013 where wind accounted for 4.7%, and solar accounted for 0.4%.[6] This means that 6% of all generation received 72% of federal financial support for the total electric power sector. Wind power, which generated 4.7% of total electricity consumption, received 37% of such support. Solar power, a 0.4% of total generation, received 27% of the support. This combination of substantial policy support and weak market competitiveness is an inefficient usage of federal fund which results in unnecessary higher cost for electricity consumers and tax payers alike.

Although much economic analysis has already shown the costly nature of renewable electricity policies, the true cost of renewable electricity is severely understated and the contradictory interaction effects between the federal level subsidies and the state level mandates are not well understood. Much of this is attributable to diverse and ever-changing policies and difficulty in calculating the costs associated with renewable electricity generation. Since 2000, Congress has extended wind PTC six times and allowed it to expire six times. On the state-level, each state has different standards of varying degrees all with different pricing mechanisms. Levelized cost of energy (LCOE) estimates (defined in detail later), often used to gauge the competitiveness of various energy sources, normally ignores additional costs associated with renewable energy such as intermittency cost and back up cost. Renewable sources also require substantial transmission grid changes because the best wind and solar locations are often remote, and special technology is required to deal with fluctuations in solar and wind supply. This intermittency makes wind and solar power far less valuable than levelized cost estimates indicate, since backup power is needed to compensate for lapses in supply, and wind often produces during less valuable, off-

[6] EIA has US total electricity generation data for 2015, but its latest data for energy subsidy is for year 2013.

peak hours. Such costs are not included in renewable electricity price, and therefore represents an additional transfer from electricity consumers to renewable energy producers. Previous studies suggest transmission costs add at least $15/MWh for wind power, and backup generation adds another $44.50/MWh. Combined with a $54/MWh tax benefit, wind power in California costs nearly 2.5 times the EIA's levelized cost projection for natural gas in 2020.

California, with the most complicated renewable electricity market and the most rigorous standard for RPS, can serve as an empirical example to draw implications about the hidden costs behind the renewable energy market, and the interaction of different policies that impact the market. In 2014, California Energy Commission (CEC) reported that subsidies for wind electricity in the state was $54/MWh, 1.4 times the natural-gas peak electricity price, and 2.3 times the subsidy for U.S. wind-electricity production reported by the EIA (2015). Despite such high subsidies, the price premium that renewable electricity producers receive from the RPS is as high as $49.21. Renewable's market price is actually 2.2 times the peak market price of natural gas electricity in California. Although in theory consumer electricity prices could decline with an RPS (and even more so with production subsidies) California's residential electricity prices however are 40% higher than the national average and eighth highest in the country.[7]

Tables 1.2 and 1.3 illustrate this point with the prices and costs of peak electricity and renewable energy. Compared to natural gas powered peak electricity price, renewable electricity price is on average 3.6 times higher including the tax benefits it receives. Given such high costs and prices, it would be crucial for us to

[7] There are other reasons why California's consumer electricity prices are higher, such as no coal usage in their generation portfolio

examine the policies involving the renewable electricity and how they affect entities in the market.

The purpose of this paper is to 1) discuss the key issues existent in the California electricity market including the incidence of RPS and federal subsides, and the interaction effects of the two policies, 2) qualitatively discuss other issues in the market including issues affecting the costs of renewable electricity and the value and purpose of RECs in the market, and 3) to provide a welfare analysis of the different policy scenarios.

Though empirical studies of interaction effects between tax credit and mandate as environmental policies are scarce in number, de Gorter and Just (2009, 2010) have done extensive work in biofuel policies and found that the interaction effects between the two policy measures creates reversal of the intended policy effects, by supporting more gasoline consumption and generating unnecessary deadweight loss to the society. Our paper adapts the model by de Gorter and Just (2009) and construct a computational partial equilibrium model to provide quantitative estimates of welfare benefits and costs resulting from the interaction of subsidies and mandates in wholesale renewable electricity market in California. Our model specification allows endogenous determination of equilibrium prices and quantities and is calibrated to represent a recent benchmark dataset for the year 2013. By assuming different policy scenario sets, we see how the changes in these policies affect the equilibrium prices and quantities of different resources, and using standard welfare measures, also show the net welfare implications of the policies and how they affect different groups in the market. Based on the result, we discuss the interaction effect of our two policy measures, renewable portfolio standard (a binding blend mandate) and renewable production subsidies, and recommend policies based on the policy goals.

Table 1.2 Renewable Price and Costs in US and in CA ($/MWh)

	NG	Wind	Solar	Biomass
Market Price				
CA	40	85	143	95
National	35-65[8]	25[9]	40-125[10]	-
LCOE without TB				
CA[11]	117	139	238	176
National (Lazard)[12]	165-218	32-77	70-193	83-125
National (EIA)[13]	70-86	66-82	98-193	90-117

Note: Market price data is from CPUC, California levelized cost data is from CEC, for plants entering service in 2013 and are in 2013$/MWh

Table 1.3 Renewable Price Premium over Natural Gas in California

	NG	Wind	Solar	Bio-mass	Other	Over-all
Market Price ($/MWh)	40	85	143	95	82	91
Subsidy ($/MWh)	-	54	129	54	62	73
Price as a % of NG price	-	213	358	238	205	228
Subsidy as a % of NG price	-	135	323	135	153	163
Price and subsidy as a % of NG price	-	348	680	373	358	390

Note: For other renewable and overall renewable, weighted average value of the sources is used.

The thesis is structured as follows: In Chapter 2 we discuss in detail the two policy parameters of our model, Renewable Portfolio Standard on the state level, and the federal subsidies on the federal level. Chapter 3 provides data for quantity and price of California renewable electricity as well as the levelized cost of renewable electricity.

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8 http://www.power-eng.com/articles/2013/07/wholesale-electricity-prices-increase-across-the-lower-48-states.html

9 http://energy.gov/sites/prod/files/2014/08/f18/2013%20Wind%20Technologies%20Market%20Report_1.pdf

10 https://emp.lbl.gov/sites/all/files/lbnl-1000917.pdf and http://www.greentechmedia.com/articles/read/utility-scale-solar-is-back-from-the-dead

11 http://www.energy.ca.gov/2014publications/CEC-200-2014-003/CEC-200-2014-003-SF.pdf

12 https://www.lazard.com/media/2390/lazards-levelized-cost-of-energy-analysis-90.pdf

13 https://www.eia.gov/forecasts/aeo/electricity_generation.cfm

Trend for wind and solar prices and costs are also provided in this section. Chapter 4 discusses the hidden costs that are often left out, or underestimated in calculating levelized costs, such as transmission costs and intermittency costs. In Chapter 5, model assumptions and conditions are described, endogenous and exogenous variables are introduced, and equilibrium conditions are provided. Chapter 6 explains concepts such as social cost of carbon, environmental cost to the society, and carbon leakage and show how those are incorporated into the model. In Chapter 7, I analyze the sole effect of RPS on the California electricity market and social welfare, the sole effect of federal subsidies, and the interaction effects of RPS and the federal subsidies. How the interaction effect of the two polices affect carbon leakage is also analyzed. Lastly, I also discuss how pricing carbon affects the market and welfare. Chapter 8 provides summary of the findings and conclusion.

2. Policies affecting the Renewable Electricity Market

Although we are yet to find a consensus on the most appropriate form of government support for renewable energy, it is nevertheless generally accepted that government intervention is needed to some degree, because of the presence of negative externalities in the market. In the power sector, this exists in the form of GHG emissions, resulting from the production and consumption of conventional fuel-heavy power mix. The society as a whole bears the cost of pollution, and as a result, too much of energy is consumed, resulting in an economically inefficient market.

In our model, we consider two policy measures for addressing this market failure in the power market. The first one is a blend mandate at the state level, namely Renewable Portfolio Standard, and the second one is tax benefits for renewable energy provided by the federal government. Several studies have already suggested that the subsidies are not the most efficient way to achieve the policy objective, as subsidies encourage energy consumption by reducing the cost of energy as well as reduce tax revenues. A more economically efficient way of achieving environmental goals in the power market would be a direct tax on emissions. Fell et al (2012) argue that the renewable tax credits are not cost effective environmental policies compared to others such as RPS or carbon tax, and Metcalf (2008) also found that the tax expenditures are particularly expensive policy instrument for reducing emissions, and a better policy would be a carbon tax or cap and trade system.[14] We see whether this holds true in the case of California renewable electricity market, and also discuss the interaction effect of the tax subsidies and the RPS. We also analyze the effect of having a carbon tax instead, and compare its impact relative to the status quo policies in effect now.

2.1 State Policy: Renewable Portfolio Standard

Currently, 29 states, Washington, D.C., and two territories have adopted a RPS, and eight other U.S. states and two territories have set renewable energy goals. Amongst all the varying level of mandates each state has employed, the one required for California electricity providers is one of the most rigorous and ambitious standards in the country. Established in 2002 under Senate Bill 1078, accelerated in 2006 under Senate Bill 107 and expanded in 2011 under Senate Bill 2, California's RPS program requires the retail sellers of electricity, which include investor-owned utilities (IOUs), electric service providers, and community choice aggregators, to increase procurement from eligible renewable energy resources to 33% of total procurement by 2020. On

September 2015, the RPS requirement was yet again expanded to a 50% standard by 2030, when Governor Brown signed the clean energy legislation SB350.

While California Public Utilities Commission (CPUC) implements and administers RPS compliance rules and tracks the aforementioned retail sellers (IOUs, ESPs, CCAs), California Energy Commission (CEC) certifies generation facilities as eligible sources and adopt regulations for the enforcement of RPS procurement requirements of Publicly Owned Utilities (POUs). According to CPUC, California's three large IOUs, have collectively served 22.7% of their 2013 retail electricity sales with renewable sources.

How do the LSEs then, procure the renewable energy supply to meet the RPS mandates? California's renewable market is an extremely complex one with different regulations and pricing mechanisms depending on different power sources, capacities, entities involved, contract terms, etc. But to put it simply, there are mainly five procurement mechanisms.

Competitive procurement (through competitive solicitations) is the most common way that LSEs select renewable generation for RPS compliance in California, as it encourages competition between project developers, and help secure renewable electricity supply at the lowest cost.[15] In a competitive solicitation, the procurement agent (usually the LSE) issues a request for proposal (RFP), collects and evaluates qualifying bids, and executes contracts with winning bidders. Both price and non-price criteria are considered.

Bilateral contract negotiation is also an option for LSEs in order to secure long-term contracts for renewable electricity sources. Such long term contracts signed

[15] http://www.nrel.gov/docs/fy12osti/52983.pdf

between an LSE and project developers usually include energy payments, capacity payments, and REC payments and possibly a fixed-price escalator. This form of contract is rarely seen in California, but do exist.

Other than competitive solicitations and bilateral contract negotiations, there are feed-in-tariff (FIT) policies and auction. A FIT is a procurement mechanism that offers guaranteed grid access and guaranteed energy payment over a long-term contract to all developers within a set of eligible technologies, project sizes, and locations. In California, powers smaller than 3MW are subject to FIT. The utilities are required to offer open and standardized contracts for the electricity the renewable energy producers generate for a predetermined period of time. Renewable market adjusting tariff (ReMAT) mechanism is used to determine the payment rate for FIT contracts. CPUC has acknowledged three project categories eligible for FIT: Baseload (bioenergy and geothermal), As-Available Peaking (Solar), and As-Available Non-Peaking (Wind) and they all have different prices.

Powers between 3MW and 20MW in California bid into the Renewable Auction Mechanism (RAM). RAM is a procurement mechanism for renewable distributed generation (DG) projects on the system side of the meter. Developers with a project in the utility's service territories compete for a contract in RAM. The utility selects the bids by least-cost price first until the auction capacity is reached. The way auctions differ from competitive solicitation (though both are bidding process) is that auctions select bids based on price alone and the solicitations include a number of non-price criteria. As such, the auctions are expected to promote competition, elicit the lowest costs for ratepayers, encourage the development of resources that can utilize existing transmission and distribution infrastructure, and contribute to RPS goals.

Finally, the big three IOUs can generate RPS eligible renewable electricity through Utility Solar Rooftop (SPVP) program. The Energy Commission authorized SCE, PG&E, and SDG&E to own and operate solar PV facilities (Utility Owned Generation) as well as to execute solar PV power purchase agreements with IPPs through a competitive solicitation process. The eligible project sizes vary by the utilities, but in 2010, their goal was to collectively generate 1,100MW from the SPVP program in five years

2.2.1 Renewable Energy Certificate (REC)

The LSE's compliance of RPS mandates is tracked with tradable renewable energy certificates (RECs), which are defined as: "a certificate of proof, issued through the accounting system established by the Energy Commission… that one unit of electricity was generated and delivered by an eligible renewable energy resource." When one MWh of renewable electricity is generated from an RPS eligible facility, corresponding REC is created, from which these RECs (including RECs associated with energy imports/exports) can be counted towards a utility's RPS compliance obligations. The RECs can be sold either "bundled" with the underlying energy (included with the sale) or "unbundled", as a separate commodity from the energy itself. There are two different markets for RECs. RECs can be sold as a compliance REC, either bundled or unbundled, to the LSEs for their compliance with state RPS, or can be sold in a voluntary market, almost always unbundled, to a progressive organization or a business to offset their energy consumption and emissions.

The value of these RECs are determined by its ability to financially incentivize new generation of renewable energy source that otherwise would be too costly for developers (Pinkel and Weinrub).[16] In other words, the RECs are only valuable only when they represent additional electricity generated from renewable sources made possible from the sales from RECs, because a mere exchange in the ownership of the RECs does not have any societal or environmental impact. But the reality is, the price of RECs are too low and volatile, and the purchase too short-termed to incentivize new renewable energy development in California. While donning a false appearance of replacing fossil-fuel electricity with renewable electricity, RECs are simply making the renewable electricity producers more profitable without actually contributing to new renewable generation.

In theory, the price of a REC should reflect the difference between the market price of the associated renewable electricity and the market price of natural gas fired (peak) electricity. In real world, the price of REC depends on the market conditions including the regulatory policy, type of renewable facility, supply and demand in the market, etc. For bundled RECs, whose sales are included with the electricity sold, the price of REC is thus taken to be the difference between the wholesale price of the associated renewable electricity and non-renewable electricity. For unbundled RECs, the price is determined by the market factors mentioned above.

2.2 Federal Level: Financial Incentive

Though on the state level, California only offers regulatory policies to motivate renewable production, the federal government offers several financial incentives. The primary federal financial incentives to encourage wind and solar deployment are production tax credit, investment tax credit, and accelerated depreciation shown in Table 2.2.1.

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[16] http://www.localcleanenergy.org/files/What%20the%20Heck%20is%20a%20REC.pdf

The accelerated tax depreciation provides a preferential incentive for wind and solar projects because of the time value of money. For example, although wind and solar power projects are designed to operate for twenty years or longer, the vast majority (as much as 95%) of investments can be depreciated for tax purposes over an accelerated five to six-year period, using the 5-year Modified Accelerated Cost-Recovery System (MACRS) schedule. In recent years, projects that were placed in service in certain time frame have also been eligible for an even more attractive depreciation schedule based on either 50% or 100% "bonus" depreciation. Wind and solar projects also have the option to elect a 12-year straight-line depreciation schedule in lieu of 5-year MACRS.

Table 2.2.1—Federal Renewable Energy Tax Incentives

Technology	Wind	Solar	Biomass Open Loop
Investment Tax Credit			
Credit	30%	30%/10%	30%
Depreciable Value Reduced		15%/5%	
Present Expiration	2014	2017	2014
Assumed Expiration	2030	2030	2030
Loss Carry Forward Period (Years)		20	
Eligibility	Merchant/IOU	Merchant/IOU	Merchant/IOU
Production Tax Credit			
Credit (2008$)/MWh	$21		$10
Credit (1993$)/MWh	$15		$7.5
Duration (Years)	10		10
Expiration	2014		2014
Eligibility	Merchant		Merchant
Accelerated Depreciation			
Normal Depreciation	30	20	20
Accelerated Depreciation	5	5	5
Eligibility	Merchant/IOU	Merchant/IOU	Merchant/IOU

Source: California Public Utilities Commission

The Production Tax Credit (PTC) is a per kWh credit for electricity generated using qualified energy resources, which can be claimed for a ten-year period once a qualifying facility is in service. It was first enacted by the Energy Policy Act of 1992 and provided a production incentive of $15/MWh for qualifying projects since 1994. The maximum credit rate is adjusted annually for inflation; In years 2013, 2014, and 2015, the PTC stood at $23/MWh for wind, closed-loop biomass, and geothermal technologies and at a reduced amount of $12/MWh for open-loop biomass, municipal solid waste, and qualified hydropower. Despite the multiple expiration and renewal of the policy that threatened investment and deployment decisions and introduced the boom and bust cycle of added wind capacity, PTC has provided substantial assistance to the U.S. wind industry. PTC enables wind power producers to reduce the price at which the electricity can be sold, effectively making them less costly for power purchasers and ultimately end-use consumers. Wiser and Bolinger (2013) have estimated that the PTC reduces contract prices for wind power by approximately $20/MWh on a 20-yer levelized basis. In fact, with the PTC, wind power is now economically competitive with conventional sources in some parts of the country (mostly interior regions) On the other hand, PTC imposes a cost to U.S. taxpayers in the form of forgone federal tax revenue. The Joint Committee on Taxation (JCT) estimated that in 2014, the tax expenditures for PTC were $1.2 billion. Between years 2014 and 2018, JCT estimates PTC related revenue losses to be $16.6 billion where $13.8 billion are due to wind energy.[17]

The business energy investment tax credit, ITC, has been available to solar projects for many years. Originally a 10% credit, it was increased to a 30% credit in 2006. It will step down to 26% in 2020 and 22 in 2021, and revert back to a permanent 10% after 2012. The ITC is based on the amount of investment in solar property, and helps the tax liability of residential, commercial, and utility investors in solar property. Although ITC has historically been considered solar's tax credit, utility-scale wind projects that were under construction by the end of 2013 is also eligible, in lieu of the PTC. Unlike PTC, which is based on the production of electricity, the ITC is based on investment in a project. The investment or "basis" to which the 30% credit applies is equivalent to the amount that qualifies for depreciation and generally comes to a 95% or more of a project's total installed cost. The ITC is realized in the year in which the project begins commercial operations, but vests linearly over a 5-year period.

[17] http://nationalaglawcenter.org/wp-content/uploads/assets/crs/R43453.pdf

3. Data Description

3.1 Quantity of Renewable Electricity

Every year California Energy Commission publishes California total system power mix, defined as the annual total energy requirement for all load serving entities with end-use loads in the state. Table 3.1.1 shows California in-state generation and its power mix for years 2010–2014. Power mix is calculated by adding net imports to in-state generation, where net imports is total imports minus total exports. The share of renewables in the entire power mix has been growing steadily in California for the past years. From 13.9% in 2010, it has grown to 20.15% by 2014. In 2014, power mix for wind was 23,913 GWh, and solar was 12,566 GWh. Solar PV experienced significant growth in 2014. More than 2,000 MW commercial-scale capacity and 45 utility scale capacity were added over the year. By the end of 2014, in-state solar capacity was 5,939 MW and annual in-state energy totals for solar more than doubled to 10,557 GWh from 4,291 GWh in 2013. This is not including the increasingly widespread residential and business level PV systems with less than one MW each. But the installations of such “behind the meter” distributed generation technologies are growing at a fast pace and as they grow to be a more significant portion of the state’s generation mix, may impact the total system power.

Table 3.1.1 California Total Electricity Power (GWh)

In-State Generation	2010	2011	2012	2013	2014
Wind	6,172	7,598	9,152	12,694	12,997
Solar	908	1,097	1,834	4,291	10,557
Biomass	5,798	5,807	6,031	6,423	6,721
Other	23,530	24,641	23,021	22,251	21,333
Total Renewables*	30,610	33,336	34,007	39,236	44,887
Total	205,350	200,987	199,101	199,783	198,973
Renewables Percent	14.91	16.59	17.08	19.64	22.56
Power Mix					
Wind	13,536	14,575	19,135	25,356	23,913
Solar	959	1,234	2,609	5,389	12,566
Biomass	6,947	6,226	7,079	9,929	7,507
Other	25,906	25,639	24,771	24,934	23,324
Total Renewables*	40,401	41,448	46,515	55,679	59,803
Total	290,518	293,652	301,966	296,628	296,843
Renewables Percent	13.91	14.11	15.40	18.77	20.15

Source: California Energy Commission
Note: Other renewables include biomass, geothermal, and small hydro. Power mix is sum of in-state generation and net imports.

3.2 Price of Renewable Electricity

The price of renewable electricity in our model is the price received by the producers (generators) and has two components: the price paid by the load serving entities to the producers, and the tax benefit the federal government pays to the producers. And it is the latter that enables the price for renewable to be competitive enough to exist in the market. Since we covered the tax benefits in 2.2, we focus on the price the LSEs pay to the producers in this section. The price paid by the LSEs to the generators are normally measured by the long-term power purchase agreement (PPA) price, a contract price between two parties, usually an electricity generator and power purchaser (typically a utility), and is the financing deal of choice for wind and solar. PPA prices for wind and solar on the national level have decreased continuously past few years. The national average levelized price of wind PPAs that were signed in 2013 was approximately \$25/MWh including the PTC, and for 2014 was \$23.5/MWh, a big drop from $70/MWh in 2009 (DOE, 2015). For solar PPAs signed in 2014, prices ranged between $50-$70/MWh (SEIA, 2015), showing a 60% decrease from 2008. The lowest PPA prices for wind are found in the interior region of the States, with the best wind resource in the nation, and for solar they are found in California and Southwest. Figure 3.2.1 shows the trend in average levelized PPA prices for utility scale wind nationwide, and Figure 3.2.2 shows the trend in the utility solar PV PPA prices nationwide.

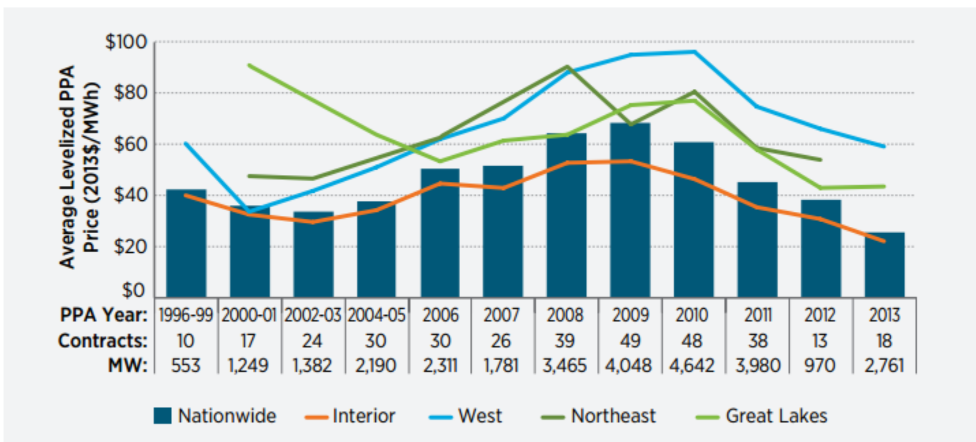

Figure 3.2.1 The Trend of US. Average Utility Wind PPA Prices
Source: Lawrence Berkeley National Laboratory[18]

[18] http://energy.gov/sites/prod/files/2015/08/f25/2014-Wind-Technologies-Market-Report-8.7.pdf

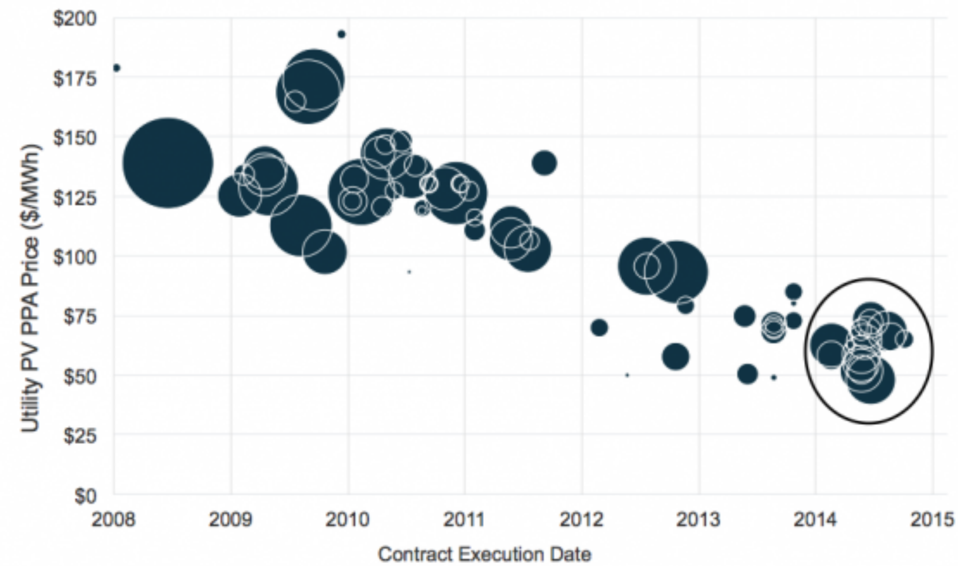

Figure 3.2.2 The Trend of U.S. Average Utility Solar PV PPA Prices

Source: Lawrence Berkeley National Laboratory[19]

The price data for renewable electricity and wholesale electricity for years 2010–2015 in California is shown below in Table 3.2.1. For price data in California, we use the RPS procurement expenditure data of the big three IOUs, PG&E, SCE, and SDG&E, reported by CPUC in their annual Padilla Report. The weighted average TOD-adjusted RPS procurement expenditure is for all PRS eligible projects, including contracts for the procurement of renewable energy credits, REC-only. The key factor that drives the costs of the utilities is the resource mix of RPS-eligible resources within an IOU's portfolio and the vintage of the IOU's RPS contracts. Again, the RPS procurement expenditure reflects the receipt of federal and state incentives on the generation side, and would be higher if not for the incentives. Wholesale electricity also

[19] https://emp.lbl.gov/sites/all/files/lbnl-1000917_0.pdf

is reduced by any financial incentives provided to fossil-fueled generation and does not fully reflect the costs involved.

Table 3.2.1 Wholesale Electricity Prices in California ($/MWh)

	2010	2011	2012	2013	2014	2015
Wholesale electricity	39.49	38.39	37.59	39.99	52.32	34.18
Retail Electricity	130.1	130.5	135.3	143.0	151.5	155.0
Wind (on-shore)	69	72.3	79.5	85.1	88.7	86.5
Solar PV	145.5	151.5	172.8	142.8	135.8	135.5
Biomass	87.2	81.4	88.6	95.1	92.6	89.7
Overall Renewable	71.7	69.7	78.3	90.6	99.6	100.0

Source: Energy Information Administration, California Public Utilities Commission[20]

3.3 Cost of Renewable Electricity

Levelized cost of energy (LCOE) is the most popular method used to compare the competitiveness of different energy sources. Energy Information Administration (EIA) defines LCOE as “a convenient summary measure of the overall competiveness of a generating technology,” which is represented by a constant cost per unit of generation over an assumed financial life and duty cycle. Though what constitutes LCOE differ by studies, EIA’s calculation of LCOE takes into account the capacity factor, capital cost, fixed and variable operations and maintenance cost (including the fuel cost), and transmission investment for each plant type. For wind and solar, LCOE depends mainly on the estimated capital cost of generation capacity, and less on the fuel costs and variable O&M costs, while for conventional technologies, fuel cost is a significant component. The EIA reported the U.S. average levelized cost of natural gas to be $75.2/MWh, for wind $73.6/MWh and for solar PV $125.3/MWh in year 2013.

[20] http://www.cpuc.ca.gov/uploadedFiles/CPUC_Website/Content/Utilities_and_Industries/Energy/Reports_and_White_Papers/FINALPadillaReport2015PUBLICFINAL.pdf

Table 3.3.1 shows the mid-case levelized costs for natural gas-fired, wind, and solar technologies by developer (merchant owners, IOUs, and POUs) in California. The costs are provided in nominal 2013 dollars per MWh, and are for generation units that began operation in 2013. The costs vary depending on the ownership of the project as well as on the location of the plants. The IOU plants generally have the highest LCOEs, and merchant plants have the lowest due to differences in eligibility for tax incentives. Taking the average of all merchant, IOU, and POU owned plants, the levelized cost of natural gas is $107.79, of wind $88.56/MWh, and solar $130.26. All three are higher than national average.

Table 3.3.1 Estimated Levelized Cost of Energy by Plant types ($/MWh)

Technology	Merchant	IOU	POU
Combined Cycle 500MW	116.51	104.54	102.32
Solar PV Single Axis 100MW	109	165.22	116.57
Wind - 100MW	85.12	104.74	75.8
Biomass Fluidized Bed Boiler 50MW	122.04	141.53	123.51

Source: California Energy Commission[21]

Table 3.3.2 shows the components of the levelized cost reported by CEC. As merchant owned facilities are the dominant ownership in the market, we focus on the LCOE borne by the merchant owned facilities. Table 3.3.3 shows mid-case levelized cost of different technologies by merchant facilities, and their components.

[21] http://www.energy.ca.gov/2014publications/CEC-200-2014-003/CEC-200-2014-003-SF.pdf

Table 3.3.2 Components of the Levelized Cost

Types of Costs	Explanation
Fixed Costs	
Capital and Financing	The total cost of all equipment and construction
Insurance	The cost of insuring the power plant
Ad Valorem	Property taxes
Fixed O&M	Staffing and other costs independent of operating hours
Corporate Taxes	State and federal taxes
Variable Costs	
Fuel Cost	The cost of the fuel used
GHG Cost	Cap-and-trade allowance costs
Variable O&M	Operation and maintenance costs in function of operating hours
Total Cost	Fixed Cost + Variable Cost

Source: California Energy Commission

Table 3.3.3 Mid Case Component LCOE for Merchant Financed Plants ($/MWh)

Technology	Capital & Financing	Insurance	Ad Valorem	Fixed O&M	Taxes	**Fixed Costs**	Fuel	Variable O&M	**Variable Cost**	**Total LCOE**
Combined Cycle 500MW	24.2	1.6	2.4	9.1	8.0	**45.3**	70.4	0.8	**71.2**	**116.5**
Solar PV (Single Axis) 100MW	141.0	6.2	1.8	16.5	-56.6	**109.0**	0.0	0.0	**0.0**	**109.0**
Wind - Class 3 100MW	80.2	6.9	10.0	0.0	-24.2	**72.9**	0.0	12.2	**12.2**	**85.1**
Biomass Fluidized Bed Boiler 50 MW	62.7	5.3	7.9	19.7	-24.5	**71.1**	44.1	6.9	**50.9**	**122.0**

Source: California Energy Commission

The reported PPA prices and LCOE of wind and solar is determined to a large degree by the tax benefits it receives, and would be higher if not for them. Table 3.3.4 below shows the LCOE with and without tax benefit for wind and solar generated from merchant owned plants and Figure 3.3.1 graphically shows the developer costs (LCOE) and tax benefits, also for merchant owned plants in California. There are two parts to the tax benefits: 1) tax deductions including accelerated depreciation solar exemption from ad valorem, and tax deductions from manufacturing activities, and 2) tax credits such as PTC for wind and ITC for solar. The tax benefit for wind class 3 in 2013 totaled $54/MWh and for solar single axis 100MW, $129/MWh.

The levelized cost reported by CEC are reported at the point of interconnection, meaning that the LCOE figures include the cost of transmission and related losses. Table 7 shows the amount of transmission cost calculated into the LCOE. The transmission costs for solar is $3.3/MWh and for wind is $5.5/MWh. This is significantly lower than what previous literature has suggested it to be: $15/MWh.

Table 3.3.4 Effect of Tax Benefits on LCOE (2013$/MWh)

Technology	LCOE w/	LCOE w/o	Accl. Dep	ITC PTC	TB	As a %
Combined Cycle 500MW	117	117	-	-	-	-
Solar PV - Single Axis 100 MW	109	238	62	67	129	54%
Solar PV - Single Axis 20 MW	118	259	68	73	141	54%
Solar PV – Thin Film 100 MW	111	242	63	68	131	54%
Solar PV – Thin Film 20 MW	121	267	70	75	146	55%
Wind – Class 3 100 MW	85	139	25	29	54	39%
Wind - Class 4 100 MW	84	138	25	29	54	39%
Biomass fluidized Bed Boiler 50 MW	122	176	22	32	54	31%

Source: California Energy Commission

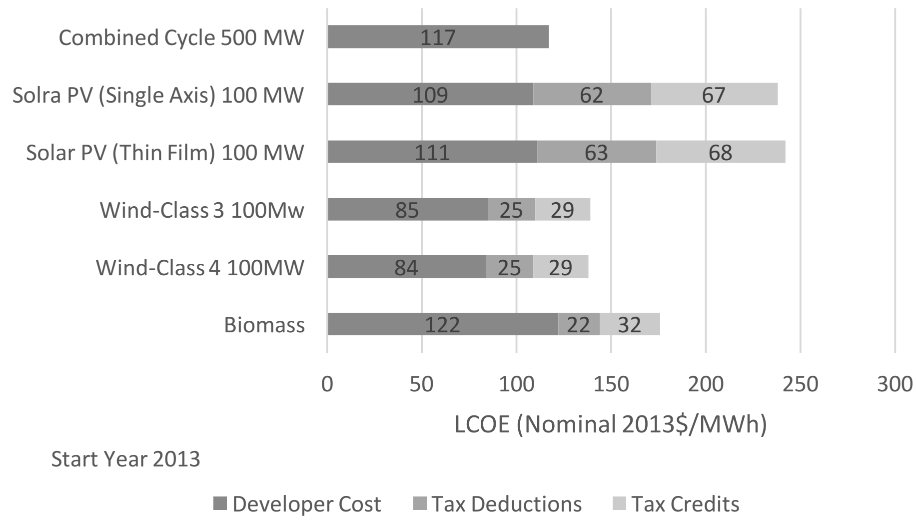

Figure 3.3.1 Merchant Mid-Cost LCOE with Tax Benefits
Source: California Energy Commission

3.4 Price and Cost Trend

Now that we have all the data for price and levelized cost, we can see how the price and cost for wind and solar have changed throughout the years. Figure 3.4.1 shows the trend of wind power price and levelized cost through years 2009 and 2015, and Figure 3.4.2 shows the trend of solar power price and levelized cost throughout the same period. The data for levelized cost is for national average and is from Lazard's Cost Analysis, and the data for market price is for California and is from CPUC's Section 910 Report. We see that in both cases the levelized costs have continuously decreased (wind by 61% from 2009 to 2015, and solar by 82%), while prices have slightly increased for both wind and solar. It should be noted that the market prices for wind and solar shown are prices without the federal tax incentives the producers receive and are the prices that the utilities pay the renewable producers. So in reality, the renewable producers end up getting paid more, partly from the utilities as the market price, and partly as a form of tax deduction and tax credit from the government. The fact that the market prices haven't fallen for wind and solar while the levelized costs of the sources have means that the ratepayers are being denied the benefits of lowered costs.

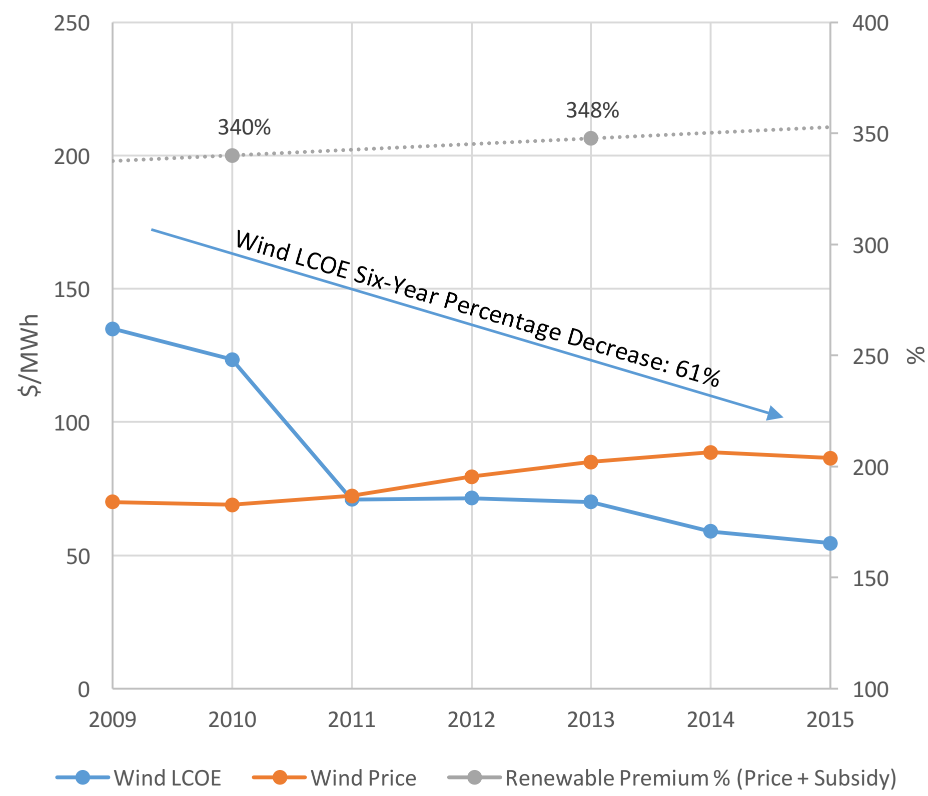

Figure 3.4.1 Wind Power Price and Cost Trend
Source: Lazard, California Public Utility Commission
Note: If California LCOE is used, renewable premium for wind rises from 343% to 353% from 2009 to 2015.

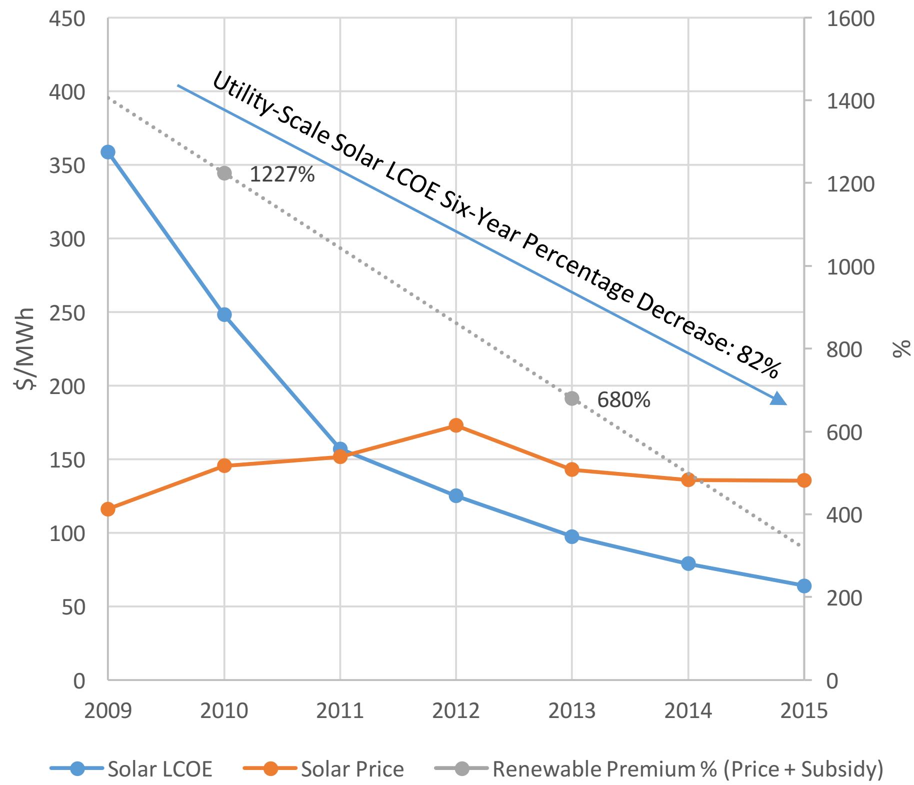

Figure 3.4.2 Solar PV Power Price and Cost Trend
Source: Lazard, California Public Utility Commission
Note: If California LCOE is used, renewable premium for solar rises from 113% to 663% from 2009 to 2015.

4. Issues affecting the Cost of Renewable Energy

4.1 Low Energy Capacity Factor, Low Power Density

There are several reasons the renewable energy is expensive. The most important one is that the energy capacity factor of renewable energy is much lower than that of conventional fossil fuels. Capacity factor of a power plant refers to the ratio of its actual generation over a period time to its nameplate capacity, its potential output if the plant were to operate at its fullest. Capacity factor for wind and solar are assumed to vary by time of day and season of the year, and by regions based on climate and latitude. The national average of capacity factor for wind in 2015 was 36%

and for solar PV was 29%.[22] This is substantially low compared to sources like nuclear, whose capacity factor was 92%.

This low capacity factor means that the renewable resources would naturally have lower power density, expressed as energy flux per unit of horizontal surface (W/m^2). Average global solar PV yields about 17 W/m^2 and wind yields about 2 W/m^2. In contrast, conventional power plants often have power densities in excess of 1,000 W/m^2.[23] There simply exist a physical limit to how much energy can be extracted from renewable resources for a given area of land. To put this more in perspective, we can look at a study by Nuclear Energy Institute that compares land requirements for different power sources. A 1,000MW wind farm would require 133 square miles of land. But with a capacity factor of 32-47 percent, if it were to produce the same amount of electricity as a 1,000MW nuclear plant, the figure would jump up to 260-360 square mile. Accounting for a range of capacity factors 17-28 percent, a solar PV facility would require 45-75 square miles. The same 1,000MW nuclear plant requires about 1.3 square miles.[24] Another study also shows that a wind farm of 1,000 MW capacity requires 225-300 acres of land, whereas a gas-fired plant with the same capacity requires only about 10-15.[25] These results also mean that nuclear and natural gas plants need much less steel, concrete, and other construction inputs than a renewable facilities of equal production capacity.

[22] http://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_6_07_b
[23] http://www.vaclavsmil.com/wp-content/uploads/docs/smil-article-power-density-primer.pdf
[24] http://www.nei.org/CorporateSite/media/filefolder/Policy/Papers/Land_Use_Carbon_Free_Technologies.pdf?ext=.pdf
[25] https://www.aei.org/publication/wind-and-solar-power-part-i-uncooperative-reality/

4.2 Cost of Locating and Exploiting a Site

Renewable energy not only requires a large invest in land and materials, but is also subject to a specific type of land the facilities should be built at. Wind and solar are confined to sites with a sufficient intensity and duration of wind flows and sunlight, respectively. The cost of finding and exploiting such particular sites, in a massive amount, is high and what is worse, it only rises with time as sites with the lowest cost get used up first. This is consistent with data on capacity factors in 1998-2009 that EIA published. The capacity factors for non-hydroelectric renewables declined almost monotonically from 57 percent to 33.8 percent[26], suggesting that as renewable capacity expands, developers are forced onto increasingly unfavorable sites, which results in lowering the capacity factor of the new plants.

4.3 Transmission Costs

In 2007, California Energy Commission found meeting the state's 2020 target, a 33 percent renewable energy mandate, will require around $5.7 billion in new transmission lines and $650 million for new transformer upgrades.[27] But in 2009, CPUC reported that meeting the 33 percent goal would actually cost the state $12 billion dollars total. With other costs added, this would raise the cost of renewable electricity by nearly $37/MWh in California, over the 14 years from 2008 to 2020.[28] Nationwide, different studies from different institutions have put forward varying ranges of transmission costs for renewable electricity. The most widely used and cited study is conducted by Berkeley National Laboratory, a survey from 2001 to 2008 that reviewed 40 transmission studies and found that the capacity weighted median cost of transmission to be

[26] http://pbadupws.nrc.gov/docs/ML1104/ML110410547.pdf Table 5.2
[27] http://www.energy.ca.gov/2007publications/CEC-500-2007-081/CEC-500-2007-081.PDF (pg. 26)
[28] http://docs.cpuc.ca.gov/PUBLISHED/GRAPHICS/102354.PDF (pg. 1, 22)

$15/MWh, with most studies falling below $25/MWh but with a wide range of $0/MWh-$79/MWh.[29] Giberson (2013)[30] also confirms the $15/MWh of transmission cost for wind in his paper, and Taylor and Tanton (2012)[31] calculated a $27/MWh cost for creating new transmission lines once the existing infrastructure for wind is occupied.

These transmission costs are often taken into consideration when calculating the levelized cost of energy, though in much lower numbers. CEC also estimates the transmission interconnection cost, i.e., the cost of constructing a new electric transmission lines from the generating station to the point of interconnection with the electricity grid and the cost of adding hardware at the interconnection point, when reporting LCOE. The transmission costs for solar PV in 2013 was estimated as $3.3/MWh out of $109/MWh LCOE, and for wind was $5.5/MWh out of $85/MWh. EIA also calculates the national average of the transmission cost for different generation technologies. For plants entering service in 2020, the transmission costs for coal and natural gas were both $1.2/MWh, while for wind it was $3.1/MWh and for solar $4.1/MWh in 2013$/MWh. Though much lower than what other studies have estimated, this transmission costs for wind is still 2.6 times higher and solar 3.4 times higher than those of conventional fuels within their study. Such costs of connecting a new generation project to the grid usually fall to the developer and directly adds to their levelized costs, which in turn affects the consumer electricity price.

[29] https://emp.lbl.gov/sites/all/files/REPORT%20lbnl-1471e.pdf
[30] http://instituteforenergyresearch.org/wp-content/uploads/2013/10/Giberson-study-Final.pdf
[31] Taylor and Tanton, 2012 http://www.atinstitute.org/wp-content/uploads/2012/12/Hidden-Cost.pdf

Table 4.3.1 Effect of Transmission Cost on LCOE in California (2013$/MWh)

Technology	LCOE with	LOCE without	Difference	As a %
Combined Cycle Natural Gas 500MW	116.6	114	2.4	2%
Solar PV - Single Axis 100MW	109	105.7	3.3	3%
Wind - Class 3 100MW	85	79.5	5.5	7%

Source: California Energy Commission[32]

Table 4.3.2 Effect of Transmission Cost on LCOE, National (2013$/MWh)

Technology	LCOE with	LOCE without	Difference	As a %
Combined Cycle Natural Gas	75.2	74	1.2	1.6%
Solar PV	114.3	110.2	4.1	3.6%
Wind	73.6	70.5	3.1	4.2%

Source: Energy Information Administration[33]

4.4 Intermittency Costs and Back-up Generation Costs

Another hidden cost of renewables that do not get reported as part of the levelized cost is its intermittency costs and back up costs. Unlike conventional sources, renewable energy is not available on-demand. Coal, natural gas, and nuclear plants can ramp up or down as demand rises or falls, but renewable energy sources, mainly wind and solar, are limited by how much the fuel, sunlight or wind, is available during a given period of time. This results in additional back up costs that's needed to insure there's no lapse in the power supply due to the "intermittency" of the renewable fuels.

This intermittency of renewable sources leads to two problems. First, we need other dispatchable supplies of energy to keep the system running when renewable is not available. This job mainly falls to natural gas, requiring it to be always available in order to quickly ramp up and down as needed. This not only means that there are extra hidden "fuel" costs to the renewable

32 http://www.energy.ca.gov/2014publications/CEC-200-2014-003/CEC-200-2014-003-SF.pdf
33 https://www.eia.gov/forecasts/aeo/electricity_generation.cfm

sources, but that the system requires higher flexibility of the pipeline systems, and also incurs an opportunity cost for the natural gas used solely as a back-up in the system. The backup cost for the renewable is called baseload cycling costs, and previous study by Giberson estimates it to be around $2/MWh while study by Tanton and Taylor has estimated them to be $23/MWh.

Second, the renewable sources' intermittency not only underestimates their levelized costs, but distorts the market by misrepresenting their actual value in the wholesale electricity market. Paul Joskow in MIT illustrates this point in his 2011 paper:

> "(Conventional levelized cost metric) is flawed because it effectively treats all electricity generated as a homogenous product governed by the law of one price… Wholesale electricity prices reach extremely high levels for a relatively small fraction of the hours in a year and generating units that are not able to supply electricity to balance supply and demand at those times are (or should be) at an economic disadvantage… An intermittent generating technology and a dispatchable generating technology may have the same levelized cost per MWh supplied while simultaneously having very different net economics values and profitability."[34]

This occurs because levelized cost measures the real total *life-cycle cost* per MWh supplied. The problem is that for intermittent sources, their hourly and daily output profiles change depending on the hour of the day, season of the year, and the location of the power plants. Wind is infamous for producing energy when it's least needed, and has been reported on multiple cases for producing negligent amount of energy during the peak hours. With a commodity like electricity

[34] http://web.mit.edu/ceepr/www/publications/reprints/Reprint_231_WC.pdf

whose wholesale market prices show a wide variation over different time periods, this means that the generating technologies should also be valued differently depending on when the technologies are at use in the system. As a result, the levelized costs end up overestimating the cost for peaking natural gas electricity and underestimating the cost for renewable electricity. Even between the intermittent sources, solar tends to have higher market value profile than the wind, since solar tends to produce electricity during the day time when the prices are relatively higher compared to wind who produces electricity mainly during the off-peak time periods. On the same note, Severin Borenstein (2008) also found that the solar PV power in California is about 20 percent undervalued relative to average power sold in the state, because it is produced disproportionately at peak hours.

The California Independent System Operator and the Commission estimated the cost for needed integration services, also referred to as operational flexibility. Below is the cost estimates of three big IOUs incurred to CAISO that may be attributable to renewable resources for years 2012 and 2013. The highest of all, PG&E estimates that it incurred CAISO charges totaling $7.8 million in 2012 and $9.6 million in 2013 that may be attributable to renewable resources.

Table 4.4.1 Integration Costs incurred to Big Three IOUs in California

Year	PG&E	SCE	SDG&E
2012	$7.8 million	$6.7 million	$18,198
2013	$9.6 million	$7.8 million	$35,278

Source: California Energy Commission

5. Model

5.1 Conceptual Framework

We present a simplified model of California renewable electricity market. A simple but general model of energy supply and demand can demonstrate how the relative slopes of the curves determine the equilibrium under different policies. We assume that electricity comes from five main sources: wind w, solar s, other renewables OR, natural gas NG, and baseload technologies n. Other renewables are mainly biomass, geothermal, and small hydro. Baseload generation consists of large hydro and nuclear, and is characterized by fixed and fully utilized generation capacity, with little output variation. In our model, baseload generation is fixed at a supply of 110 million MWh. Coal and oil together account for less than 0.5% of in-state generation and is omitted from the model. The non-baseload generations are assumed to have weakly upward sloping inverse supply curves while the baseload generation is assumed to have fixed and perfectly inelastic supply curves. These supply curves can also be thought of as marginal cost curves, where the technologies receive competitively determined prices, so that their marginal costs equal the price received.

The basic elements of the model consist of one demand curve for electricity, and four supply curves for wind, solar, other renewable, and non-renewable, where non-renewable supply is simply a function of natural gas plus the baseload quantity. Following are the functions of the demand curve and supply curves for each resources:

$$D_E(P_E) = A{P_E}^{\varepsilon} \tag{1}$$

$$S_w = B_w {P_R}^{\eta w} \tag{2}$$

$$S_S = B_S {P_R}^{\eta s} \tag{3}$$

$$S_{OR} = B_{OR} {P_R}^{\eta_{OR}} \tag{4}$$

$$S_{NR} = B_{NG}(P_{NG} - m)^x + n \tag{5}$$

Where P_E stands for consumer price of electricity, P_R stands for one renewable price wind, solar, and other renewables all share, and P_{NG} stands for the natural gas electricity price, aka the peak electricity price. ε represents price elasticity for demand, and η_W, η_S, and η_{OR} stand for price elasticity of supply for wind, solar, and other renewables respectively. m stands for a minimum price needed for natural gas production and is equal to \$20/MWh. The prices P_E, P_R, and P_{NG}, and the quantity supplied D_E, S_w, S_s, S_{OR}, and S_{NR} are all endogenous variables in our model that will be determined by the equilibrium conditions.

Now consider a mandate where a minimum share of eligible renewable, α is required in all electricity sold, with $\alpha \in (0,1)$, and production subsidy for wind $\mathscr{s}_w$ and solar $\mathscr{s}_s$ the government pays to the developers. These two parameters, blend mandate α and production subsidy $\mathscr{s}_w$ and $\mathscr{s}_s$ for renewable are our two exogenous parameters. Then the supply for wind and solar becomes:

$$S_w = B_w(P_R + \mathscr{s}_w)^{\eta w} \tag{6}$$

$$S_s = B_s(P_R + \mathscr{s}_s)^{\eta s} \tag{7}$$

Table 5.1.1 shows the value of the variables at the status quo. All data are for year 2013 and was gathered from California Public Utilities Commission, California Energy Commission, and U.S. Energy Information Administration.

Table 5.1.1 Value of Variables at the Status Quo (Raw data for year 2013)

Parameter	Symbol	Value	Source
Quantity			
Total power mix generation	S_T	297	CEC
Wind generation	S_W	25	CEC
Solar generation	S_S	5	CEC
Other renewable generation (excluding wind and solar)	S_{OR}	25	Calculated
NG generation	S_{NG}	131	CEC
Baseload generation (nuclear + hydro)	n	110	Calculated
Total renewable generation	S_{TR}	55	CEC
Total non-renewable generation	S_{NR}	241	Calculated
Percentage of renewables	α	0.19	
Price			
Consumer Retail Electricity Price	P_E	143	EIA
Wholesale Electricity Peak Price	P_{NG}	40	EIA
Overall Renewable RPS procurement expenditure	P_R	90	CPUC
Minimum Price of NG for production	m	20	de Gorter
Tax Benefit			
CEC Tax Benefit for Wind-Class3 100MW	$\mathscr{s}_W$	54	CEC
CEC Tax Benefit for Solar PV (single axis)100MW	$\mathscr{s}_S$	129	CEC

Note: Quantity is in million MWh and price and tax benefit are in \$/MWh.

5.2 Calibration of the Model

In order to calibrate the model, we need to specify the values of the exogenous parameters, our two policy variables α and $\mathscr{s}$, and the supply functions for wind S_W, solar S_S, other renewables S_{OR}, and the demand for total electricity D_E. These are all provided in the previous section 5.1, and we calibrate our model to fit the data in Table 5.1, using the aforementioned supply and demand curves. Table 5.2.1 shows the values of the elasticities used for calibration.

Table 5.2.1 Elasticity used for Calibration

Parameter	Symbol	Value
Price elasticity of Demand	ε	-0.3
Price elasticity of supply of other renewables	η_S^{OR}	1.2
Price elasticity of supply of wind	η_S^{W}	1.3
Price elasticity of supply of solar	η_S^{S}	1.7
Price elasticity of supply of non-renewables	η_S^{NR}	0.5

We write the total electricity demand equation as

$$D_E(P_E) = AP_E{}^{\varepsilon} \tag{8}$$

Then the value of A is calibrated by

$$A = \frac{D_E}{P_E{}^{\varepsilon}} \tag{9}$$

where ε is the elasticity of demand for total electricity in California. Now we calibrate value of B_w in the supply curve for win. Since the supply for the wind can be written as

$$S_w = B_w(P_R + s_w) \tag{10}$$

Then B_w can be calibrated by

$$B_w = \frac{S_w}{(P_R + s_w)^{\eta w}} \tag{11}$$

We undergo the same process to get B_S and B_{OR} for solar and other renewable. Now let's look at the supply of non-renewable energy. We write the supply of non-renewable energy as a sum of baseload generation and natural gas generation:

$$S_{NR} = B_{NG}(P_{NR} - m)^x + n \tag{12}$$

where n is the baseload technology and is always set at 110 million MWh throughout our paper. We calibrate the values of parameters B and x. Since

$$dS_{NR} = xB_{NG}(P_{NR} - m)^{x-1} dP_{NR} \tag{13}$$

then

$$\frac{dS_{NR}}{dP_{NR}} = xB_{NG}(P_E^{NR} - m)^{x-1} \tag{14}$$

$$\frac{dS_{NR}}{dP_{NR}} \frac{P_{NR}}{S_{NR}} = xB_{NG}(P_{NR} - m)^{x-1} \frac{P_{NR}}{S_{NR}} = \eta_{NR}^S \tag{15}$$

where now η_{NR} is the elasticity of non-renewable electricity supply. We end up with two equations and two unknowns:

$$\eta_{NR}^S = xB_{NG}(P_{NR} - m)^{x-1} \frac{P_{NR}}{S_{NR}} \tag{16}$$

$$S_{NR} = B_{NG}(P_{NR} - m)^x + n \tag{17}$$

where the two unknowns are B_{NG} and x. We get B_{NG} by

$$B_{NG} = \frac{S_{NR} - n}{(P_{NR} - m)^x} = \frac{S_{NG}}{(P_{NR} - m)^x} \tag{18}$$

and x by

$$x = \eta_{NR}^S \frac{S_{NR}}{P_{NR}} \frac{P_{NR} - m}{(S_{NR} - n)} = \eta_{NR}^S \frac{S_{NR}}{P_{NR}} \frac{P_{NR} - m}{S_{NG}} \tag{19}$$

Specific calculated values for each parameter after calibration are shown below in Table 5.2.2.

Table 5.2.2 Parameter values at the Calibrated Point

Parameter	Symbol	Value	Source/Explanation
Parameter A for Demand	A	1314	$A = D_E/{P_E}^{\varepsilon}$
Parameter b for Supply of wind	b_w	0.3	$b_w = \eta_S^W \times S_w/(P_R + s_w)$
Parameter a for Supply of wind	a_w	-17.8	$a_w = S_w - b_w(P_R + s_w)$
Parameter b for Supply of solar	b_S	0.1	$b_S = \eta_S^S \times S_S/(P_R + s_S)$
Parameter a for Supply of solar	a_S	-9.2	$a_s = S_s - b_s(P_R + s_s)$
Parameter b for Supply of other R	b_{OR}	0.4	$b_{OR} = \eta_S^{OR} \times S_{OR}/P_R$
Parameter a for supply of other R	a_{OR}	-12.5	$a_{OR} = S_{OR} - b_{OR}P_R$
Parameter B for Supply of NR	B	43.8	$B = (S_{NR} - n)/(P_{NR} - m)^x$
Parameter x for Supply of NR	x	0.4	$x = \eta_S^{NR}(S_{NR}/P_{NR}) \times ((P_{NR} - m)/(S_{NR} - n))$

5.3 Equilibrium Price and Quantity Estimation

In order to simulate the model, we need to specify the equilibrium conditions that must hold and then set our policy instruments. For the purpose of our policy analysis, the policy instruments that we allow are blend mandate and renewable subsidies. In equilibrium, following conditions must be met:

Total demand equals total supply,

$$D_E(P_E) = S_w(P_R + s_W) + S_S(P_R + s_S) + S_{OR}(P_R) + S_{NR}(P_{NR}) \tag{20}$$

and α of total demand should come from supply of renewable.

$$\alpha D_E(P_E) = S_R(P_R) = S_w(P_R + s_W) + S_S(P_R + s_S) + S_{OR}(P_R) \tag{21}$$

Furthermore, in equilibrium, consumers must pay the marginal cost to the utilities of producing a unit of mixed electricity. This marginal cost is given by the weighted average price of renewable energy and non-renewable energy where the weights are formed by the required share of renewable sources under the mandate:

$$P_E = \alpha P_R + (1 - \alpha)P_{NR} \tag{22}$$

where P_E is the weighted average consumer price of electricity, P_R is the corresponding market price of renewable energy, and P_{NR} is the price of non-renewable energy. This constitutes the marginal cost of the mandated mixture because P_R is the marginal cost of renewable and P_{NR} is the marginal cost of non-renewable to the utilities. We assume a fixed marketing margin MM for blenders of $96/MWh. Then the consumer price can be re-written as:

$$P_E = \alpha P_R + (1-\alpha)P_{NR} + MM \tag{23}$$

Given these conditions, we now set the values for α and s_W and s_S for each policy scenarios, and after plugging in the two exogenous variables, find the values for other endogenous variables that satisfy that above market equilibrium conditions. We get the endogenous price variables by:

$$P_E = \left(\frac{D}{A}\right)^{\frac{1}{\varepsilon}} \tag{24}$$

$$P_{NR} = \frac{P_E - \alpha P_R - MM}{1-\alpha} \tag{25}$$

$$P_W = P_R + s_W \tag{26}$$

$$P_S = P_R + s_S \tag{27}$$

And the endogenous quantity variables by equations (5.1)–(5.4)

$$S_W = B_W(P_R + s_w) \tag{28}$$

$$S_S = B_S(P_R + s_s) \tag{29}$$

$$S_{OR} = B_{OR}P_R \tag{30}$$

$$S_{NR} = B_{NG}(P_{NG} - m)^x + n \tag{31}$$

From the individual supply curves we get the total supply by

$$S = S_W + S_S + S_{OR} + S_{NR} \tag{32}$$

and we get the total demand by

$$D = \frac{S_R}{\alpha} = \frac{S_W + S_S + S_{OR}}{\alpha} \tag{33}$$

6. Emissions

Our two policy instruments, blend mandate and renewable production subsidy both aim to solve market failure of producing too much emissions in the free market. Thus, it will be critical for us to take emissions into consideration when looking at how the alternative policy scenarios affect the market and the society. We first define social cost of carbon and the current central estimate we use in the paper, and then talk about how we can calculate the cost of emissions to the society under each policy scenario using the carbon footprint of energy sources. Then we move on to talking about carbon leakage, to examine whether our policy instruments are as effective in decreasing emissions as we think they do.

6.1 Social Cost of Carbon

The social cost of carbon, SCC, is a way of putting a price on carbon. The EPA defines it as "an estimate of the economics damages associated with a small increase in carbon dioxide (CO_2) emissions, conventionally one metric ton, in a given year." This number also "represents the value of damages avoided for a small emission reduction."[35]

The US government first published its estimates of SCC in 2010 as a $21 per metric ton of CO_2. They used three most cited models from peer reviewed literature – William Nordhaus' DICE model, Richard Tol's FUND model, and Chris Hope's PAGE model – and different discount rates

[35] https://www3.epa.gov/climatechange/EPAactivities/economics/scc.html

to get these estimates. In 2013, the figures were updated to be $57, $37, and $11 per metric ton in 2007 USD using a 2.5 percent, 3 percent, and 5 percent discount rates respectively.[36] The central estimate is the one that uses a 3 percent discount rate, a $37/ton, and is considered the current SCC amongst many studies. But there also exist a number of other works that have estimated much higher numbers. A study published in the Journal of Environmental Studies and Sciences estimated the figure to be between $55 and $255 per ton[37] and a study by Stanford researchers have estimated it to be $220/ton.[38] This is because the models used by the interagency working group omit several climate impacts. Thus, it is also generally accepted fact that the central figure of $37/ton should be interpreted as a lower bound estimate.

In our paper, we use the $37/ton figure in calculating the cost of emissions under different policy scenarios because this estimate is the best available estimate for now.

6.2 The Environmental Cost under Alternative Scenarios

In order to estimate how much it costs the society to emit or to save carbon dioxide emissions under a policy scenario, we will have to know how much of carbon dioxide was emitted. In order to do this, we will need to figure out the carbon footprint of each energy sources. Carbon footprint of an energy source is the amount of greenhouse gas emissions produced expressed as carbon dioxide equivalent tons CO_2e. Table 6.2.1 shows the carbon footprints of different energy sources in our model expressed in carbon dioxide equivalent tons per MWh. Total renewable, other renewable, non-renewable, and baseload carbon footprints are calculated using the weighted

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[36] https://www.whitehouse.gov/sites/default/files/omb/inforeg/scc-tsd-final-july-2015.pdf
[37] http://thinkprogress.org/climate/2012/09/18/866441/how-the-federal-government-greatly-underestimates-the-true-cost-of-carbon-pollution/
[38] https://news.stanford.edu/2015/01/12/emissions-social-costs-011215/

average of corresponding sources' 2013 data. With given carbon footprint data, we can then calculate the level of total emissions under the status quo and alternative policies. Total emission is calculated by:

$$\text{Total } CO_2\text{e Emissions} = e_W Q_w + e_s Q_s + e_{OR} Q_{OR} + e_{NG} Q_{NG} + e_B Q_B \tag{34}$$

Given the equation, for example, the total emissions under status quo would be 69 million tons and under laissez faire case 86 million tons. Then, the environmental cost to the society can be calculated as:

$$\text{Environmental Cost (Million \$)} = \$37/\text{ton} \times \text{Total emissions (Million ton)} \tag{35}$$

expressed in million dollars. Total environmental cost in status quo would be 2,562 million dollars, and under laissez faire 3,154 million dollars.

Table 6.2.1 Carbon Footprint of Energy Sources (CO_2e/MWh)

Technology	Symbol	Value	Source
Total Renewable	e_R	0.034	Calculated
Wind	e_W	0.011	NREL
Solar	e_S	0.044	NREL
Other Renewable	e_{OR}	0.045	Calculated
Biomass	e_B	0.040[39]	NREL
Geothermal	e_G	0.040	NREL
Small Hydro	e_{SH}	0.070	NREL
Non-Renewable	e_{NR}	0.372	Calculated
Natural Gas	e_{NG}	0.477	NREL
Baseload	e_{BL}	0.045	Calculated
Nuclear	e_{Nuc}	0.016	NREL
Large Hydro	e_{LH}	0.070	NREL

Note: Carbon footprint of biomass varies widely among previous studies. Please see footnote.

[39] The carbon footprint of biomass varies greatly depending on the source and methods of production, and is also controversial regarding its "carbon neutral-ness" As such, biomass is often excluded from energy-related emissions. http://www.eia.gov/totalenergy/data/monthly/pdf/sec12.pdf
and http://www.parliament.uk/documents/post/postpn_383-carbon-footprint-electricity-generation.pdf

6.3 Carbon Leakage

Carbon leakage refers to a situation when the emission reductions expected by an environmental policy are partially or more than offset by the market effects. de Gorter and Just (2009a) identify two components of carbon leakage: "market leakage effect" (or 'indirect output use change effect') which refers to the effect of clean fuels displacing fossil fuels consumption, and the "emissions savings effect," the relative carbon emissions of clean fuels versus those of fossil fuels. The idea is that we expect an environment policy to decrease the overall carbon emissions because of increased production of renewable energy, which emits less greenhouse gases (GHG). But that can only be the case if a unit of renewable energy replaces a whole unit of non-renewable energy, which often is not true. Thus, it is critical to take the market effect into consideration when assessing an environmental policy's ability to reduce GHG.

Drabik et al. (2013) have shown that in the case of biofuel policies, market leakage due to a tax credit is always greater than that of a mandate, while the combination of a mandate and subsidy generates greater leakage than a mandate alone. We extend this idea to the California electricity market, and see whether and how the renewable portfolio standard and the tax credits for renewable energy, acting as a binding mandate and subsidies for clean energy source respectively, result in carbon leakage.

We use the following formula to calculate the carbon leakage under alternative policy scenarios:

$$\text{Carbon Leakage} = \text{Expected } \mathrm{CO_2e} \text{ savings} - \text{Actual } \mathrm{CO_2e} \text{ savings} \tag{36}$$

Where we calculate expected CO_2e savings for a scenario as:

$$\text{Expected } \mathrm{CO_2e} \text{ savings} = \mathrm{S_w} \times |\mathrm{e_{NR}} - \mathrm{e_w}| + \mathrm{S_S} \times |\mathrm{e_{NR}} - \mathrm{e_S}| + \mathrm{S_{OR}} \times |\mathrm{e_{NR}} - \mathrm{e_{OR}}| \tag{37}$$

And we calculate actual CO_2e savings as:

$$\text{Actual } \mathrm{CO_2e} \text{ savings} \tag{38}$$

$$= \mathrm{CO_2e} \text{ emissions in Status Quo} - \mathrm{CO_2e} \text{ emissions in a scenario}$$

$$= \quad (S_{W1}e_W + S_{S1}e_S + S_{OR1}e_{OR} + \Delta S_{NR1}e_{NR}) - (S_{W0}e_W + S_{S0}e_S + S_{OR0}e_{OR} + S_{NR0}e_{NR})$$

where subscript 1 stands for changed values under a policy scenario and subscript 0 stands for original values in status quo. This will allow us to gauge the effectiveness of different policy mixes to decrease emissions.

7. Market and Welfare Analysis

Now that we have all the tools to perform welfare analysis, we proceed onto simulating the equilibrium under different assumptions of policy scenarios. We illustrate changes in economic welfare for electricity consumers and producers using linear approximations from the non-linear supply and demand curves, as well as the changes in CO_2 emissions. We first analyze the effect of blend mandate and renewable production subsidy as sole policy parameters and proceed to analyzing the interaction effect of the two policies. We also analyze the incidence of pricing carbon, and how the interaction effect of blend mandate and production subsidy impacts carbon leakage.

7.1 Sole Policy Parameters

Table 7.1.1 illustrates a policy box with possible combinations of our two policy parameters, blend mandate α and renewable subsidies $\mathcal{s}_W$ and $\mathcal{s}_S$. For the purpose of this section, a number of policy scenarios are left blank.

The subscript 0 for the parameters indicates laissez faire state, where values for α and s equal zero. Subscript 1 stands for the status quo values where blend mandate α equals 0.19, and subsidy s for wind equals \$54/MWh and for solar equals \$129/MWh. Subscript 2 stands for increased value of α equal to 0.24, and increased values for both s_w and s_S equal to \$232/MWh, which is the amount of subsidy with an implied 24% procurement from renewable energy without the presence of a binding blend mandate.

Table 7.1.1 Policy Box I

(α_0, s_0) 0% \$0, \$0	(α_0, s_1) 0% \$54, \$129	(α_0, s_2) 0% \$232, \$232
(α_1, s_0) 19% \$0, \$0	(α_1, s_1) 19% \$54, \$129	
(α_2, s_0) 24% \$0, \$0		

Note: Subsidies are in \$/MWh and are presented in the order of wind, then solar.

Table 7.1.2 illustrates the market effects of the alternate policy scenarios and Table 7.1.3 illustrates the welfare effects of the same scenarios. The welfare effects are all relative to the status quo scenario. The calculations of the change in consumer surplus, producer surplus, tax costs, and the dollar value of carbon dioxide equivalent can be found in the Appendix.

In this section, we will mainly be looking at seven different scenarios, from which six are shown above in the policy box (status quo scenario (α_1, s_1) is provided for reference) and the other is pricing carbon, aka imposing a carbon tax τ_c on the consumption side.

Table 7.1.2 Market Effects of Alternate Policy Scenarios

	Status Quo (α_1, s_1)	*Laissez Faire* (α_0, s_0)	Introduce α (α_1, s_0)	Increase α (α_2, s_0)	Introduce s (α_0, s_1)	Increase s (α_0, s_2)
Price						
Consumer	143	146	147	153	142	130
Producer						
Renewable (Total)	91	53	117	141	49	37
Wind	145	53	117	141	103	269
Solar	220	53	117	141	178	269
Other renewable	91	53	117	141	49	37
Natural Gas	40	53	39	34	49	37
Quantity						
Consumer	297	295	294	291	297	305
Renewable (Total)	56	20	55	70	32	73
Wind	25	7	19	25	16	57
Solar	5	1	2	3	4	8
Other renewable	25	13	34	42	12	9
Non-Renewable (Total)	241	274	239	221	265	232
Natural Gas	131	165	129	111	156	122
Other non-renewable	110	110	110	110	110	110
Emissions						
Total Emissions	69	84	68	60	80	65
Environmental Cost	2562	3115	2529	2231	2959	2389
Carbon Leakage		22	18	15	22	21

Notes: All prices are in $/MWh, quantities are in million MWh, and emissions are in million tons. We assume η_W^s=1.3, η_S^s=1.7, η_{OR}^s=1.2, and η_{NR}^s=0.5

Table 7.1.3 Welfare Effects of Alternate Policy Scenarios relative to Status Quo (in Million Dollars)

	Status Quo $(\alpha_1, \mathscr{s}_1)$	*Laissez Faire* $(\alpha_0, \mathscr{s}_0)$	Introduce α $(\alpha_1, \mathscr{s}_0)$	Increase α $(\alpha_2, \mathscr{s}_0)$	Introduce $\mathscr{s}$ $(\alpha_0, \mathscr{s}_1)$	Increase $\mathscr{s}$ $(\alpha_0, \mathscr{s}_2)$
Changes in						
Consumer Surplus		-964	-1310	-2999	183	3737
Producer Surplus (Total)		599	-367	-82	419	3874
Wind		-1481	-610	-80	-870	5136
Solar		-490	-371	-311	-191	324
Other renewable		-717	788	1712	-767	-894
NG		1890	-94	-738	1275	-371
Baseload		1398	-79	-666	973	-320
Tax Cost		-2068	-2068	-2068	-700	12938
Tax Revenue		-	-	-	-	-
Total Social Welfare		1703	391	-1013	1302	-5328
Emissions		15	-1	-9	11	-5
Environmental Cost		554	-32	-331	398	-173
Cost of Emissions/ton		77		76	84	1105
Total Social Welfare + EC		1150	423	-682	904	-5155

Notes: For environmental cost, we assumed $25/ton cost for emissions.

The questions we seek to answer by analyzing the suggested scenarios are: "What are the effects of the renewable production subsidy and of the renewable portfolio standard (blend mandate) on the market, environment, and the society as a whole? How do the direction and the size of such effects change as the amount of subsidy and the stringency of the mandate change? What about the interaction effect of the two policies?"

Studies in the past have examined the effects of the environmental policies and compared their cost effectiveness. Fell et al. (2012) found that the production tax credit is the least cost effective renewable energy policy, as its equilibrium electricity prices are lowest and thus subsidizes electricity consumption. They argued that the renewable portfolio standard out performs the PTC since the RPS puts more upward pressure on the electricity prices, and concluded that a carbon price is the most cost-effective because it results in the highest electricity prices and thus reduces electricity demand the most.

Some studies have focused on the interaction effects of overlapping policies in the energy market. De Gorter and Just (2009) found that in the case of biofuels, tax credits in conjunction with blend mandate end up subsidizing fuel consumption instead of biofuels, which contradicts the policy goals and increases social costs. Fischer and Preonas (2010) also found that when renewable portfolio standard is in action, additional subsidies to renewables will drive up the emissions. By lowering the cost of renewable electricity generation, subsidies in turn lower electricity prices and allow the fossil fueled electricity, and thereby emissions, to expand. Drabik (2011) has studied the effects of biofuel policies on the corn prices and find that if the biofuel mandate binds, blender's tax credit, ethanol production subsidies, and corn production subsidies subsidize fuel and thus the consumption of gasoline.

Such results are in accordance with the general consensus of the literature that one policy variable is optimal for facing one market failure, and as the number of policy variable increases, more harm is done to the market than good (Tinbergen, 1952). Then, in the case of California wholesale electricity market, is the combination of production subsidy for renewables and blend mandate (renewable portfolio standard) too much? Or is it just the right amount to fix its market failure?

Based on the results from previous studies, we also expect to see an analogous empirical effect the blend mandate and production subsidy have on the renewable electricity market in California. We see such effects through choosing the different mixture of policies and comparing the different ways each policies affect the consumer electricity price, total consumption and fossil fuel consumption, emissions, and the general social welfare. We conclude that the existence of production subsidy, or increasing the amount of the subsidy, end up going against the policy goals by decreasing the consumer price, increasing the total consumption and fossil fuel consumption, and in turn increasing the emissions. If decreasing emissions is our end goal, then increasing the stringency of mandate without the renewable production subsidy is the best policy, and if achieving the highest social welfare is our goal, then imposing a carbon tax on the consumption would be the best policy.

Tables 7.1.4 to 7.1.8 are provided to help the readers quickly grasp the trend in equilibrium prices and quantities, emissions, and total social welfare with environmental cost under the alternative policy scenarios, using policy boxes of different endogenous variables.

Table 7.1.4 P_E ($/MWh)

146	142	131
147	143	
153		

Table 7.1.5 Q_T (million MWh)

295	297	305
294	296	
291		

Table 7.1.6 Q_{NG} (million MWh)

165	156	122
129	131	
111		

Table 7.1.7 Emissions (million tons)

84	80	65
68	69	
60		

Table 7.1.8 Δ Social Welfare
with Environmental Cost (million $)

1150	904	-5155
423	0	
-682		

Note: Figures are relative to Status Quo

7.1.1 The Effect of a Blend Mandate

In this section we will select and compare policy scenarios that can show us the effect of a blend mandate. The effect of a blend mandate on the consumer price of energy has been studied and debated by others. Palmer and Burtraw (2005) have found that national RPS policies ranging 5-20% would raise the U.S. electricity price, but Fischer (2009) and de Gorter and Just (2009) argue that blend mandates can raise or lower the consumer price. Fischer (2009) claims that the direction of the effect depends on 1) the relative price elasticity of supply for renewable energy to that of non-renewable energy and 2) the stringency of the blend mandate. She wrote "if the renewable energy supply curves are sufficiently elastic and the RPS targets relatively low, an RPS serves more as a subsidy for renewable energy producers than as an energy tax on fossil fuel producers." We also find this to be true, as the direction of the change in the consumer price varied depending on the set of elasticity values for renewable energy and non-renewable energy we chose, and on the stringency of our α. Please look at the Appendix to see the case when an increase in the stringency of the blend mandate decreases the consumer price.

Table 7.1.1A compares scenarios $(\alpha_0, \mathscr{s}_0)$, $(\alpha_1, \mathscr{s}_0)$, and $(\alpha_2, \mathscr{s}_0)$ to see the effect of increasing the stringency of alpha without the production subsidies. This would give us the sole effect the blend mandate has on the market.

The effect of increasing the stringency of α is as follows: consumer price for electricity rises, total consumption falls, non-renewable energy consumption falls, and as a result, emissions fall. Social welfare with environmental cost falls as well.

Going from a no mandate to a 19% mandate state, our consumer price rises from \$146/MWh to \$147/MWh, and raising the mandate again to 24% further increases the consumer price to \$153/MWh. As price increases, total consumption decreases from 295 million MWh to

294 to 291. The first one million MWh decrease consists of 35 million decrease in natural gas fired electricity and a 34 million MWh increase in renewable energy, and the second 3 million MWh decrease consists of 18 million decrease in natural gas fired electricity and a 15 million MWh increase in renewable energy. We see from here that the renewable portfolio standard, aka blend mandate, increases electricity price relative to a no policy case, and is quite successful in decreasing emissions as well as environmental costs. Going from a no mandate to a 24%, emissions decrease by 24 million tons and the environmental cost decreases by 884 million dollars.

But the decrease in emissions come with a cost to the society. An increase in consumer price for electricity and decrease in non-renewable energy consumption decrease welfare for consumers and the non-renewable electricity producers while for renewable producers and the government, their welfare increases. Overall, the former effect overrides the latter and we end up with lowering total social welfare as α increases. This decrease in social welfare is mitigated when we include environmental cost though, because as α increases, the environmental cost decreases.

Total social welfare with the environmental cost is 1,150 million dollars under laissez faire, and as we increase the stringency of mandate this number drops to 423 million dollars and again to -682 million dollars.

Tables 7.1.1B–7.1.1F are provided with bolded borderlines to help the readers quickly grasp the changes in the market as we increase the stringency of the blend mandate.

Table 7.1.1A Market and Welfare Effects of Increasing the Stringency of α without the Subsidy

	Laissez Faire (α_0, s_0)	No s (α_1, s_0)	Increase α, No s (α_2, s_0)
P_E	146	147	153
S_{Total}	295	294	291
S_{TR}	20	55	70
S_{NG}	165	129	111
CO_2 Emissions	84	68	60
Environmental Cost	3115	2529	2231
Changes in			
Total Social Welfare	1703	391	-1013
Total Social Welfare + EC	1150	423	-682

Notes: All prices are in \$/MWh, quantities are in million MWh, and emissions are in million tons.

Table 7.1.1B P_E ($/MWh)

146 147 153	142 143	131

Table 7.1.1C Q_T (million MWh)

295 294 291	297 296	305

Table 7.1.1D Q_{NG} (million MWh)

165 129 111	156 131	122

Table 7.1.1E Emissions (million tons)

84 68 60	80 69	65

Table 7.1.1F Δ Social Welfare
with Environmental Cost (million $)

1150 423 -682	904 0	-5155

Note: Figures are relative to Status Quo

7.1.2 The Effect of a Production Subsidy

In this section, we select and compare policy scenarios that can show us the effect of a production subsidy only. We compare scenarios laissez faire, (α_0, s_1), and (α_0, s_2) to see how increasing the amount of subsidy without any binding mandate will affect the market. Renewable production subsidy as an environmental subsidy is generally viewed as an inferior option compared to other policies in terms of its cost effectiveness. We also find that in our model, renewable production subsidy puts a downward pressure on the consumer price and thus increases the total consumption. But at the same time, it does decrease the amount of non-renewable energy consumption and emissions as well.

As we introduce \$54/MWh and \$129/MWh subsidy for wind and solar respectively to laissez faire, consumer price declines from \$146/MWh to \$142/MWh and total consumption rises by 2 million MWh. Out of the 2 million MWh increase, a 12 million MWh increase came from renewable energy while 10 million decrease came from non-renewable energy. All such effects maintain the same direction but decline in size as we increase the renewable production subsidy to \$232/MWh for both wind and solar subsidy, so that the implied renewable electricity supplied is 24% of total procurement. Going from zero subsidy scenario to \$232/MWh scenario, consumer price declines from \$146/MWh to \$131/MWh and total consumption rises by 10 million MWh from which renewable increased by 53 million MWh and non-renewable decreased by 43 million MWh. Emissions decrease from 84 million tons to 65, and environmental cost decreases from 3,115 to 2,389 million dollars.

Social welfare with the environmental cost also falls as we increase renewable production subsidy, though the fall is the environmental cost mitigates the decreasing rate. Under lasses faire (zero subsidy assumption) social welfare was $1,150 million dollars, with status quo subsidies $904 million dollars, and with increased subsidies -$5155 million dollars.

We find that renewable production subsidy lowers consumer electricity price and raises total consumption of electricity but still decreases emissions because most of the increase in consumption comes from the renewable sources. As blend mandate, social welfare drops in proportion to the amount of renewable production subsidy. Please look at Table 7.1.2A and Tables 7.1.2B–Tables 7.1.2F.

Table 7.1.2A Market and Welfare Effects of Increasing Subsidy without a Mandate

	Laissez Faire (α_0, s_0)	Introduce s (α_0, s_1)	Increase s (α_0, s_2)
P_E	146	142	131
S_{Total}	295	297	305
S_{TR}	20	32	73
S_{NG}	165	156	122
CO_2 Emissions	84	80	65
Environmental Cost	3115	2959	2389
Changes in			
Total Social Welfare	1703	1302	-5328
Total Social Welfare + EC	1150	904	-5155

Notes: All prices are in $/MWh, quantities are in million MWh, and emissions are in million tons.

Table 7.1.2B P_E (\$/MWh)

146	142	131
147	143	
153		

Table 7.1.2C Q_T (million MWh)

295	297	305
294	296	
291		

Table 7.1.2D Q_{NG} (million MWh)

165	156	122
129	131	
111		

Table 7.1.2E Emissions (million tons)

84	80	65
68	69	
60		

Table 7.1.2F Δ Social Welfare with Environmental Cost (million $)

1150	904	-5155
423	0	
-682		

Note: Figures are relative to Status Quo

7.1.3 Comparing the Blend Mandate and the Production Subsidy

Now that we have looked at both the effects of a blend mandate and renewable production subsidy, we are in a position to compare the two policies. Specifically, we can compare scenarios $(\alpha_2, \mathscr{s}_0)$ and $(\alpha_0, \mathscr{s}_2)$ with laissez faire, and see how procuring 24% of total consumption from renewable electricity with a blend mandate and with a renewable production subsidy affect the market differently. Table 7.1.3A compares the market and welfare effects of scenarios $(\alpha_2, \mathscr{s}_0)$ and $(\alpha_0, \mathscr{s}_2)$ to the laissez faire. Under both scenarios, 24% of total procurement comes from renewable sources; $(\alpha_2, \mathscr{s}_0)$ assumes a binding blend mandate of 24% while $(\alpha_0, \mathscr{s}_2)$ assumes an implicit blend mandate of 24% with a renewable production subsidy of \$232/MWh for both wind and solar alike. We see that the price to consumers is lower with production subsidy, which also means total consumption is higher. This also means that the society will be consuming greater amount of renewable electricity with production subsidy, but also greater amount of non-renewable electricity as well. With a binding blend mandate of 24%, total emissions are 60 million tons, but with a renewable production subsidy of \$232/MWh, total emissions are 65 million tons. Naturally, environmental cost is higher with production subsidy by 158 million dollars. Most importantly, total social welfare under the blend mandate is higher than under the renewable production subsidy; society bears a loss of 682 million dollars with blend mandate while society bears a loss of 5,155 million dollars with renewable production subsidy. In terms of cost of emissions saved/emitted per ton, blend mandate costs society about \$76 dollars to decrease a ton of emissions while renewable production subsidy costs society about \$1,105 dollars to decrease a ton of emissions.

From this, we conclude that blend mandate is a relatively more cost effective environmental policy compared to renewable production subsidy, since it puts an upward pressure on the consumer price and downward pressure on total consumption and by doing so also decreases non-renewable energy consumption and emissions. Lastly, blend mandate decreases emissions more with a lower cost to the society than renewable production subsidy does.

Table 7.1.3A Market and Welfare Effects of Increasing the Stringency of α without the Subsidy

	Laissez Faire (α_0, s_0)	Increase α, No s (α_2, s_0)	No α, Increase s (α_0, s_2)
P_E	146	153	131
S_{Total}	295	291	305
S_{TR}	20	70	73
S_{NG}	165	111	122
CO_2 Emissions	84	60	65
Environmental Cost	3115	2231	2389
Changes in			
Total Social Welfare	1703	-1013	-5328
Total Social Welfare + EC	1150	-682	-5155

Notes: All prices are in $/MWh, quantities are in million MWh, and emissions are in million tons.

7.2 The Interaction Effect of a Renewable Production Subsidy and a Blend Mandate

In this section, we compare selected pairs of policy scenarios to see the interaction effect between production subsidy for renewable energy and a blend mandate. We compare consumer electricity price, total electricity consumption, renewable energy consumption, and non-renewable energy consumption under different assumptions of levels of subsidy and mandate to see how the interaction effect changes the way renewable production subsidy and the blend mandate affects the market on their own.

For the purpose of this section, we now set s_2 to be a 20% increase from status quo renewable production subsidy s_1, instead of \$232/MWh as we have used when studying the effect of sole policy measures. As such, s_2 for wind is now set as \$55/MWh and for solar is \$165/MWh. Below is another policy box, with a different set of policy scenarios to help us find out the interaction effect of a subsidy and mandate. Tables 7.2.2–7.2.5 are provided for full market and welfare effects.

Table 7.2.1 Policy Box II

(α_0, s_0) 0% \$0, \$0	(α_0, s_1) 0% \$54, \$129	(α_0, s_2) 0% \$65, \$155
(α_1, s_0) 19% \$0, \$0	(α_1, s_1) 19% \$54, \$129	(α_1, s_2) 19% \$65, \$155
(α_2, s_0) 24% \$0, \$0	(α_2, s_1) 24% \$54, \$129	(α_2, s_2) 24% \$65, \$155

Note: Subsidies are in \$/MWh and are presented in the order of wind, then solar.

Table 7.2.2 Market Effects of Alternate Policy Scenarios relative to Status Quo

	Status Quo (α_1, s_1)	Increase α (α_2, s_1)	Increase s (α_1, s_2)	Increase α Increase s (α_2, s_2)
Price				
Consumer	143	147	142	146
Producer				
Renewable (Total)	91	115	85	109
Wind	145	169	150	174
Solar	220	244	240	264
Other renewable	91	115	85	109
Natural Gas	40	35	40	35
Quantity				
Consumer	297	294	297	295
Renewable (Total)	56	71	56	71
Wind	25	31	27	32
Solar	5	6	6	7
Other renewable	25	33	23	31
Non-Renewable (Total)	241	223	241	224
Natural Gas	131	114	132	114
Other non-renewable	110	110	110	110
Emissions				
Total Emissions	69	61	69	62
Environmental Cost	2562	2270	2569	2279
Carbon Leakage		16	19	17

Notes: All prices are in $/MWh, quantities are in million MWh, and emissions are in million tons. We assume η_W^s=1.3, η_S^s=1.7, η_{OR}^s=1.2, and η_{NR}^s=0.5

Table 7.2.3 Market Effects of Alternate Policy Scenarios relative to Laissez Faire

	Laissez Faire (α_0, s_0)	Introduce α (α_1, s_0)	Increase α (α_2, s_0)	Introduce s (α_0, s_1)	Increase s (α_0, s_2)	Carbon Tax $(\alpha_0, s_0) + t_c$
Price						
Consumer	146	147	153	142	141	158
Producer						
Renewable (Total)	53	117	141	49	48	50
Wind	53	117	141	103	113	50
Solar	53	117	141	178	203	50
Other renewable	53	117	141	49	48	50
Natural Gas	53	39	34	49	48	50
Quantity						
Consumer	295	294	291	297	298	288
Renewable (Total)	20	55	70	32	35	19
Wind	7	19	25	16	18	6
Solar	1	2	3	4	5	0
Other renewable	13	34	42	12	12	12
Non-Renewable (Total)	274	239	221	265	263	269
Natural Gas	165	129	111	156	153	159
Other non-renewable	110	110	110	110	110	110
Emissions						
Total Emissions	84	68	60	80	79	82
Environmental Cost	3115	2529	2231	2959	2922	3017
Carbon Leakage	22	18	15	22	22	19

Notes: All prices are in \$/MWh, quantities are in million MWh, and emissions are in million tons. We assume η_W^s=1.3, η_S^s=1.7, η_{OR}^s=1.2, and η_{NR}^s=0.5

Table 7.2.4 Welfare Effects of Alternate Policy Scenarios relative to Status Quo (in Million Dollars)

	Status Quo $(\alpha_1, \mathscr{s}_1)$	Increase α $(\alpha_2, \mathscr{s}_1)$	Increase $\mathscr{s}$ $(\alpha_1, \mathscr{s}_2)$	Increase α Increase $\mathscr{s}$ $(\alpha_2, \mathscr{s}_2)$
Changes in				
Consumer Surplus		-1287	289	-913
Producer Surplus (Total)		279	148	434
Wind		681	133	846
Solar		143	117	283
Other renewable		699	-141	513
NG		-657	21	-639
Baseload		-587	18	-569
Tax Cost		440	631	1175
Tax Revenue		-	-	-
Total Social Welfare		-1448	-193	-1654
Emissions		-8	0	-8
Environmental Cost		-292	7	-283
Cost of Emissions/ton		147		180
Total Social Welfare + EC		-1156	-200	-1372

Notes: For environmental cost, we assumed $25/ton cost for emissions.

Table 7.2.5 Welfare Effects of Alternate Policy Scenarios relative to Status Quo (in Million Dollars)

	Laissez Faire $(\alpha_0, \mathscr{s}_0)$	Introduce α $(\alpha_1, \mathscr{s}_0)$	Increase α $(\alpha_2, \mathscr{s}_0)$	Introduce $\mathscr{s}$ $(\alpha_0, \mathscr{s}_1)$	Increase $\mathscr{s}$ $(\alpha_0, \mathscr{s}_2)$	Carbon Tax $(\alpha_0, \mathscr{s}_0) + t_c$
Changes in						
Consumer Surplus	-964	-1310	-2999	183	450	-4305
Producer Surplus (Total)	599	-367	-82	419	457	-84
Wind	-1481	-610	-80	-870	-693	-1500
Solar	-490	-371	-311	-191	-84	-494
Other renewable	-717	788	1712	-767	-778	-748
NG	1890	-94	-738	1275	1137	1516
Baseload	1398	-79	-666	973	875	1142
Tax Cost	-2068	-2068	-2068	-700	-138	-2068
Tax Revenue	-	-	-	-	-	3974
Total Social Welfare	1703	391	-1013	1302	1045	1654
Emissions	15	-1	-9	11	10	12
Environmental Cost	554	-32	-331	398	360	455
Cost of Emissions/ton	77		76	84	70	97
Total Social Welfare + EC	1150	423	-682	904	684	1198

Notes: For environmental cost, we assumed \$25/ton cost for emissions.

7.2.1 The effect of renewable production subsidy on the blend mandate

In section 7.1.1, we saw how the renewable portfolio standard, aka blend mandate, affected the market. Now, by adding a renewable production subsidy into the market while maintaining the same level of α, we will see how the presence of renewable production subsidy changes the way blend mandate affects the market and social welfare.

We first start off with a zero subsidy scenario and proceed to adding production subsidy of \$54/MWh and \$129/MWh for wind and solar respectively, and then to adding an increased subsidy of \$65/MWh and \$155/MWh for wind and solar respectively. The first move will show us how the presence of subsidy changes the way mandate affects the market and second will show us how those effects change as we increase the amount of the subsidies.

Previously in section 7.1.1 when we studied the sole effect of blend mandate α, as α increased from α_0 to α_1 to α_2, consumer price of electricity rose from \$146/MWh to \$147/MWh to \$153/MWh, total consumption fell from 295 to 294 to 291 million MWh, and natural gas fired electricity fell from 165 to 129 to 111 million MWh. Naturally, with a decrease in non-renewable energy sources, emissions also fell from 84 to 68 to 60 million tons, and social welfare decreased from 1,150 to 423 to -682 billion dollars.

Now, we increase α with the same increments, from α_0 to α_1 to α_2 but now with a renewable production subsidy $\mathcal{s}_1$ added to the market. We subsidize wind with \$54/MWh and solar with \$129/MWh production subsidy. Consumer price of electricity now rises from \$142/MWh to \$143/MWh to \$147/MWh, total consumption falls from 297 to 296 to 294 million MWh, and natural gas fired electricity rises falls from 156 to 131 to 114 million MWh. Emissions fall from 80 to 68 to 60 million tons. Social welfare decreases from 904 to 0 to -1,156 billion dollars.

From these changes, we see that adding a renewable production subsidy to a blend mandate diminishes the effect of blend mandate as an environmental policy. When blend mandate and renewable production subsidy coexists, consumer price rises less, total consumption falls less, and non-renewable energy consumption falls less as well. As a result, the rate at which emission falls also decreases with presence of subsidy. Social welfare still decreases but now with a faster rate. We see that the benefits of α as an environmental policy is mitigated when α coexists with a renewable production subsidy.

Now, let's see how the amount of the subsidy changes the outcome. If we now assume production subsidy of \$65/MWh for wind and \$155/MWh for solar, then, as we increase the stringency of α, consumer price of electricity rises from \$141/MWh to \$142/MWh to \$146/MWh, total consumption falls from 298 to 297 to 295 million MWh, and natural gas fired electricity falls from 153 to 132 to 115 million MWh. Emissions fall from 79 to 70 to 62 million tons, and social welfare falls from 684 to -200 to -1,372 million dollars.

We see from this trend that higher the amount of subsidy, the further it erodes the benefit of the blend mandate. For example, under zero subsidy assumption, consumer price rises by \$1/MWh and \$6/MWh going from α_0 to α_1 to α_2. But under $\mathcal{s}_1$ and $\mathcal{s}_2$ assumption, consumer price rises by \$1/MWh and \$4/MWh going from α_0 to α_1 to α_2. The declining gap between increase in prices indicate as the amount of subsidy increases, the worse its effect on the incidence of α.

If we look at emissions, this trend still holds. Under zero subsidy assumption, emissions fall by 16 and 8 million tons going from α_0 to α_1 to α_2. Under $\mathcal{s}_1$ assumption, emissions fall by

11 and 8 million tons. Under s_2 assumption, emissions fall by 9 and 8 million tons. Again, the declining gap between decrease in emissions indicate that as the amount of subsidy increase, it interferes more with α's effectiveness as an environmental policy.

Tables 7.2.1A to Tables 7.2.1E show the trend of the consumer price of electricity, total consumption of electricity, natural gas fired electricity, total amount of emissions, and total social welfare as α increases, under different assumptions of amount of production subsidy.

Table 7.2.1A P_E ($/MWh)

146	142	141
147	143	142
153	147	146

Table 7.2.1B Q_T (million MWh)

295	297	298
294	296	297
291	294	295

Table 7.2.1C Q_{NG} (million MWh)

165	156	153
129	131	132
111	114	115

Table 7.2.1D Emissions (million tons)

84	80	79
68	69	70
60	61	62

Table 7.2.1E Δ Social Welfare
with Environmental Cost (million $)

1150	904	684
423	0	-200
-682	-1156	-1372

Note: Figures are relative to Status Quo

Let's now examine changes in social welfare. Without a renewable production subsidy, as α increases from α_0 to α_1 to α_2, social welfare with the environmental cost decreased from 1,150 to 423 to -682 million dollars. With a renewable production subsidy of $\mathcal{s}_1$, as α increases from α_0 to α_1 to α_2, social welfare decreases from 904 to 0 to -1,156 million dollars. We find that the direction of the change in social welfare stays the same (the welfare decreases both with α with and without the subsidy), but the size of the effect increases when we have a positive amount of production subsidy. Furthermore, the rate at which welfare decreases increases as we assume higher production subsidy. Under the $\mathcal{s}_2$ assumption, we find that social welfare decreases from 684 to -200 to -1,372 million dollars as α increases from α_0 to α_1 to α_2, whose rate at which the welfare decreases is faster than under the assumption of $\mathcal{s}_0$ and of $\mathcal{s}_1$.

From this, we find that the benefits of blend mandate as an environmental policy is mitigated with it coexists with a renewable production subsidy, and the higher the amount of subsidy, the worse its impact on the market. We conclude that blend mandate by itself is a relatively more effective environmental policy than renewable production subsidy and blend mandate put together, as all the positive effects of blend mandate decreases in size in conjunction with subsidies, and the presence of subsidy is detrimental to social welfare.

This is consistent with the way previous studies have viewed production subsidies for renewable electricity. Fell et al. (2012) have argued that the subsidies that are financed out of the tax revenue erodes the cost effectiveness of the policies because they render higher electricity consumption. Borenstein (2008) claimed that the subsidies for renewable sources are problematic because subsidizing renewable sources: 1) is different from taxing non-renewable sources 2) fails to recognize the heterogeneity among the renewable sources and among the non-renewable sources, and 3) addresses the policy goal only indirectly and might result in benefit leakage.

National research council (2013) also found that energy related tax subsidies have had ambiguous or almost no impact on reducing the emissions (in some cases they found energy sector subsidy contributing to US and global emissions.) and that the revenue forgone in the form of tax expenditure for renewable sources are substantial compared to the effects such subsidies had on the emissions. They also addressed the concern that the effects of many tax provisions are complicated by their interactions with regulatory policies such as RPS. They conclude that the most efficient way to reduce emissions is through pricing carbon, which is in agreement with our own findings.

7.2.2 The effect of blend mandate on the renewable production subsidy

In section 7.1.2, we saw how the renewable production subsidy affects the market as a sole policy parameter. Now, by adding a binding blend mandate into the market, we will see how the presence of binding blend mandate changes the way subsidy affects the market. We first add status quo mandate level of 19% and an increased level of 24% to see how the effects also change as we increase the stringency of the mandate.

Previously in section 7.1.2 when we studied the sole effect of renewable production subsidies, as subsidy increased from $\mathcal{s}_0$ to $\mathcal{s}_1$ to $\mathcal{s}_2$, consumer price of electricity fell from \$146/MWh to \$142/MWh to \$131/MWh, total consumption rose from 295 to 297 to 305 million MWh, and natural gas fired electricity fell from 165 to 156 to 122 million MWh.

Now, as we increase the renewable production subsidy from $\mathcal{s}_0$ to $\mathcal{s}_1$ to $\mathcal{s}_2$ while requiring α=19% of total consumption to come from renewable energy, consumer price of electricity falls from \$147/MWh to \$143/MWh to \$142/MWh and total consumption rises from 294 to 296 to 297 million MWh. What's interesting is that while in previous section when we were studying the sole effect of production subsidy, non-renewable electricity actually fell with an increase in the amount of subsidies, now with a presence of 19% blend mandate, natural gas fired electricity actually rises as we increase the subsidy. Natural gas fired electricity now rises from 129 million MWh to 131 and 132 million MWh, and emissions naturally also rises from 68 to 69 to 70 million tons. Social welfare decreases from 423 to 0 to -200 billion dollars, which shows a faster rate of decrease than when we were studying the sole effect of production subsidies.

Table 7.2.2A to Table 7.2.2E show us shows us such effects. In order to help the readers, the necessary boxes are bolded. Going from left to right on the first row of each policy boxes shows us the sole effect of renewable production subsidy while second and third rows show us the way how such effect changes with a blend mandate of 19% and 24% respectively.

Table 7.2.2A P_E ($/MWh)

146	142	141
147	143	142
153	147	146

Table 7.2.2B Q_T (million MWh)

295	297	298
294	296	297
291	294	295

Table 7.2.2C Q_{NG} (million MWh)

165	156	153
129	131	132
111	114	115

Table 7.2.2D Emissions (million tons)

84	80	79
68	69	70
60	61	62

Table 7.2.2E Δ Social Welfare
with Environmental Cost (million $)

1150	904	684
423	0	-200
-682	-1156	-1372

Note: Figures are relative to Status Quo

What is interesting here is the composition of the change in the total consumption, or put in other words, the difference in the direction of the non-renewable consumption change. Without the mandate, when we increased the amount of subsidy, total consumption rose but non-renewable consumption fell. With the mandate, as we increase the amount of subsidy, total consumption still rises but we find that non-renewable consumption also rises. For example, from scenario (α_1, s_0) to (α_1, s_1), total consumption rises by 2 million MWh, and this 2 million MWh increase mostly came from non-renewable energy. Same trend holds for going from scenario (α_1, s_1) to (α_1, s_2); total energy rose by one million MWh from which non-renewable energy consumption rose by one million MWh.

The presence of mandate also takes its toll on the emissions. Without the mandate, emissions fall as we increase the amount of subsidy, but with the mandate, emissions rise with the subsidy, which also means the environmental cost for the society rises at a faster rate.

Now, let's examine whether the sizes of the aforementioned effects change as we increase the stringency of the blend mandate. We now assume a blend mandate of 24% and see how that affects the market and welfare compared to when we don't have any blend mandate and to when we have a mandate of 19%.

With a blend mandate of 24%, as we increase the amount of subsidy from s_0 to s_1 to s_2, consumer price falls from \$147/MWh to \$143/MWh to \$142/MWh, total consumption rises from 294 to 296 to 297million MWh, and natural gas fired electricity consumption rises from 129 to 131 to 132 million MWh.

Such trends differ from the ones we saw when α=0 and α =19% in terms of the rate at which prices and quantities are changing. We see a fall in the price, increase in total consumption, and an increase in non-renewable energy, so we have the same direction of changes as we saw when α =19%. But we see that the sizes of the changes are larger now. While both α =0% and α =19% saw a decrease in consumer price of \$4/MWh and \$1/MWh going from s_0 to s_1 to s_2 respectively, alpha=24% sees a decrease in consumer price of \$6/MWh and \$1/MWh. While α=0 and α=19% saw an increase in total consumption of 2 million MWh and 1 million MWh respectively going from s_0 to s_1 to s_2, α=24% shows an increase of 3 million MWh and 1 million MWh.

So far, we have found that adding a positive level of mandate α to a renewable production subsidy decreases the consumer price more, increases total consumption more, increases fossil fuel consumption more, and thus increases the emissions more compared to when we just have a renewable production subsidy in the market. Total social welfare still decreases as subsidy rises, but the rate at which it decreases increases with blend mandate. Lastly, we also found that all such effects increase in size as we increase the stringency of α.

From this, we conclude that renewable production subsidy by itself is a relatively more effective environmental policy than renewable production subsidy and blend mandate put together. When both policies coexist, the already detrimental effect renewable production subsidy has on the market is worsened. Most importantly, non-renewable energy consumption rises as well as the emissions when we have both policies in the market, whereas the directions of these effects are flipped when we just have a subsidy.

Let's finish off this section by listing the two ways the presence of binding mandate affects the way subsidy affects the market: 1) When a binding mandate is present, consumer price falls more and the total consumption rises more, and 2) the production subsidy that should be subsidizing renewable energy ends up subsidizing non-renewable energy more which results in higher emissions This favorable effect the renewable subsidy has on the fossil fuel sources confirms that the renewable subsidy, combined with a binding mandate, goes against its original policy goal.

7.2.3. The interaction effect on the carbon leakage

Let's briefly look at how the interaction effect influences carbon leakage. Below in Table 7.2.3A we see a policy box with carbon leakage for each scenario cases. Carbon leakage under a carbon tax scenario is 19 million tons.

Table 7.2.3A Carbon Leakage
(million tons)

22	22	22
18	-	19
15	16	17

Let's first look at the sole effect of blend mandate and of renewable production subsidy.

We see that without the subsidy, as we increase the stringency of blend mandate α from α_0 to α_1 to α_2, carbon leakage declines from 22 to 18 to 15 million tons.

Without the blend mandate, as we increase the amount of renewable production subsidy $\mathscr{s}$ from $\mathscr{s}_0$ to $\mathscr{s}_1$ to $\mathscr{s}_2$, carbon leakage stays the same throughout as 22 million tons.

Now, let's assume a positive amount of production subsidy, $\mathscr{s}_1$. Then, as α rises from α_0 to α_2, carbon leakage falls from 22 to 16 million. This is a lower drop in carbon leakage compared to a no-subsidy scenario where carbon leakage dropped from 22 to 15 million tons. If we assume a production subsidy of $\mathscr{s}_2$, then, as α rises from α_0 to α_1 to α_2, carbon leakage falls from 22 to 19 to 17 million. Again, while in no subsidy scenario carbon leakage decreased by 4 million tons and 3 million tons, now with a higher amount of subsidy carbon leakage decreased by 3 million tons and 2 million tons. This is another example of how positive amount of renewable production subsidy negatively influences the way blend mandate α affects the market.

Let's now see how a positive level of blend mandate changes the way production subsidy itself affects carbon leakage. Assuming stringency of mandate level α_1, carbon leakage rises from 18 to 19 million tons as subsidy rises from s_1 to s_2. Assuming stringency of mandate level α_2, carbon leakage rises from 15 to 16 to 17 million tons. Compared with how under no mandate scenario carbon leakage stayed the same throughout increase in subsidy, we conclude yet again that the existence of blend mandate worsens the way subsidy affects carbon leakage.

7.2.4 Takeaway for the Interaction effect between the mandate and subsidy

From what we have gathered in the previous sections, we conclude that the interaction effect between blend mandate α and renewable production subsidy s is mutually harmful, because the presence of the subsidy mitigates the beneficial effect blend mandate α has on the market and presence of the blend mandate exacerbates the detrimental effect renewable production subsidy s has on the market.

With the presence of the subsidy, blend mandate increases the consumer price less, decreases total consumption less, decreases non-renewable energy consumption less, and thus decreases the emissions less, compared to when we only have a blend mandate. Overall, social welfare falls at a faster rate when we have a higher amount of subsidy.

With the presence of a binding blend mandate, subsidy decreases the consumer price more, increases total consumption more, increases non-renewable energy consumption (rather than decreasing it), and thus increases the emissions (rather than decreasing it) compared to when we only have a renewable production subsidy. Overall, social welfare falls at a faster rate when we have a stricter level of blend mandate.

If the policy makers were to choose a more effective environmental policy mix, they would end up with the lowest emissions with a strict blend mandate itself. But they should bear in mind such case also comes with a loss of welfare to the society, and if their goal is to find a cost-effective environmental policy mix, they should weigh both the change in welfare and the change in emissions to find the policy that best fits their goals.

In general, it is widely accepted by the previous literature, and confirmed again in our paper that as a lone policy parameter, renewable portfolio standard works better as an environmental policy than a renewable production subsidy because it puts an upward pressure on the price (albeit dependent on the relative elasticity of supply of renewable sources and non-renewable sources). Then, the question should be what would be the optimal stringency of α that emits the least emissions with the highest social welfare.

According to our model, the optimal blend mandate level that yields the highest social welfare of \$1,236 million dollars is 9.7%, and the optimal production subsidy level for wind and solar (assuming they receive the same amount of subsidy) is \$21/MWh, which yields social welfare of \$1,200 million dollars.

Under optimal blend mandate, the price to consumers is \$145/MWh, total energy consumption is 295 million MWh, total natural gas fired electricity consumption is 157 million MWh, and emissions are 81 million tons. This is a 3 million tons less of emissions compared to laissez faire, and 80 million dollars rise in social welfare.

Under optimal renewable production subsidy, the price to consumers is \$145/MWh, total energy consumption is 295 million MWh, natural gas fired electricity consumption 162 million

MWh, and emissions 83 million tons. This is a one million ton less of emissions compared to lasses faire, and a 50 million dollars rise in social welfare.

7.3 The Effect of an Optimal Carbon Tax

In this section we will analyze the effect of imposing an optimal carbon tax of $13.8/MWh on consumption[40]. Imposing a carbon tax acts as a price increase for the "dirtier" fuels. Since we can think of it as a price increase, it's natural that we see an increase in the consumer price of electricity, and decrease in the overall consumption. From laissez faire to carbon tax, our total consumption decreases by 7 million MWh. But from the 7 million MWh decrease, only one million MWh decrease came from the renewable sources and the other 6 million MWh decrease came from the non-renewable sources.

This is a stark comparison to the case where we increase renewable production subsidy with the presence of a blend mandate. In section 7.3.1, we found that when we increase the amount of subsidy, total consumption rises and that most of the increase comes from non-renewable energy and little from renewable energy. In this sense, carbon tax on its own is more effective as an environmental policy compared to renewable production subsidy combined with a binding mandate, as it supports the renewable energy more and ultimately decreases the environmental costs to the society.

Following the drop in the "dirtier" sources, carbon dioxide emissions also decrease three million tons, and environmental cost drops 455 million dollars.

What's interesting to see in the case of carbon tax, is that the total social welfare without the environmental cost is higher in laissez faire but total social welfare with the environmental cost

[40] We define optimal policy as the one that yields the highest change in social welfare relative to status quo.

is higher in the case of carbon tax. Without environmental cost, total social welfare under laissez faire is 49 million dollars higher than the carbon tax case, but with it, is lower by 48 million dollars. The relative size of the total social welfare between laissez faire and carbon tax would depend on the set of elasticity of supply for renewable and non-renewable energy, and the social cost of carbon we choose.

Overall, we see that carbon tax is the policy scenario that gives us the highest total social welfare, though not the lowest emissions and lowest environmental cost.[41] If our policy goal is to decrease the emissions no matter the amount and at the same time maximize social welfare (or minimize welfare loss) by doing so, carbon tax would be our best policy to achieve such goals.

[41] Social welfare under optimal blend mandate and optimal renewable production subsidy (mentioned in section 7.2.4) are higher than the social welfare under optimal tax, but the differences are minimal and considered as measurement errors.

Table 7.3.1 Market and Welfare Effects of Carbon Tax

	Laissez Faire (α_0, s_0)	Carbon Tax $(\alpha_0, s_0) + t_c$
P_E	146	158
S_{Total}	295	288
S_{TR}	20	19
S_{NG}	165	159
CO_2 Emissions	84	82
Environmental Cost	3115	3017
Changes in (relative to Status Quo)		
Total Social Welfare	1703	1654
Total Social Welfare + EC	1150	1198

Notes: All prices are in \$/MWh, quantities are in million MWh, and emissions are in million tons.

8. Conclusion

In this paper, we discussed the market effects and welfare effects of different levels of renewable portfolio standard and federal tax benefit for renewable energy in California electricity market. True costs for renewable electricity is very difficult to gauge, because there are costs specific to renewable energy that are often left out in their cost studies, and also because the interaction effect between federal level and state level support for the renewable electricity is understudied.

We found that the existence of both policies, renewable portfolio standard and tax benefits for renewable energy, are less effective and less conducive to decreasing emissions compared to just having a sole policy in the market. Specifically, renewable production subsidy interferes with the way renewable portfolio affects the market, because it lessens the downward pressure on the consumer price and the upward pressure on the total consumption of electricity. As a result, we end up with more emissions when we have production subsidy on top of a blend mandate compared to when we just have the mandate. The most effective environmental policy is having renewable portfolio standard (blend mandate) by itself, without any production subsidies. The stricter the mandate, the more emissions it will decrease, but it also comes with a loss in social welfare so it's best to weigh both gains and losses before setting the optimal stringency level. We also found the most cost-effective environmental policy to be carbon tax, as it maximizes welfare gain (or minimizes welfare loss) while still decreasing emissions.

As such, choosing an optimal environmental policy would depend on the policy goals of the state. If the goal is to minimize emissions, a sole policy of blend mandate would be best, and if the goal is to minimize welfare loss while still decreasing emissions, the state should put a price on carbon.

It should be noted that our model is sensitive to assumptions of price elasticity of supply for renewable electricity and for non-renewable electricity. We chose the figures based on past literature and talking to the experts in CEC, and further provide how the results would change with different assumptions of elasticities in the Appendix.

As part of the future work, we can extend such analysis to other renewable policies such as cap and trade. The cap and trade came into effect on 2013 in California and requires large electric power plants to hold enough emission allowances, where such allowances are freely traded in the open market. It would be interesting to see the way cap and trade system interacts with RPS in California, especially when both serves similar functions. Since we also learned that the model is sensitive to price elasticity of supply for renewable and non-renewable sources, it would be insightful to see how the results change with different ranges and sets of elasticities.

APPENDIX

Appendix A. Calculation of Total Social Welfare

The change in consumer surplus is calculated by:

$$\Delta CS = (P_1 - P_0)(Q_1 + \frac{1}{2}(Q_0 - Q_1)) \tag{32}$$

The change in producer surplus is calculated by:

$$\Delta PS = (P_0 - P_1)(Q_1 + \frac{1}{2}(Q_0 - Q_1)) \tag{33}$$

Where in case of producer surplus, P_0 is the baseline market price for different types of energy each producer receives, and P_1 is the changed market price each producers receive under a policy scenario. Q_0 is the baseline production of each energy and $Q_1$is the changed production of each energy with different scenario changes. Tax cost is calculated by:

$$\Delta Tax\ cost = (\mathcal{s}_{w1}Q_{W1} + \mathcal{s}_{S1}Q_{S1}) - (\mathcal{s}_{w0}Q_{W0} + \mathcal{s}_{S0}Q_{S0}) \tag{35}$$

Total surplus is simply calculated by taking the sum of all the aforementioned elements.

$$\Delta TS = \Delta CS + \Delta PS_w + \Delta PS_S + \Delta PS_{OR} + \Delta PS_{NR} + \Delta Tax\ Cost \tag{39}$$

Appendix B. Two Directional Changes in P_E

We consider six different scenarios under two cases, where in the first case, the price of electricity rises as the blend mandate α rises, and in the second case, the price of electricity falls as α rises. In the first case, we set the price elasticity of supply for RPS-eligible renewables as 0.2 and for non-RPS eligible sources such as natural gas and baseload as 8. In the second case, the elasticities are reversed. The big gap in the elasticities can be explained by the increasing strictness of α; The stricter the blend mandate, bigger gap is required between the elasticity of supply for renewable and non-renewable sources in order for consumer price of electricity to rise and fall as mandate rises. We start off with the status quo value of 0.19, and increase this figure to 0.33 in different scenarios, which is the level California is expected to reach by year 2030. As the strictness in alpha increases, the gap between the elasticities also has to get bigger in order for the consumer price to fall with the rise in α.

We see from comparing columns one, two, and three that under the assumptions of case (1), consumer price of electricity falls as blend mandate rises from $\alpha_1$to α_2, but rises under the assumptions of case (2). We see from here that the direction of the change in consumer price of electricity is dependent on the relative elasticity of supply for renewable and non-renewable sources.

Table A-B1. Market Effects of Alternate Policy Scenarios under Two Elasticity Cases

	Status Quo	*Laissez Faire*		Carbon Tax		Increase α		No Subsidy		Increase α No Subsidy		Increase Subsidy	
		(1)[42]	(2)[43]	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)
Price													
Consumer	143	134	176	146	168	245	142	147	145	251	149	142	142
Producer													
Renewable (Total)	91	41	83	41	86	381	102	112	105	401	123	87	86
Wind	145	41	83	41	86	435	156	112	105	401	123	151	150
Solar	220	41	83	41	86	510	231	112	105	401	123	226	225
Other renewable	91	41	83	41	86	381	102	112	105	401	123	87	86
Natural Gas	40	41	83	41	74	38	22	40	39	38	22	40	40
Quantity													
Consumer	297	302	279	295	283	252	297	294	295	250	293	297	297
Renewable (Total)	56	22	7	22	15	83	98	55	55	83	97	56	56
Wind	25	0	0	0	0	36	41	24	0	34	0	26	34
Solar	5	0	0	0	0	7	8	5	0	6	0	5	7
Other renewable	25	22	7	22	15	41	49	26	55	42	97	25	16
Non-Renewable (Total)	241	280	271	273	267	169	199	239	240	168	196	241	241
Natural Gas	131	171	162	163	158	60	90	129	130	58	87	131	132
Other non-renewable	110	110	110	110	110	110	110	110	110	110	110	110	110
Emissions													
Total CO_2 Emissions	69	87	83	84	81	36	51	68	70	35	51	69	69
Change in Emissions		18	13	14	12	-33	-19	-1	0	-34	-19	0	0
Cost per ton to Society		106	164	20	760	266	208	-69	2,755	261	116	-120	4,911

Notes: All prices are in \$/MWh and quantities and emissions are in million MWh.

[42] Column (1) refers to the case where the consumer price of electricity goes up with an increase in the blend mandate α (we assume η_R^s=0.2 and η_{NR}^s=8).
[43] Column (2) refers to the case where the consumer price of electricity goes down with an increase in α (we assume η_R^s=8 and η_{NR}^s=0.2).

Table A-B2. Welfare Effects of Alternative Policy Scenarios relative to Status Quo (in Million $)

	Laissez Faire		Carbon Tax		Increase α		No Subsidy		Increase α No Subsidy		Increase Subsidy	
	(1)[44]	(2)[45]	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)
Consumer Surplus	2628	-9,506	-895	-7,191	-27,917	258	-1,196	-580	-29,592	-1,759	189	174
Producer Surplus (Total)	-2787	9,613	-2,827	-7,536	19,772	-2,998	-807	-454	18,667	-2,463	120	180
Wind	-1319	-788	-1,321	-741	8,861	370	-801	-509	7,664	-271	168	171
Solar	-483	-370	-483	-360	1,776	72	-551	-311	1,060	-260	26	35
Other renewable	-1174	-129	-1,176	-87	9,553	414	555	559	10,372	1,985	-85	-85
NG	110	6,241	88	4,965	-195	-1,936	-5	-105	-199	-1,955	1	33
Baseload	79	4,659	65	3,759	-224	-1,919	-5	-88	-230	-1,962	1	27
Tax Cost	-2068	-2,068	-2,068	-2,068	735	1,129	-2,068	-2068	-2,068	-2,068	327	989
Tax Revenue			1,946	1,883								
Total Social Welfare	1,910	2,176	4,389	10,746	-8,880	-3,869	65	1,034	-8,857	-2,153	-18	-634

Notes: We assume $25/ton for the cost of carbon dioxide equivalent to the society.

[44] Column (1) refers to the case where the consumer price of electricity goes up with an increase in the blend mandate α (we assume η_R^s=0.2 and η_{NR}^s=8).
[45] Column (2) refers to the case where the consumer price of electricity goes down with an increase in α (we assume η_R^s=8 and η_{NR}^s=0.2).

Appendix C. P_E falls as α rises with lower α and sufficiently elastic renewable supply curve

Table A-C1 and A-C2 shows the market effects and welfare effects respectively when we assume η_w^s=1.7, η_s^s=2.7, η_{OR}^s=1.5, and η_{NR}^s=0.4. Compared to the elasticity assumptions used in the text, Tables A-C1 and C2 assume higher elasticities for supply for each renewable sources and lower elasticity for supply for natural gas fired electricity. In this case, the consumer price of electricity still rises as blend mandate α jumps from α_1 to α_2, but falls as α jumps from α_0 to α_1. This is consistent with the findings of Fischer (2006) and de Gorter and Just (2009) where they argued that blend mandate can decrease consumer price of electricity or of fuel depending on the relative elasticity of supply for renewable and non-renewable sources and on the strictness of the blend mandate. With more elastic supply for renewable sources and more inelastic supply for non-renewable sources, combined with a less strict blend mandate, we see that it is indeed possible for the consumer price of electricity to fall as mandate increases.

Table A-C1. Market Effects of Alternate Policy Scenarios

	Status Quo (α_1, s_1)	*Laissez Faire* (α_0, s_0)	Carbon Tax $(\alpha_0, s_0) + t_c$	Increase α (α_2, s_1)	No s (α_1, s_0)	Increase α No s (α_2, s_0)	Increase s (α_1, s_2)	Increase α Increase s (α_2, s_2)
Price								
Consumer	143	153	162	157	148	167	142	156
Producer								
Renewable (Total)	91	60	57	141	120	171	86	137
Wind	145	60	57	195	120	171	150	201
Solar	220	60	57	270	120	171	225	276
Other renewable	91	60	57	141	120	171	86	137
Natural Gas	40	60	57	26	39	25	40	26
Quantity								
Consumer	297	291	286	288	294	283	297	289
Renewable (Total)	56	12	11	95	55	93	56	95
Wind	25	0	0	41	18	33	27	42
Solar	5	0	0	9	0	2	6	9
Other renewable	25	12	11	46	37	58	23	44
Non-Renewable (Total)	241	278	274	193	239	190	241	194
Natural Gas	131	169	165	84	129	80	132	84
Other non-renewable	110	110	110	110	110	110	110	110
Emissions								
Total CO_2 Emissions	69	86	84	48	68	46	69	48
Δ in Emissions		17	15	-22	-1	-23	0	-21
Cost of Emission/ton		100	113	194	-631	153	-1152	203
Carbon Leakage		21	18	11	18	9	19	11

Notes: All prices are in \$/MWh, quantities are in million MWh, and emissions are in million tons. We assume η_w^s=1.7, η_s^s=2.7, η_{OR}^s=1.5, and η_{NR}^s=0.4

Table A-C2. Welfare Effects of Alternate Policy Scenarios relative to Status Quo (in Million Dollars)

	Status Quo (α_1, s_1)	*Laissez Faire* (α_0, s_0)	Carbon Tax $(\alpha_0, s_0) + t_c$	Increase α (α_2, s_1)	No s (α_1, s_0)	Increase α No s (α_2, s_0)	Increase s (α_1, s_2)	Increase α Increase s (α_2, s_2)
Changes in								
Consumer Surplus		-2980	-5587	-4217	-1405	-6900	218	-3,819
Producer Surplus (Total)		3017	2281	745	-117	735	100	849
Wind		-1080	-1110	1671	-532	773	142	1,904
Solar		-432	-438	359	-269	-184	30	409
Other renewable		-573	-602	1792	914	3331	-110	1,595
NG		2951	2548	-1524	-125	-1565	20	-1,517
Baseload		2152	1883	-1552	-105	-1619	17	-1,542
Tax Cost		-2068	-2068	1251	-2068	-2068	461	1,904
Tax Revenue			3284					
Total Social Welfare		2106	2046	-4723	546	-4096	-144	-4,873
Environmental Cost	1731	2151	2099	1192	1708	1156	1734	1197
Changes in								
Environmental Cost		420	368	-539	-23	-575	3	-534
Total Social Welfare +EC		1686	1670	-4184	568	-3522	-147	-4339

Notes: For environmental cost, we assume \$25/ton cost for emissions. We assume η_w^s=1.7, η_S^s=2.7, η_{OR}^s=1.5, and η_{NR}^s=0.4

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