The Efficiency and Sectoral Distributional Impacts of Large-Scale Renewable Energy Policies

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Abstract: Renewable energy policies have grown in popularity. Given that renewable energy costs are mostly nonmarginal, due to the large presence of fixed costs, there are many different ways to implement these policies in both the environmental design and retail pricing margins. I show that the efficiency and distributional implications of large-scale policies crucially depend not only on the design of wholesale policies to incentivize renewables but also on how the costs of such policies are passed-through to consumers. Using data from the California electricity market, I develop a model to illustrate the interaction between large-scale renewable energy policies (carbon taxes, feed-in tariffs, and renewable portfolio standards) and their pricing to final consumers under alternative retail pricing schemes (no pass-through, marginal fees, fixed flat tariffs, and Ramsey pricing). I focus on the trade-off between charging residential versus industrial consumers to highlight tensions between efficiency, distributional, and environmental goals.

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LARGE-SCALE RENEWABLE ENERGY policies have become ubiquitous in the United States and many other countries. While most policies share the common pursuit of encouraging investment in renewable resources (mostly wind and solar), their implementation varies substantially across jurisdictions. For example, some countries have opted to provide feed-in tariffs to renewable producers, which offer guaranteed retri-

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bution for renewable generation at regulated rates. Other countries offer a complement or a subsidy to the wholesale electricity market price. Some markets have opted for market-based solutions, establishing targets regarding the percentage of renewable energy generation, with renewable portfolio standards (RPS). Finally, some countries have also established carbon prices. While not specifically targeted to renewable generation, carbon prices encourage investment in cleaner technologies.

In this paper, I study the efficiency and distributional impacts of alternative large-scale renewable energy policies in wholesale electricity markets. I focus on the trade-off between their efficiency as a mechanism to reduce greenhouse gases (GHGs), and their cost incidence on consumers and producers. While cost-effectiveness is an important dimension when evaluating renewable energy policies (Fell and Linn 2013), their distributional implications are also an important dimension to consider (Goulder and Parry 2008).

Carbon taxes can be the efficient mechanism to reduce GHGs at their optimal Pigouvian level; however, they tend to increase electricity prices. Such price increases have often generated windfall profits for incumbent producers, particularly if implemented as a cap-and-trade program with grandfathered permits. In such a setting, the impact of the policy is a rent transfer from consumers to producers.[1] Renewable subsidies, in contrast, tend to depress wholesale prices by stimulating entry from cheaper sources at the margin. Such entry can potentially generate a transfer of rents from traditional producers to consumers.[2]

Simulation studies looking at the impact of large-scale renewable energy policies often assume that final consumers face real-time wholesale prices, which tend to increase under carbon taxes but fall in the presence of renewable subsidies (Fischer and Newell 2008; Palmer et al. 2011; Fell and Linn 2013; Wibulpolprasert 2014). In the absence of explicit charges to final consumers, the costs of subsidizing renewable investments can be seen as a fixed cost that may be recovered in a lump-sum fashion, for example, by raising taxes elsewhere in the economy. Yet, in practice, final prices to consumers can differ substantially from wholesale prices and often include renewable taxes or fees that increase the marginal consumer price of electricity. Indeed, as discussed in Borenstein (2016), the recovery of fixed costs by utilities is a growing problem, and it often involves distorting retail prices at the margin.

1. For example, Fabra and Reguant (2014) document a high degree of pass-through of carbon costs to electricity prices in the Spanish electricity market, which generated substantial windfall profits for incumbent producers and a substantial increase in the costs of electricity for final consumers.

2. For example, Liski and Vehviläinen (2016) document that renewable subsidies have reduced electricity costs in the Nordic electricity markets, largely benefiting renewable producers and consumers.

The contribution of this paper is to extend simulation models to explicitly model how renewable costs are passed-through to consumers. I examine how this retail design interacts with alternative environmental policies, finding that incorporating retail design can change or revert earlier results under wholesale pricing. A broad takeaway is that the efficiency and distributional effects of large-scale renewable energy policies depend substantially on the interaction between renewable energy policies and the retail tariff design. Therefore, evaluations of renewable policy design are incomplete without accounting for retail pricing.

I build an electricity investment model with competitive entry by natural gas, solar, and wind producers. New firms enter the market until the break-even point. The electricity wholesale price is determined at each hour, clearing the market by equating demand and supply. To quantify the interaction between environmental policies and retail design, I use data from the California market between 2011 and 2015 on power generation from each source, generation capacity, and prices. Demand and price data are used to calibrate demand from the three consumer classes (industrial, commercial, and residential). Power plant data are used to calibrate the supply of existing generators. Engineering cost estimates and renewable output data are used to calibrate capital costs and relative performance of potential new investment (natural gas, wind, and solar).

In the baseline model, consumers pay the wholesale price of electricity and there are no environmental policies. I then consider three environmental policies: a carbon tax, a feed-in tariff, and a renewable portfolio standard. Environmental policies affect wholesale prices by either increasing producers' marginal costs in the case of a carbon tax or by reducing renewable marginal costs due to the presence of a subsidy. Given the partial equilibrium nature of the exercise, I focus on the case in which renewable subsidies are funded explicitly within the electricity sector, as opposed to being funded by taxes elsewhere in the economy. I allow for environmental policies to impact retail prices, either as part of the policy design (e.g., as in the case of renewable portfolio standards) or indirectly as a way to raise the revenue necessary to fund the cost of the environmental policy (e.g., to pay for renewable subsidies).

I consider three alternative retail tariffs: flat tariffs high enough to recover the renewable energy policy costs, a marginal renewable charge added to the wholesale price that ensures cost recovery, and Ramsey prices that are constant but can differ across customer classes (residential, commercial, and industrial). It is not uncommon for environmental-related charges to differ between residential and industrial customers, raising questions about the distributional implications of such burdens. I explicitly consider mechanisms that differentially charge consumers in different classes, analyzing the merits of such practices from an efficiency and distributional point of view.

There are several takeaways that arise from the simulation results. First, in line with the literature, carbon prices are substantially more efficient at reducing GHGs than explicit renewable energy policies, in the absence of additional justifications to fund renewable investments. Reducing emissions by 10% has average abatement costs in the order of $12/ton for the case of a carbon tax, but they are up to $78/ton for the case of RPS and close to $185/ton for the case of a feed-in tariff. The advantage of the carbon tax is due to two main channels: natural gas has a substantial cost advantage when compared to renewable generation in the baseline simulation, and carbon taxes also encourage demand reductions as they signal the externality at the margin. Due to this increase in prices, consumers particularly suffer from a carbon tax. Producers of hydro and nuclear are the clear winners. That said, such transfer of rents can be partially mitigated with the use of revenues from carbon taxes, although such rebating, if performed at the margin, undermines the environmental objectives.

As a second takeaway, I find that renewable energy policies are substantially more cost-effective if their associated renewable payments are reflected in retail prices. In a context like renewables, fixed costs account for most of the total cost, and therefore passing-through costs at the margin is typically inefficient. However, such charges help circumvent a major limitation of renewable energy policies: they do not explicitly price the externality coming from pollution and might artificially depress wholesale prices.[3] If renewable costs are priced into retail tariffs, I find that the performance of alternative mechanisms (feed-in tariff vs. RPS) is comparable, with average abatement costs around $78/ton, although still less efficient than a carbon tax. The distributional implications on the producer side are still substantially different between renewable energy policies and carbon taxes, with renewable producers being the clear winners, and preexisting generation suffering from the still artificially low wholesale prices.

As a final takeaway, when looking at alternative retail tariffs, I find that Ramsey prices do not maximize welfare when accounting for the presence of a pollution externality, as highlighted also by the transportation literature (Oum and Tretheway 1988). Ramsey prices that maximize welfare in the electricity market do not account for the cost of the externality, as the wholesale price signal is distorted in the absence of a carbon tax. In fact, I find that recovery of costs under Ramsey pricing is less efficient than a simpler flat rule. Even though increasing retail rates more steeply to residential customers can be justified due to their more inelastic demand, the implicit transfer to industrial customers hampers their incentives to reduce demand. Given that industrial customers are the most price-sensitive consumers, such implicit reward reduces demand reductions as a source of emissions abatement. Importantly, this result is subject to the assumption that electricity reductions in the industrial sector are one to one associated with emissions reductions. If one instead assumes that emissions in the industrial sector would leak, due to self-generation or relocation of production, then passing-through renewable charges only to residential customers can be more efficient. The

3. Accounting for the additional benefit of avoiding distortionary taxes elsewhere in the economy reinforces this result.

result highlights the importance of addressing leakage concerns in the industrial sector if the industrial sector is expected to contribute with emissions reductions.

Several papers have examined the distributional and efficiency impacts of energy and environmental policies.[4] Bento et al. (2009) examine the distributional and efficiency impacts of gasoline taxes, using a structural model of household car choice. Borenstein and Davis (2012) examine the impacts of energy tax credit using tax return data, finding that they are substantially more regressive than other policies. Böhringer et al. (2012) focus on the equity implications of alternative ways to regulate emissions leakage. Borenstein and Davis (2016) and Borenstein (2015) study the distributional implications of clean energy US tax credits and solar photovoltaic (PV) subsidies in California, respectively. Feger et al. (2017) also examine the distributional implications of rooftop solar using data from Switzerland and compute optimal tariffs to attenuate distributional impacts. I contribute to this literature by focusing on the more aggregate trade-off between different customer classes and abstract away from redistributional issues within the residential sector.

A large literature examines the impacts of environmental policies in a general equilibrium setting, taking into account the impacts of environmental regulations on several sectors of the economy. Fullerton and Heutel (2007; 2010) present a theoretical model to study the impacts of environmental taxes and mandates. Goulder et al. (2016) examine the impact of federal clean energy standards, and highlight its potential advantage over carbon taxes in the presence of preexisting distortions in capital markets. Rausch et al. (2011) present a general equilibrium model of the United States with detailed household-level data to study the impact of alternative carbon pricing schemes on income groups. I abstract away from these important general equilibrium issues by focusing on the case in which revenues for renewable subsidies are raised within the electricity sector.

The modeling approach I utilize is closest to the literature examining the design of environmental policies in the specific context of electricity markets (Fischer and Newell 2008; Palmer et al. 2011). The model that I develop is closely related to Bushnell (2010). The environmental policies I consider follow Fell and Linn (2013), to which I add retail tariffs and customer classes. The paper is also closely related to Bushnell et al. (2015), who build a model of the Western interconnection to understand the impacts of the Environmental Protection Agency's Clean Power Plan, emphasizing the distributional implications between consumers and producers, as well as different regions within the interconnection. Abrell et al. (2017) explore the impact on retail prices from renewable energy policies in Germany and Spain, using also a supply model with retail pricing.

The paper proceeds as follows. Section 1 motivates the importance of understanding the interaction between renewable energy policies and retail design, with a discus-

4. See Bento (2013) for a more detailed review.

sion about their efficiency and distributional impacts. Section 2 presents the model used to simulate alternative policies. Section 3 presents the data used to calibrate the model. Section 4 presents the main results, and section 5 concludes.

1. CONTEXT AND MOTIVATION

1.1. Large-Scale Renewable Energy Policies

Large-scale renewable energy policies can take many forms. I consider three of the main large-scale renewable energy policies that are used in practice to incentivize renewable production:[5]

1. *Carbon tax*. A tax on CO_2 emissions from polluting resources, such as gas and coal. Albeit not explicitly a renewable policy, it taxes other technologies that compete with renewable generation, making them more attractive at the margin.
2. *Feed-in tariff*. It provides a flat payment to renewable technologies per megawatt-hour (MWh) of production, which is guaranteed over a certain period of time, either constant or with a known schedule. A related policy is a production subsidy, which provides a complement to the wholesale price per MWh to renewable generation, often also targeted to specific technologies.
3. *Renewable portfolio standard (RPS)*. A requirement that retailers procure a certain share of their electricity from renewable sources. Firms can trade renewable electricity certificates (RECs) to ensure their compliance with the target.

Note that there are other renewable energy policies that directly encourage investment, for example, through production tax credits (PTCs) or investment tax credits (ITCs), and which are often targeted to specific technologies. While not the focus of this paper, I take ITCs as given in the empirical model, as a complement to the above policies.[6]

With the exception of carbon taxes, most renewable energy policies incentivize renewable generation explicitly, instead of taxing the pollution externality. Therefore, when looking at wholesale electricity prices, many renewable energy policies have an effect of depressing wholesale marginal prices, in spite of increasing total production

5. These alternative policies follow Fell and Linn (2013) closely.

6. Allowing for complementary ITC policies is important to rationalize the presence of solar investment in the data. Therefore, I include such incentives as a complement to all policy scenarios. PTCs are not strictly part of the simulations, but they can be considered as part of the equilibrium RPS price, as they are also proportional to output. To make the comparison more stark, I abstract away from PTCs when considering a carbon tax policy.

Table 1. Large-Scale Renewable Energy Policies and Their Price Impacts

Policy	Wholesale Prices	Retail Impacts	Notes
Carbon tax	Tend to increase	Passed-through by design	A carbon tax is reflected at the margin at the wholesale level; at the retail level, it depends on how rates are set. Under real-time pricing, carbon taxes signal the pollution externality to both producers and consumers.
Feed-in tariff	Tend to decrease	Indetermined	Feed-in tariffs do not account for heterogeneity at the margin and are not passed-through to retail prices explicitly.
Production subsidy	Tend to decrease	Indetermined	Production subsidies are a complement to wholesale prices, providing a market-value signal to renewable sources. Depending on cost recovery, they might not be directly passed-through to consumers.
RPS	Tend to decrease	Passed-through by design	Renewable sources see their effective opportunity cost reduced by the RPS price, acting as an implicit subsidy. Because retailers are responsible for acquiring credits, RPS costs will tend to be passed-through to final retail consumers. There might be heterogeneity on how such costs are charged.

Note. This table summarizes the main features of alternative large-scale renewable energy policies. The key differences are on whether incidence is at the wholesale or retail level, whether the signal is marginal with regards to the market price (carbon tax, RPS, and subsidy), and whether the signal is marginal with regard to the externality (carbon tax). As stated in the table, retail impacts are very dependent on how renewable costs are passed-through to consumers. RPS = renewable portfolio standards.

costs. Previous research has emphasized the negative effect of depressed electricity prices, which is counter to the environmental goal of reducing emissions. In this setting their impact on final prices is unclear, as it depends on whether renewable prices are passed-through at the retail level.

Table 1 provides a summary of alternative policies and their impacts on wholesale and retail prices. A carbon tax will tend to increase wholesale prices. On the contrary, the other policies will tend to reduce wholesale prices.[7] Does this mean that end consumers will face lower prices at the margin? The retail impacts can be quite ambiguous, and they will depend heavily on tariff design. By default, the carbon tax and the

7. Note that wholesale prices also tend to decrease in the presence of RPS policies, as the burden of RPS obligations is typically imposed on the retailers, not the generators.

RPS design will be reflected in retail prices, tending to increase them.[8] Other renewable support schemes might impact retail prices if these are recovered within the electricity market, but not necessarily if these are funded with revenue from other taxes, for example, through federally funded programs.

1.2. Retail Tariff Design and Ramsey Pricing

When designing renewable energy policies, two important questions arise. How are the costs of environmental policies recovered in the long run? What are the implications from an efficiency and distributional point of view? Studies have often considered the impact from wholesale policies in a stylized fashion, assuming consumers face the wholesale market price (Fell and Linn 2013; Wibulpolprasert 2014). However, wholesale prices are seldom the prices that final consumers face. For example, most customers do not directly face real-time wholesale prices. Therefore, even when carbon taxes signal the environmental externality to investors in real time, it is less clear that such an externality signal is transferred to end consumers at a high frequency.

It has been common that increased renewable presence causes depressed electricity prices at the wholesale level. This often coincides with retail price increases at the residential level to fund the costs of renewable energy (explicitly in the case of renewable portfolio standards, but often in the case of direct subsidies).[9] Alternatively, these increased costs might be funded through tax increases elsewhere in the economy, for example, with revenues from income taxes.[10]

I focus on renewable energy policies that recoup investment costs within the electricity market, either by having direct impacts on wholesale market prices or by funding additional payments through retail tariffs. I consider four different ways in which renewable costs are recouped through retail tariffs:

(*a*) *Flat tariffs with lump-sum fees (baseline)*. Environmental policies do not affect retail prices at the margin other than through their effects on wholesale prices.

(*b*) *Flat tariffs with marginal renewable fees*. Prices are constant and sufficiently high to recover both production and environmental costs, independently of whether environmental costs are reflected in wholesale prices.

8. Note that RPS does not necessarily increase retail prices, as discussed in Fischer (2010).

9. For example, Spain has a very aggressive subsidy and feed-in tariff program for both wind and solar. In spite of substantial drops in wholesale prices, renewable charges to end consumers have put substantial upward pressure on final prices at the retail level. Germany has had similar experiences with substantial increases in renewable charges. See Frondel et al. (2015) for an examination of the distributional impacts in Germany.

10. General equilibrium effects from funding these policies are an important issue but not the focus of this paper.

(*c*) *Real-time prices with marginal renewable fees*. Additional marginal fees are added to wholesale prices (instead of flat tariffs), to recover both production and environmental costs.

(*d*) *Ramsey retail tariffs*. Prices are constant and also sufficiently high to recover both production and environmental costs but can differ across customer classes (residential, commercial, and industrial).

As is well known, Ramsey prices recommend higher prices to the less price elastic consumer types. In the simplest setting in which the environmental policy is taken as given (e.g., the level of the feed-in tariff), traditional Ramsey prices recommend,

$$\frac{p_s - c}{p_s} = \frac{\lambda}{1 + \lambda}\frac{1}{\epsilon_s},$$

where s indexes a given sector and ϵ_s represents its elasticity of demand, and λ is the shadow value of the revenue-raising constraint, which establishes that profits need to equal total costs (marginal and fixed). Typically, Ramsey prices are not explicitly derived in practice, but many of the arguments justifying lower prices to the industrial sector are related to the potential relocation of industrial production (i.e., higher elasticity).

In the model and quantitative exercise, I examine whether such a prescriptive result can rationalize charging the residential sector more heavily and whether it is still socially optimal in the presence of environmental goals. Indeed, in many markets renewable subsidies are utilized without accounting for environmental externalities (or pricing them below the social cost of carbon (SCC)). Therefore, Ramsey prices as typically prescribed might not correlate one to one with environmental goals. If prices do not reflect the externality, then optimal Ramsey prices become:

$$\frac{p_s - c}{p_s} = \frac{\lambda}{1 + \lambda}\frac{1}{\epsilon_s} + \frac{1}{1 + \lambda}\frac{e_s \times \mathrm{SCC}}{p_s},$$

where e_s is the marginal emissions rate from consumption by sector s.[11] In the presence of both a revenue-raising component and an environmental externality, the additional externality term brings prices closer together in relative terms as long as e_s is the same for all sectors.[12] Intuitively, if there is no revenue-raising motive ($\lambda = 0$), then the price equals marginal cost plus the environmental externality. Note that, if one still

11. This can be derived in a traditional Ramsey framework by modifying the objective function to include the externality from emissions times the social cost of carbon.

12. In the presence of industrial leakage, the marginal emissions rate from reducing consumption is not necessarily equal across sector, in which case optimal Ramsey prices may not become more similar.

enforces the zero profit condition typical in a Ramsey setting, it can even be that the zero-profit constraint binds from below ($\lambda < 0$). This could happen if the renewable target is not in line with the social cost of carbon, and a carbon tax raises revenue above and beyond the costs of the renewable policy. In such a case the result is reversed and more elastic consumers should be taxed more. I evaluate the distributional implications of these Ramsey designs in section 4.4.

1.3. Efficiency and Distributional Implications

Due to their different designs, environmental policies have seldom the same efficiency and distributional implications, even conditional on achieving a certain emissions target. Furthermore, as explained above, such environmental policies interact with retail design, which also impacts both the efficiency and distributional implications of these policies. Before presenting the model and empirical implementation, I discuss the potential impacts of these policies.

1.3.1. Impacts to Producers

The effects of environmental policies on producers depend quite heavily on their implementation and vary considerably across technologies. Existing generation sources tend to suffer losses in the presence of explicit large-scale renewable energy policies, as these policies encourage the entry of resources that are very cheap at the margin. The costs will be particularly acute if renewable entry is large enough to substantially affect the distribution of wholesale prices in those hours of highest demand, which tend to provide a large share of revenues to incumbents. Carbon taxes, in contrast, are not necessarily detrimental to incumbent producers. Due to the impact of carbon taxes on wholesale prices, incumbent producers will tend to benefit if they are relatively clean with respect to the marginal producer. For example, hydro and nuclear power plants will benefit favorably from such policies.

Renewable technologies, as highlighted by other studies (Joskow 2011; Borenstein 2012a; Callaway et al. 2015), have distinct benefits at the margin, which can depend on the correlation of generation with demand or the existing generation mix in a given area. Several studies have examined the contributions of renewable sources in reducing emissions and also in displacing generation costs from traditional power producers (e.g., see Cullen 2013; Callaway et al. 2015; Novan 2015). These are often called the environmental and market value of renewable generation, referring to avoided emissions and saved fuel costs, respectively. Depending on the choice of renewable policy, such costs and benefits might be signaled more effectively (Fell and Linn 2013).

Importantly, alternative renewable energy policies differentially affect investment across renewable technologies. For example, policies focused on the environmental value of renewables (e.g., a flat feed-in tariff rewarding cleaner technologies) will tend to favor technologies whose investment costs relative to production are most favorable, independently of when production occurs. A subsidy or RPS mechanism that complements the wholesale price, on the other hand, will tend to favor resources whose output is more correlated with electricity demand.

1.3.2. Impacts to Customer Classes

Consumers tend to experience price reductions in the presence of renewable subsidies or feed-in tariffs that are not recovered through the electricity market and tend to experience price increases in the presence of RPS policies or carbon taxes. If environmental costs are recovered in the electricity market with environmental charges, electricity prices often increase. In such a case, consumers tend to face larger electricity bills than in the absence of renewable energy policies, although this is not necessarily true in general. For example, Liski and Vehviläinen (2016) show that, in the Nordic market, consumers have likely benefited from lower prices due to subsidies to renewables, even after taking into account renewable charges, at least in the short run.

Controversially, there are also important differences in how different customer classes are charged for renewable services. For example, Germany has been a leader in renewable investment policies with very ambitious targets. These high targets in both wind and solar have increased the total costs of electricity production, yet most retail price increases appear to have fallen on smaller residential and commercial consumers. This has generated an intense policy debate both from an equity point of view and from an industrial policy point of view.[13] In the United States, the costs of RPS are also not necessarily equally passed-through to final consumers. Greenstone and McDowell (2015) estimate the pass-through of RPS policies to retail tariffs and find that renewable portfolio standards have affected residential rates most significantly, followed by commercial rates and industrial rates.

Ultimately, the sectoral efficiency and distributional impacts depend on several margins: the price elasticity of each consumer class, their consumption profiles, and whether these differences are accounted for when designing tariffs and allocating the costs of renewables. In particular, differences in how environmental costs are passed-through at the retail level are particularly important from an efficiency point of view for those sectors that are most elastic. From a distributional point of view, how the cost recovery is implemented also affects which sectors benefit the most. Furthermore, with real time pricing, hourly consumption profiles and how they correlate with renewable resources affect the costs and benefits to different kinds of consumers.

1.3.3. Impacts between Regulated and Unregulated Regions

The efficiency and distributional implications of these policies also depend on how emissions from other regions are treated. For example, in the presence of RPS policies

13. Other members of the European Union argued that such uneven pass-through to different sectors could be considered an industrial subsidy, which was carefully examined by the European Commission; e.g., see http://europa.eu/rapid/press-release_IP-16-3525_en.htm.

with heterogeneous targets across regions, the optimality of investments depends crucially on whether trade across regions is allowed. The effects of carbon taxes can also be substantially different depending on whether imports are appropriately taxed for their carbon content. More generally, the impacts of these policies depend substantially on whether imports are subject to such regulations, which determines whether the marginal cost of compliance is efficiently equalized at the margin.

In the absence of regulation of imports, leakage of emissions to unregulated regions tends to occur whenever wholesale prices increase, as importers become relatively more competitive at the margin (Fowlie 2009). Therefore, imports tend to increase in the presence of a carbon tax. Such emissions leakage dilutes reductions in environmental damages and also distorts the efficient share of imports versus in-state production. For the purposes of the counterfactual analysis, I consider both the case in which imports are included in the environmental policy and the case in which importers can circumvent such regulations and leakage occurs, for example, due to contract reshuffling (Bushnell et al. 2014).

Leakage can also become an important concern in the industrial sector.[14] If electricity consumption at the industrial level is reduced, it can come from two sources: (*a*) true reductions in industrial output or improvements in industrial processes and (*b*) relocation of production to other regions. The potential for leakage thus interacts with the optimal retail design and may justify reducing the incidence of environmental costs to the industrial sector even further, aggravating the redistributional impacts across classes.

2. MODEL

To analyze the interaction between renewable energy policies and tariff design in an empirical fashion, I construct a partial-equilibrium model with three demand sectors (residential, commercial, and industrial), different generation technologies, and imports. Some of the modeling choices are motivated by features from the California market, which is used later to calibrate the model. Apart from this, the model is a relatively standard investment model for electricity, with the added feature that environmental policies and retail tariffs coexist.

In this section, I lay out the main ingredients and also explain how environmental policies and retail tariffs are implemented in the model. I discuss the calibration of the model in the next section.

2.1. Demand

I specify an hourly demand curve for three different sectors: residential, commercial and industrial.

14. See Fowlie et al. (2016) for a discussion of industrial leakage in the context of California.

$$q_{sth} = \alpha_{sth} - \gamma_{sth} p_{sth}, \qquad \forall s, t, h, \tag{1}$$

where s indexes the sector, t indexes the day, and h the hour of the day. Demand levels might change over time (e.g., as a function of weather, day of the week, etc.), which is captured by the intercept α_{sth}. Note that retail electricity prices p_{sth}, and the responsiveness to prices γ_{sth}, can be sector specific.

2.2. Imports

Imports from other regions are represented by an import supply curve. Given that California is practically always a net importer, I focus on the net import supply curve:

$$m_{th} = \alpha^m_{th} + \rho_{th} p^w_{th}, \qquad \forall t, h\,. \tag{2}$$

The parameter ρ_{th} captures the responsiveness of imports to wholesale prices p^w_{th} at a given day and hour. As in the demand model, the import supply intercept might fluctuate over time, as captured by the intercept α^m_{th}.

To allow for the potential of leakage or contract reshuffling, I consider two extreme cases, one in which imports face carbon taxes and one in which they do not. When firms face carbon costs, their supply curve shifts, which can be captured as

$$m_{th} = \alpha^m_{th} + \rho_{th}(p^w_{th} - e^m \tau), \qquad \forall t, h, \tag{3}$$

where τ represents the carbon tax and e^m the marginal emissions rate of imports.

2.3. Generation

Generation is assumed to be competitive. Thermal generators produce as long as the marginal price of energy is above their marginal cost:

$$g_{ith} = \begin{cases} 0, & \text{if } p^w_{th} < mc_i(g_{ith}), \\ [0, K_i], & \text{if } p^w_{th} = mc_i(g_{ith}), \\ K_i, & \text{else,} \end{cases} \qquad \forall i, t, h, \tag{4}$$

where i indexes a given technology. Note that the price that power plants receive is the wholesale electricity price p^w_{th}, which is different from the retail electricity prices faced by consumers. Marginal costs are assumed to be potentially increasing in the amount of generation. Because the model is aggregated by technology, this increase in marginal cost should be interpreted as heterogeneity in marginal costs within a certain class of generators, not necessarily within a plant.

Renewable production is very different in nature to thermal production. To first order, wind and solar power is used as long as it is available, subject to potential curtailment needs. Therefore, I assume its production is exogenously given by weather conditions, which determine availability factors and limit total production, which is constrained by

$$r_{jth} \leq \omega_{jth} K_j, \qquad \forall j, t, h, \tag{5}$$

where j represents a particular renewable resource (e.g., wind or solar), ω_{jth} is an exogenously given capacity factor between zero and one for a given day and time, and K_j is the installed capacity of a given resource.[15]

Hydro production decisions are also very different from those of thermal generators, as they are subject to availability constraints that create dynamic links. In this paper, I simplify the hydro decision problem and I hold production hydro at its observed levels in the sample, that is,[16]

$$h_{th} = \bar{h}_{th}, \qquad \forall t, h. \tag{6}$$

I treat nuclear power, n_{th}, in the same fashion as a "must-run," holding its production as observed in the data.

2.4. Environmental Policies

I consider the implementation of large-scale renewable energy policies, which incentivizes investment in renewable technologies. In the model, these policies are reflected as follows:

1. *Carbon tax*. The marginal cost for a given generation goes up by τe_i, where τ is the carbon tax and e_i the emissions rate of generation technology i.
2. *Feed-in tariff*. Renewable technologies do not receive payments from the wholesale electricity market and receive a flat tariff instead, p^{fit}.
3. *Renewable portfolio standard (RPS)*. A certain share of electricity production needs to be purchased from renewable sources, $\overline{RPS}$. I calculate the equilibrium RPS price that ensures a certain percentage of renewable production, p^{rps}, that is,

$$p^{rps} \quad \text{s.t.} \quad \frac{\sum_{j,t,h} r_{jth}}{\sum_{s,t,h} q_{sth}} = \overline{RPS}.$$

15. Note that capacity could potentially change over time, e.g., as more investment in renewables occurs. I consider a long-run investment model where capacity is constant.

16. Hydro power represents a relatively small fraction of in-state production in California, although this assumption clearly abstracts away from peak-shaving behavior, i.e., selling at the hours with highest prices, which might endogenously change in the counterfactual scenarios considered.

Under RPS, renewable technologies receive the RPS supplement p^{rps}, in addition to the wholesale market price. I assume that the burden of satisfying RPS falls into the retailers' side. Retailers need to pay their share of RPS obligations at the margin, that is, the marginal cost of serving demand increases by $\overline{RPS} \times p^{rps}$.[17]

2.5. Equilibrium

Several variables are defined implicitly as functions of equilibrium prices (e.g., demand, generation, imports). To close the model, I add the following additional constraints.

2.5.1. *Wholesale Prices*

In equilibrium, production and demand clear the market. For given retail prices p_{sth}, wholesale prices p^w_{th} are such that,

$$\sum_s q_{sth} - m_{th} = \sum_i g_{ith} + \sum_j r_{jth} + h_{th} + n_{th}, \forall t, h. \tag{7}$$

The wholesale price is determined by the marginal cost of the most expensive unit being used (the marginal unit). The solution can be expressed as a system of first-order conditions with complementarities:

$$g_{ith} \geq 0 \perp p^w_{th} - mc_i(g_{ith}) - \psi_{ith} \leq 0, \qquad \forall i, t, h, \tag{8}$$

where $\psi_{ith} \geq 0$ represent the inframarginal rents of a given unit that is producing a positive amount of energy. Note that for wind and solar generators the condition is similar, although in such cases the marginal cost of production is close to zero. Environmental policy payments (or taxes) are also different depending on the technology and affect the effective marginal cost.

2.5.2. *Wholesale Investment*

I allow for endogenous investment in the model, both of new gas power plants and renewable generators (wind and solar).[18] Because there are already several generators in place, I only consider new investment at the margin. Following Bushnell (2010),

17. Other papers have considered the case in which integrated utilities take into account the effect of their own production on their RPS obligations and, therefore, incorporate the RPS price at the generation level (Fischer and Newell 2008; Fell and Linn 2013). I assume retailers are the ones charging renewable energy credit (REC) prices at the margin, as this is how it is implemented in practice. The key difference is whether the incidence of the RPS price falls onto wholesale prices or retail prices. This is analogous if retail prices are assumed to be equal to the wholesale price.

18. Note that I do not allow for new investment in hydro resources, nuclear, and coal, given that these are unlikely to happen in the California context. These technologies are also not playing a major role in many other mature electricity markets, due to their cost uncertainty, lack of economic viability, or the difficulties in placing new hydro projects.

generators of new technologies enter the market until their zero profit condition is satisfied. For gas investment, this implies

$$K_i^{new} \geq 0 \perp F_i(K_i^{new}) - \sum_{th} \psi_{ith} \leq 0, \qquad \forall \; i \in new. \tag{9}$$

where F_i is a function determining the fixed costs of installing new generators. For renewable plants, the zero profit condition also includes any additional payment that comes from the renewable energy policies (e.g., feed-in tariff or subsidies), as well as potentially an investment tax credit (ITC_j), which rewards renewable investment proportionally to the capacity of the investment.

$$\begin{aligned} K_j^{new} \geq 0 \perp F_i\left(K_j^{new}\right) - ITC_j K_j^{new} - \sum_{th} \psi_{jth} \\ - AddtionalPolicyPayments_j \leq 0, \qquad \forall \; j, \end{aligned} \tag{10}$$

where the additional policy payments come from rewards not explicitly priced in the electricity market (and thus not reflected in ψ_{jth}). In the case of the feed-in tariff, renewables do not receive the market price, and therefore all revenues come from these additional policy payments and $\psi_{jth} = 0$.

I allow the fixed cost to depend on the level of investment, which introduces some convexity in the costs of investment and can be considered as a proxy for the fact that locations in which to place generators might become more scarce as power plants are built. Construction costs for new power plants could also increase as demand for raw materials increases. Similarly, suitable locations for renewable power might become more scarce or less desirable from a reliability point of view, potentially decreasing the value of the investment.[19]

2.5.3. *Retail Prices*

Because the recovery of electricity expenses and its distributional implications is the main focus of the paper, I consider a situation in which retail prices for electricity have to at least cover the total payments to electricity producers, that is,

$$\sum_t \sum_h \sum_s (p_{sth} - p_{th}^w) \cdot q_{sth} \geq AdditionalPolicyPayments. \tag{11}$$

This expression implies that electricity-specific policies, even if not explicitly passed-through to wholesale prices, are ultimately charged to final consumers to recover the

19. In practice, the impact of reliability costs on the value of investment depends quite heavily on market design, but it is not uncommon that wind and solar farms pay part of these additional costs, thus effectively reducing their investment value as renewable penetration increases.

costs of renewables. The additional policy payments are only relevant for those renewable energy policies that offer renewable payments outside of the wholesale electricity market clearing, that is, for the feed-in tariff. In the baseline case, additional policy payments are not recovered within the electricity sector.[20] The additional policy payments can take on negative values. For example, carbon tax revenues are additional policy revenues that can rebated to electricity consumers in a lump-sum fashion or at the margin.

Because there are many degrees of freedom to set up retail prices that ensure revenue sufficiency as expressed in equation (11), I consider several stylized alternatives:

(*a*) *Flat prices with lump-sum fees*. This is the baseline scenario in which consumers face flat prices, plus a fixed lump-sum fee Φ to ensure full recovery, which only has distributional implications. Therefore, $p_{sth} = \bar{p}^w$, where $\bar{p}^w$ is the weighted average price in the wholesale market.

(*b*) *Constant retail tariffs*. I consider a case in which retail electricity prices are flat and exogenously set at $\bar{p}$. The revenue constraint is again sufficient to determine $\bar{p}$.

(*c*) *Real-time prices with marginal fee*. I assume consumers pay the real-time price of electricity plus a constant retail fee that ensures recovery of environmental charges, that is, $p_{sth} = p^w_{th} + \phi$. The revenue constraint is sufficient to determine ϕ. When combined with a carbon tax that equals the social cost of carbon, it provides a first-best benchmark.

(*d*) *Ramsey retail tariffs*. I consider optimal Ramsey prices that maximize welfare, in which prices are allowed to be different by sector (residential, commercial, and industrial). To simplify the problem, I impose that retail tariffs are constant at the sector level, and thus there are only three sectoral prices, and solve,

$$\mathbf{p} = \arg\max_{\mathbf{p}} W(\mathbf{p}) \equiv CS(\mathbf{p}) + PS(\mathbf{p}).$$

Note that the measure of welfare that I use to determine Ramsey prices does not include the emissions externality, and therefore the Ramsey solution should be interpreted as the sectoral retail tariffs that maximize welfare in the electricity sector in a narrow sense. The reason to focus on this narrow definition of welfare is that most large-scale renewable energy policies are set up to incentivize renewable technologies, but they do not directly target emissions damages. The assumption is that retail tariffs cannot be justified based on the externality unless it is being taxed explicitly, as in the

20. Given the partial equilibrium nature of the model, the impact of such policy payments outside of the electricity model is left unspecified.

case of a carbon tax. In section 4.4, I compare this baseline to the case in which the objective function appropriately takes into account emissions damages.

2.6. Solving the Model

To reduce the dimensionality of the data and make the computations more tractable, I use a k-means algorithm to reduce the dimensionality of the data to 100 representative hours, based on the full data from 2011–14 with over 43,000 hours.[21] The algorithm tries to find similar hours in terms of key variables: load, hydro and nuclear production, imports, consumption by the residential, commercial, and industrial sector, and capacity factors of solar and wind. It then provides an average and weight for each of the representative hours to make the reduced sample as representative as possible. Figures A.1 and A.2 (figs. A.1–A.4 are available online) show how the clustered data successfully capture the main patterns in the data.

Using the clustered data, I solve the supply model as a mathematical complementarity problem for given environmental policy parameters, in the spirit of Bushnell et al. (2008) and Bushnell (2010). The model is iterated to find the equilibrium tax, feed-in tariff, and RPS price levels that ensure a certain level of emissions reductions. Additionally, to compute the endogenous retail rates, I nest the complementarity problem into one that solves for the revenue requirement constraint (in the case of fees) and the welfare maximizing price mix (in the case of the Ramsey prices).[22]

3. DATA

The goal of the exercise is to explore the trade-off between alternative combinations of large-scale renewable energy policies and retail tariff designs. To calibrate the investment model and illustrate its implications, I use data from the California electricity market (CAISO) during the years 2011–15.[23]

3.1. Demand Data

To obtain load profiles, CAISO reports hourly load data at the trading hub level for three different trading areas. These data are aggregated across all consumer types. Additionally, I collect data from the three main utilities (Pacific Gas and Electric, South-

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21. See Green et al. (2014) for an application of k-means clustering to electricity demand forecasting in the United Kingdom. In line with their findings, I find that the results are very similar as a function of the number of clusters (100, 200, or 500), but the smaller number of clusters allows me to consider a wider range of scenarios in a computationally faster way.

22. Because the revenue constraint is nonlinear, I cannot solve for it in one step. Similarly, total welfare is a nonlinear object that I need to maximize, and therefore the full problem cannot be expressed as a one-step complementarity problem.

23. Some data span longer time horizons, but some of the renewable data are limited to 2013 onward. All data used are publicly available, which can have some advantages, such as replication ability, but it also leads to some shortcomings.

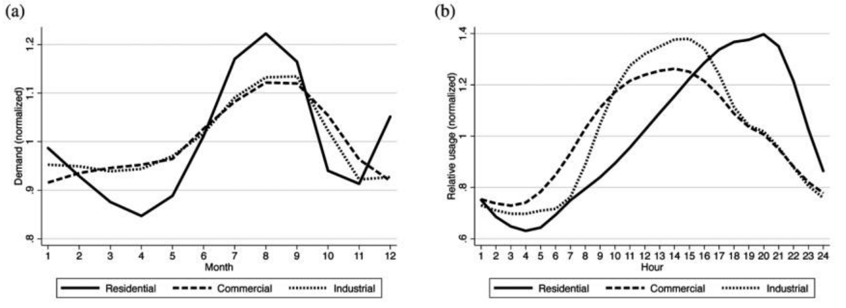

Figure 1. Consumption patterns across customer classes. *a*, Electricity consumption across sectors over the year. *b*, Electricity consumption across sectors in the summer.

ern California Edison, and San Diego Gas and Electric). In particular, I obtain dynamic load profiles by rate category from each utility, which provide hourly consumption patterns for representative agents in mainly three categories (residential, commercial, and industrial).[24] Dynamic load profiles do not provide total consumption by sector for all utilities. Instead, I use US Energy Information Administration (EIA) Form-826 data, which provides total monthly demand and number of customers by sector and utility, to scale up the hourly load profiles and obtain hourly aggregate consumption by customer class and utility.

To highlight the heterogeneity across customer classes, figure 1*a* shows average consumption by month of the year, separated across customer classes, normalized so that they all average to one. As can be seen in the data, residential consumption is much more seasonal than commercial and industrial consumption, although in all cases consumption peaks during the summer due to air conditioning. Figure 1*b* shows heterogeneity in hourly consumption across sectors, also normalized. As one can see, residential consumers exhibit substantially different patterns in their daily consumption, with consumption peaking later in the day.

The correlation of sectoral demand with electricity prices and renewable resources affects the relative gains and losses of different customer classes. In the data, I find that residential demand is most correlated with wholesale prices (with a correlation coefficient of 0.44), consistent with being a major driver of prices in the wholesale market, although commercial and industrial demand are also strongly correlated with prices (0.32 and 0.40, respectively). When looking at resource availability, I find commercial demand to be most correlated to solar production, together with industrial demand (0.61 and 0.43, respectively), whereas residential demand is positively correlated

24. Unfortunately, the dynamic load data only provide information for one representative consumer per customer class, which is an important limitation. Depending on the utility, dynamic profiles can be further disaggregated into smaller consumer classes, as a function of their rate. To homogenize across utilities, I consider only these three main categories.

Table 2. Demand Elasticities and Shares by Customer Class

Sector	Elasticity	Share (%)
Residential	−.15	41
Commercial	−.30	45
Industrial	−.50	14

with solar generation to a much lesser extent (0.07). Finally, wind production is positively correlated with demand across sectors, but less strongly than solar.

3.1.1. Elasticities

To parameterize the demand functions in the model, one needs a measure of demand elasticity. Unfortunately, the aggregate data used in this study are not well suited for estimating elasticities by customer class.[25] I perform sensitivity analysis for alternative elasticity values. The one maintained assumption across simulations is that there is a sorting in the degree of elasticity across consumers, with the residential sector being the least responsive. This is consistent with residential customers having fewer margins of adjustment—as opposed to industrial customers, who have higher incentives to better optimize their processes or switch to self-generation, and also consistent with studies for other utilities such as natural gas (Davis and Muehlegger 2010).

Table 2 summarizes the baseline elasticities assumed in the model, together with conditional average shares by consumer class, to give a sense of which sectors represent the bulk of electricity demand.[26] There is a wide range of elasticity estimates in the literature. For residential households, I use a baseline elasticity of −0.15, which is on the mid-lower end of current estimates.[27] For commercial users, I use an elasticity of −0.30, and for large industrial customers I use an elasticity of 0.50.[28]

25. Even with more disaggregate data, estimation of elasticities for electricity demand can be challenging, due to limited variation in retail tariffs.

26. Some sectors, such as the agricultural sector, are not captured by the model. Therefore, these are shares among these three customer classes.

27. Ito (2014) finds an elasticity of −0.08 with respect to average electricity prices. Reiss and White (2005) find an elasticity −0.39, with substantial heterogeneity depending on the presence of air conditioning and/or space heating. Fell et al. (2014) find much larger estimates using Consumer Expenditure Survey (CEX) data, most of them between −0.75 and −1. Deryugina et al. (2017) find an elasticity between −0.16 and −0.27 when looking at medium-run elasticities, and −0.30 to −0.35 in the long run.

28. There is limited evidence on the price response of commercial and industrial customers. Jessoe and Rapson (2015) find limited response of small commercial and industrial users to time-of-use pricing, although such response might be rather focused on the short run. Similarly, Blonz (2016) reports elasticities between −0.08 and −0.22. I use larger elasticities to reflect the potentially larger medium-run response by commercial and industrial users. Sensitivity to the assumed elasticities is presented in the appendix, available online.

With the observed prices and demand, together with the assumed elasticities, I construct the parameters α_{sth} and ρ_{sth}, as typically done in the literature (Bushnell et al. 2008). In particular, I compute,

$$\rho_{sth} = \eta_s \frac{\hat{q}_{sth}}{\bar{p}^w}, \qquad \forall s, t, h,$$

$$\alpha_{sth} = \hat{q}_{sth} + \rho_{sth}\bar{p}^w, \qquad \forall s, t, h.$$

Note that I use wholesale prices to calibrate demand. I take this approach because retail tariffs include many more services and charges that are beyond the scope of the model. Because consumers tend to face constant prices, and this is the baseline scenario considered, I use average prices instead of hourly real-time prices to calibrate demand.

3.2. Price, Production, and Imports Data

I obtain hourly wholesale electricity prices and generation data from CAISO. Hourly data for production and imports come from CAISO's Daily Watch report. Production data are disaggregated across generation types (nuclear, hydro, thermal, renewables, and imports). Additionally, renewables are further disaggregated into geothermal, biomass, biogas, small hydro, wind, photovoltaic solar, and thermal solar, all at the hourly level.

Table 3 shows summary statistics for the main variables. One can see that wholesale electricity prices average around \$35.50/MWh during this period. Nuclear is the most stable source of generation, with an extremely compressed interquantile range. Hydro power is also a baseload source of power, although it fluctuates much more seasonally and over the years. Thermal power, mainly natural gas, is the main source of generation and produces between 10 and 11 GWh per hour on average. Renewables produce an average of 3.8 GWh, although they experience substantial fluctuations.

Table 3. Summary Statistics, 2011–15

	Mean	SD	p25	p50	p75
Wholesale price (\$/MWh)	35.50	12.68	27.26	34.54	42.49
Hydro power (MWh)	2,046	1,211	1,114	1,730	2,754
Nuclear (MWh)	2,486	995	2,250	2,267	2,286
Thermal (MWh)	10,853	3,733	8,304	10,566	12,946
Renewables (MWh)	3,793	1,718	2,532	3,427	4,536
Imports (MWh)	7,416	1,423	6,424	7,448	8,446
Observations	43,560				

Note. Based on hourly data from CAISO. Average hourly production by generation type. Mean, standard deviation (SD), and 25, 50, and 75 percentile of the distribution presented in the table.

Their production has also experienced important growth, with an average of 4.8 GWh of production in the last year of the sample. Finally, imports represent about 25% of total generation in the California market.

Together with installed capacity data for each renewable resource, I construct capacity factors for wind and solar resources, respectively. Figure 2 shows the capacity factors during the years 2013–15. As one can see, wind and solar technologies have substantially different patterns in their availability, with solar being available mainly during sunlight hours. These capacity factors determine the attractiveness of investment in the two renewable technologies represented in the model, wind and solar. As highlighted by Fell and Linn (2013), heterogeneity in capacity factors can increase the differences between alternative policy designs, depending on whether they emphasize market or environmental values. In the data, wind capacity factors are negatively correlated with wholesale prices (−0.07), whereas solar capacity factors are associated positively with wholesale prices (0.32). Production data are used to construct hydro production in the model, $\bar{h}_{th}$, and to calibrate the capacity factors of renewable resources, ω_{jth}.

The import data are used to estimate imports into California as a function of prices. In line with Bushnell et al. (2008), I estimate the following import supply curve:

$$\ln m_{th} = \eta^m \ln p^w_{th} + X^m_{th}\beta^m + \delta_t + \epsilon_{th},$$

where the log of prices is instrumented with realized load, taken as exogenous to the importers. Alternative controls are considered, such as weather and fixed effects. Table 4 reports the results from the regression. As one can see, the results are very stable across specifications and suggest an average elasticity of imports around 0.30. As in the demand model, I use observed imports and wholesale prices, together with the assumed import elasticity, to back out the parameters α^m_{th} and ρ^m_{th}, following the same approach used for demand.

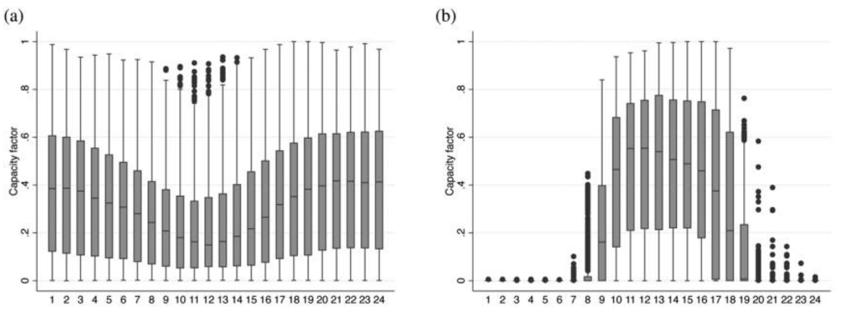

Figure 2. Distribution of capacity factors by renewable source. *a*, Wind. *b*, Solar thermal. Color version available as an online enhancement.

Table 4. Import Supply Elasticity Estimates

	Log Imports (1)	Log Imports (2)	Log Imports (3)	Log Imports (4)	Log Imports (5)
Log price	.3103	.2902	.2912	.2877	.3265
	(.0055)	(.0037)	(.0032)	(.0074)	(.0039)
Observations	43,364	43,364	43,364	43,364	43,364
Weather controls	Yes	Yes	No	No	Yes
Year and month fixed effects	No	Yes	No	No	No
Year × month fixed effects	No	No	Yes	Yes	Yes
Hour × month fixed effects	No	No	No	Yes	No

Note. Data from 2011 to 2015. Weather controls include average temperature and average wind speed. The log price is instrumented with the log of the load in California.

3.3. Cost Data

3.3.1. Existing Generators

I obtain generator-level marginal cost data from the Emissions and Generation Resource Integrated Database (eGRID).[29] These data are used to calibrate a stylized supply curve and emissions rate by type of generation.[30] To make the simulation model more tractable, I consider a supply curve with only three piece-wise linear segments, which are fit to capture the supply curve in the California market. Despite being a seemingly crude approximation, figure 3 displays marginal costs and emissions rate along the merit order curve, showing that the piece-wise linear approximation is a decent characterization of both marginal costs and emissions rates in this market. The data are also used to calibrate carbon emissions rates of these generators, which also appear to be appropriately captured by a simple piece-wise linear approximation.

3.3.2. New Investment

The model allows for new investment in both gas and renewable generation, for which I need a measure of marginal and fixed costs. I use data from the EIA to calibrate these parameters (US EIA 2016). For marginal costs, I use a value of 6,600 Btu/kWh for the heat rate of new gas generators.[31] I consider a range of gas prices between $3 and $4/MMbtu, plus additional variable operations and maintenance (O&M) costs of $3.5/MWh (US EIA 2016), which imply a marginal cost for new gas generators ranging

29. https://www.epa.gov/energy/emissions-generation-resource-integrated-database-egrid.

30. Because of the long-run nature of the model, I include in the existing supply curve only generators that were built before 2009, i.e., before renewable policies were particularly strong. I allow the model to predict investments in renewables and new natural gas.

31. This heat rate is based on new investment ideal heat rates. The EIA reports weighted average heat rates for actual new gas plants in 2015 and 2016 of 7,029 Btu/kWh.

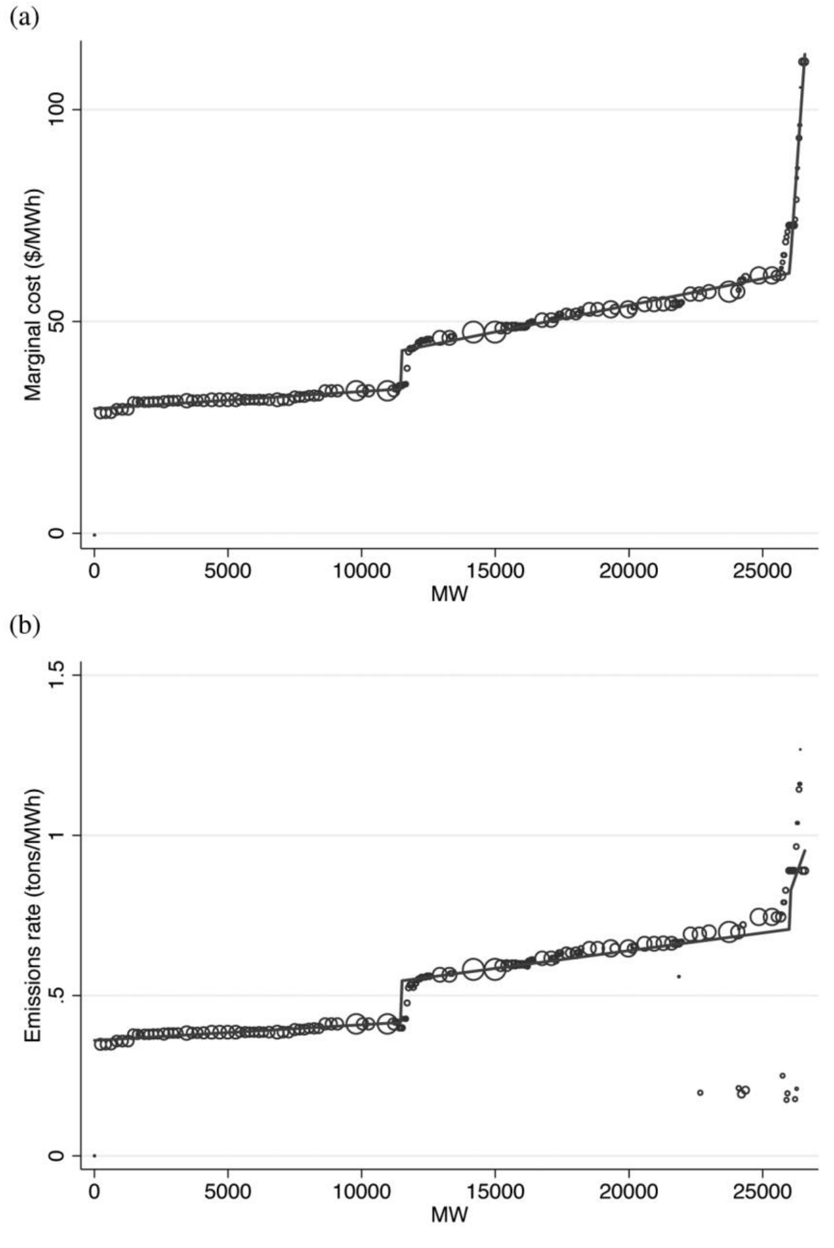

Figure 3. Thermal supply curve. *a*, Approximation of heat rates. *b*, Approximation of emissions rates. This figure shows how the supply curve is approximated by three segments. One can see that both marginal costs and emissions rates are represented quite accurately using a simple three piece-wise linear approximation when power plants are sorted according to their heat rates. Importantly, the ordering of emissions rates is very highly correlated with the ordering of heat rates, with the exception of a few small power plants which appear to have emissions rates outside the usual range. Color version available as an online enhancement.

between \$23 and \$30/MWh.[32] For fixed costs, I use values from the same report, which sets \$978/kW for natural gas generators, \$1,877/kW for onshore wind, and \$2,534/kW for PV solar. I annualize such costs over a 20-year horizon with a 5% discount rate.

As explained in the model, a constant fixed cost per generator might not be realistic, as at some point geographical limitations might make investments less attractive. Therefore, I introduce a convexity that makes fixed costs per megawatt increasing as a function of total new investment.[33] As a robustness check, and given that the costs of renewables have changed dramatically over the last few years, I also consider investment costs from the EIA report in 2013, which imply a cost of \$2,354/kW for wind and \$4,120/kW for solar. As an alternative source of cost estimates, the EIA-860 data for 2013 report average realized construction costs per kW of installed capacity by type of generation. These imply an average cost of \$1,895/kW for onshore wind and \$3,705/kW for PV solar, also consistent with the range of values considered.

3.4. Policy Parameters

3.4.1. Emissions

Emissions costs are evaluated at a \$30 social cost of carbon (SCC). Emissions rates for existing generators are based on the approximation presented in figure 3*b*. Imports are assumed to have an emissions rate of 0.428 tCO_2/MWh, which was set by Western Climate Initiative as a default emissions rate (Bushnell et al. 2014). This corresponds to assuming that marginal imports are from natural gas power plants. New gas investment is assumed to have a cleaner state-of-the-art emissions rate of 0.35 tCO_2/MWh.

3.4.2. Carbon Tax

The carbon tax is endogenized to achieve a 10% reduction in emissions. In the baseline scenario, this implies a carbon tax of around \$23, not far from expected carbon prices.

3.4.3. Renewable Targets

The feed-in tariff and RPS policies are calibrated to generate the same 10% of carbon emissions reductions in the baseline simulation. The RPS price is subsequently endogenized to hold the percentage of renewables fixed, whereas I maintain the subsidies fixed at their baseline levels for the feed-in tariff. I also consider alternative targets to trace out the abatement cost curve.

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32. Given current low gas prices, I consider \$3/MMbtu in the baseline scenario.

33. In particular, fixed costs increase by 10% for each GW of new installed capacity. The model is also feasible without increasing fixed costs, but it has a tendency of generating results that can be very dependent on the value of certain parameters such as the marginal cost of new technologies or their fixed cost (e.g., the solution may experience "bang-bang" behavior for small changes in such parameters).

3.4.4. Investment Tax Credit (ITC)

I set the ITC to be 30% of annualized fixed costs for solar installations, which in the baseline case amounts to $60/kW-year.

3.5. Limitations and Caveats

The model and its calibration are stylized and suffer from several simplifications and limitations. Therefore the exercise should be seen as a stylized representation of the California electricity market, used to highlight the differences between combinations of environmental policies and retail designs in a broader context.

The reduced form representation of the import supply curve is a limitation of the model with two main concerns. First, it does not capture potential heterogeneity in behavior by renewable and nonrenewable resources in the unregulated regions that could affect the import supply curve of traditional generators. Second, the elasticity used in the framework might not be reflective of long-run behavior by importers. I consider sensitivity analysis with respect to this parameter by considering a more elastic import curve that responds more aggressively to changes in California prices and find similar results.

Another important limitation is the absence of distributed energy resources (DERs), which are of great importance in the California market. Whereas the focus of this paper is on large-scale renewable energy policies, DERs can interact substantially with the wholesale equilibrium outcome, due to their impacts on demand profiles. Rooftop solar policies also have important distributional implications at the residential level, for example, as studied in Borenstein (2015).[34] Studying the redistributional impacts of such policies in counterfactual simulations would require a much more detailed representation of household heterogeneity and billing structure, which is beyond the scope of the investment model presented here.

4. RESULTS

I present simulations for three different policy designs (carbon tax, feed-in tariff, and renewable portfolio standard). First, I consider the case in which payments related to the environmental policy are not directly passed-through to consumers. I then consider the case in which incidence and efficiency might be affected by the tariff design and compare the efficiency and distributional impacts between these two scenarios.

4.1. Baseline Results

Table 5 presents summary statistics for basic market outcomes for the four alternative policies, together with a no-policy case.

34. See also Borenstein (2011, 2012b) for a study of the distributional implications of alternative retail tariffs with increasing block pricing.

Table 5. Baseline Simulations: Main Outcomes

	No Policy	Tax	FiT	RPS
Wholesale price ($/MWh)	34.65	43.94	33.25	33.25
Retail price ($/MWh)	34.65	43.95	29.51	37.15
Incentive ($/MWh)	.00	25.23	107.48	55.78
Demand (GWh)	27.44	25.74	28.39	26.99
In-state production (GWh)	19.98	18.39	21.01	19.60
Imports (GWh)	7.47	7.35	7.38	7.38
New gas (GW)	1.74	2.15	.38	.37
Wind (GW)	.00	.00	9.56	5.81
Solar (GW)	.00	.00	1.29	.04
% new renewable	.00	.00	.12	.07

Note. This table reports equilibrium price, average hourly outcomes, and investment for the case in which environmental policy costs are reflected by retail prices only if explicit to the policy design (i.e., for the carbon tax and RPS, but not the feed-in tariff). FiT = feed-in tariff; RPS = renewable portfolio standards.

4.1.1. Prices and Demand

Table 5 shows significant differences in wholesale and retail prices across different policy scenarios. The carbon tax increases wholesale prices significantly, reflecting a marginal impact of carbon taxes of approximately $10 on average. The other policies tend to depress wholesale prices due to the entry of marginally cheaper sources of production, such as wind and solar. Final consumers only face price increases under two scenarios, the carbon tax and RPS, where utilities are assumed to charge an additional constant marginal fee to consumers that ensures cost recovery. On the contrary, retail prices are reduced under the feed-in tariff, as the assumption is that such incentives are not paid for consumers in the electricity market. There are also substantial demand differences under these alternative policies. Under the carbon tax and RPS regimes, consumer demand is lower than in the baseline simulation, due to increased retail prices, while it is higher under the feed-in tariff. This is the demand effect of alternative designs, which has been highlighted in the literature (Fell and Linn 2013). Mechanisms that pass-through the costs to consumers at the margin tend to be preferred from a welfare standpoint, as they provide an additional incentive to reduce emissions by reducing electricity demand. Demand reductions are indeed largest under the carbon tax scenario.

4.1.2. Production and Investment

Production is also affected by the different policies. Table 5 reports the equilibrium level of production under the different policy scenarios, as well as out-of-state imports. Given the assumed costs of investment for new technologies, the carbon tax incentivizes entry by new natural gas plants only.[35] Imports are reduced across scenarios, due to the higher emissions rate of imports.[36]

Renewable energy policies are designed to encourage investment in renewables more explicitly. Therefore, investment looks quite different in the renewable policy scenarios. Given the relative capital costs of new technologies, most of the investment occurs in wind and solar. The RPS policy, which leads to overall lower investments, only sees entry by wind farms. In contrast, the feed-in tariff leads to investments in both wind and solar. Interestingly, investment in new natural gas is almost completely crowded out by renewable entry, which has spurred a distributional tension between traditional generators and renewable entry.[37]

4.1.3. *Sources of Abatement*

The abatement channels across policies are distinct across the three designs. Figure 4*a* decomposes the sources of abatement for each of the policies considered. The first bar displays the overall reduction in emissions, which by construction is the same in all scenarios. The next four bars in the graph decompose the changes in emissions across channels. The second, third, and fourth bars show emissions changes from demand, domestic production, and imports assuming that the emissions rate is fixed at its baseline level. The last bar shows the amount of emissions reductions that can be attributed to improvements in emissions rates, holding demand at the baseline level.

For the case of a carbon tax, abatement comes from both reductions in consumption and reductions in the average emissions rate. However, for the case of the feed-in tariff, demand (and thus production) is actually increasing. Thus, the only source of abatement is the transition to cleaner technologies. For this reason renewable investment needs to be much larger to achieve the same abatement in the case of a feed-in tariff. For the case of RPS, both demand reductions and improvements in the average emissions rate contribute to reductions in emissions. Compared to a carbon tax, the RPS overincentivizes the entry of renewables, decreasing the wholesale market price but increasing final prices to consumers. For that reason, demand reductions end up being largest under the RPS scenario.

Figure 4*b* shows the average abatement cost across a range of emissions reductions between 5% and 20%. One confirms that the carbon tax is the most efficient policy,

35. This finding is robust to using cost assumptions with substantially higher natural gas prices, as seen in table A.1.

36. The reductions in imports are more pronounced if imports are more elastic, as shown in table A.2. The effects are even more exacerbated if the emissions rate of imports is higher, leading to more investment in renewables, as shown in table A.3.

37. The relative investments in wind and solar are dependent on the cost assumptions. In the appendix I include a robustness check with more expensive renewables. Table A.4 shows that investment in natural gas is still crowded out by wind investment. Renewable energy policies become naturally more expensive.

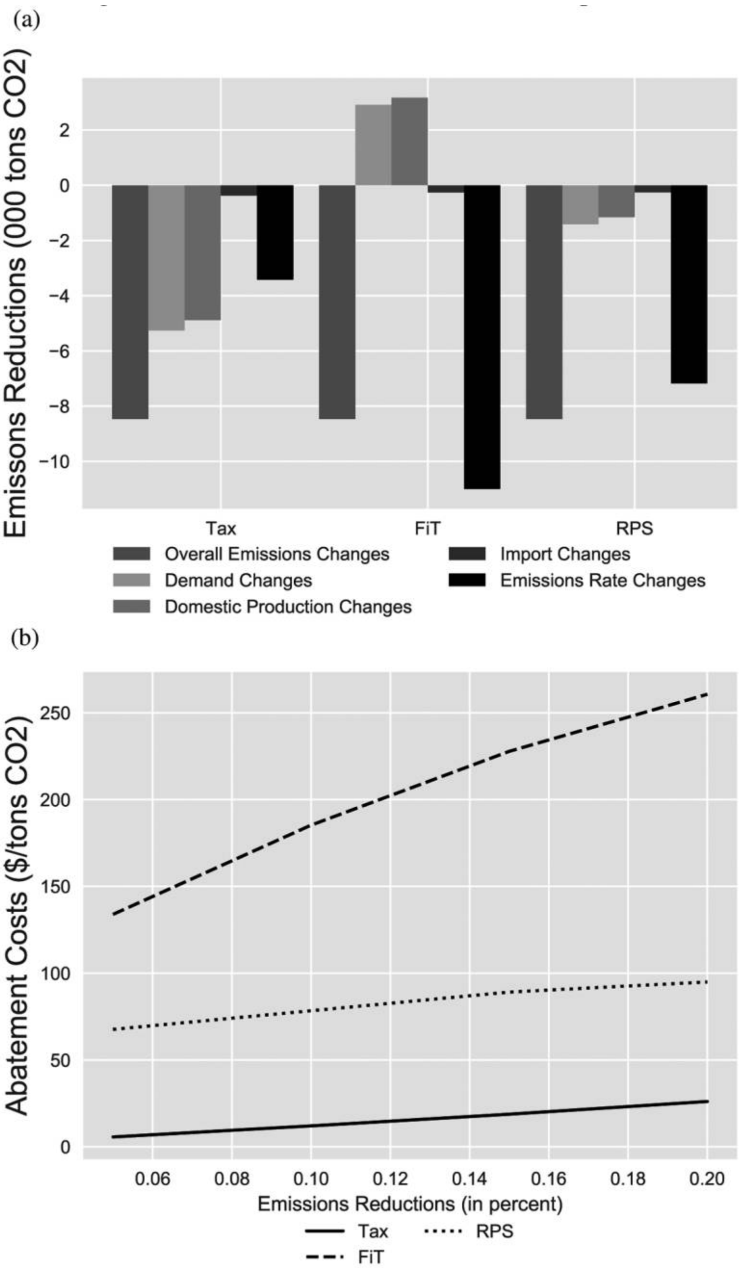

Figure 4. Abatement sources and costs across policies. *a*, Sources of abatement across policies. *b*, Average abatement cost curves. This figure shows how abatement is achieved, and at what cost, across alternative environmental policies. Panel *a* decomposes emissions reductions into demand changes and emissions rate changes for the case of a 10% emissions reduction. Panel *b* shows average abatement costs for alternative levels of stringency.

Table 6. Baseline Simulations: Welfare Impacts

	No Policy	Tax	FiT	RPS
Producer surplus	1,810	2,048	2,284	1,828
Hydro and nuclear	794	1,157	742	742
Existing gas	1,005	873	836	831
New gas	12	18	1	1
New wind	0	0	689	254
New solar	0	0	17	0
Import surplus	1,874	1,776	1,790	1,791
Consumer surplus	21,435	19,270	22,692	20,839
Residential	12,532	11,669	13,022	12,297
Commerical	7,403	6,418	7,978	7,132
Industrial	1,500	1,182	1,692	1,411
Additional policy payments	0	1,923	−3,137	0
Subtotal welfare	25,119	25,018	23,629	24,458
Emissions domestic costs	−1,701	−1,460	−1,456	−1,456
Emissions imports costs	−840	−826	−830	−831
Total welfare	22,579	22,731	21,342	22,172

Note. All numbers in millions of dollars per year. Emissions costs evaluated at \$30/ton of CO_2. FiT = feed-in tariff; RPS = renewable portfolio standards.

followed by the RPS policy, which also increases prices to final consumers. When translated into average costs per CO_2 reductions, the feed-in tariff is most expensive, given that it does not reduce demand. These abatement cost curves can also be useful to examine the robustness of the results to additional environmental considerations. Given that both the RPS policies and feed-in tariffs reduce emissions rates more dramatically, there is a question of whether such policies could be justified on the basis of achieving reduction of other copollutants, such as particulate matter or NO_x (e.g., see Muller and Mendelsohn 2009). One can see that the gap between the carbon tax and the RPS policy is substantial and unlikely to be justified only on the basis of copollutant emissions reductions.[38]

4.1.4. Incidence and Welfare

The differences in the sources of abatement are closely related to the winners and losers of these policies. Table 6 summarizes welfare impacts across different agents par-

38. Based on Holland et al. (2016), which examines damages from electricity generation in the context of electric vehicles, electricity generation in the Western Interconnection has relatively low marginal damages of at most \$4.1/MWh, based on a conversion of 300 Wh/mile. Other markets could have substantially higher benefits from expanding renewable generation, e.g., those in the Midwest with substantial emissions from coal.

ticipating in the market. In the California context, I find that producer surplus (reported in the first row) increases relative to the baseline in all alternative policy scenarios. Indeed, it is not an uncommon result that producers can benefit on average from carbon taxes if a substantial part of the inframarginal generation is clean. Expectedly, these increased profits are not equal across technologies. Hydro and nuclear benefit particularly with wholesale price increases due to a carbon tax, and renewables are the major beneficiaries when explicit renewable energy policies are implemented instead, with other technologies more likely to lose out.[39]

Absent any environmental considerations, consumers are on average worse off with a carbon tax or an RPS policy, as retail prices increase significantly. Notably, the impacts to consumers at the margin are particularly large under the carbon tax, as prices increase the most in such a scenario. On the contrary, consumers benefit at the margin from policies that subsidize renewable entry. When looking at consumer impacts across sectors, industrial customers are the ones benefiting the most from the feed-in tariff policy (in relative terms). This is mainly due to the fact that they have the most elastic demand and thus respond much more to price reductions. This also makes them most sensitive to carbon taxes, with the highest reductions in surplus.

Figure 5*a* also shows that importers tend to suffer from these policies. If imports are charged for their emissions, as assumed in the model, environmental policies tend to reduce importers' rents, as importers are not particularly clean in the model. If instead importers can avoid carbon taxes, they benefit from the regulation. Thus, the impact on importers is very dependent on the assumption that importers cannot circumvent carbon taxes through means such as contract reshuffling. Figure A.3 shows the changes in surplus and welfare when there is reshuffling for the carbon tax. In the presence of reshuffling, importers are net winners. Holding the carbon tax fixed, consumers are better off in the presence of reshuffling, as it attenuates the increase in electricity prices, at least in a partial equilibrium sense. From an overall welfare point of view, however, the case with reshuffling is naturally more inefficient, as it fails to equate marginal abatement costs across in-state producers and imports.

In terms of overall welfare, the carbon tax performs better than the no-policy case, as expected. In contrast, the other renewable energy policies reduce welfare. This is due to the relatively large costs of installed renewable capacity as compared to natural gas, which make the average cost per ton abated exceed its benefits.[40] This should be already clear from figure 4*b*, as the average abatement cost curves are substantially above the assumed social cost of carbon of \$30/ton of CO_2.

39. Note that renewable producers could be either in or out of state. My California-only model is too stylized to take a stand on where such investments occurs.

40. One would need additional channels to justify such investments, such as learning-by-doing spillovers, job creation, etc.

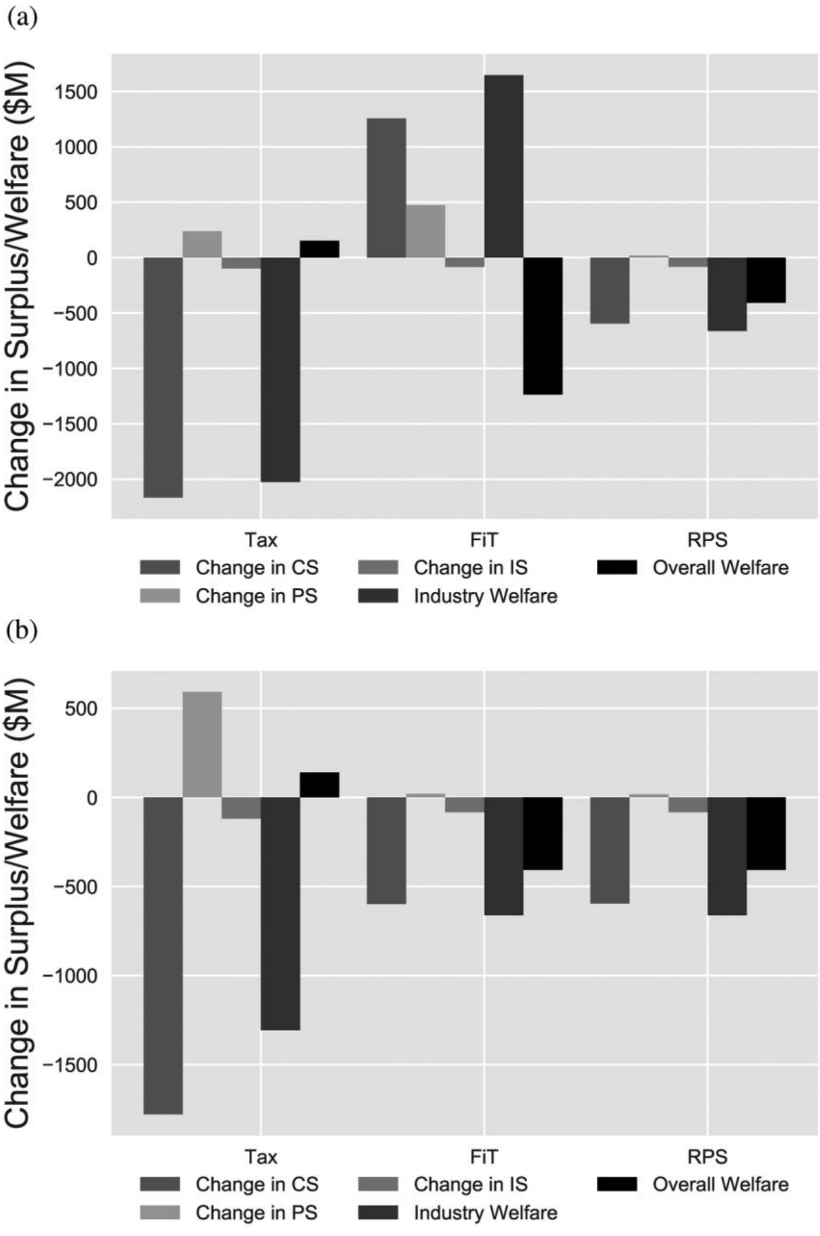

Figure 5. Incidence across producers and consumers. *a*, Abstracting from transfers. *b*, With marginal-renewable charges. This figure shows the changes in consumer surplus (CS), producer surplus (PS), import surplus (IS), and their sum (Industry Welfare), excluding any renewable payments or carbon tax revenues, when compared to the baseline case with no environmental policy. It also reports welfare changes when accounting for the environmental benefits and transfers including federal tax credits (Overall Welfare). Panel *a* shows results when renewable charges are not passed-through to consumers. Panel *b* shows changes when renewable charges are included in the retail price.

4.2. The Role of Cost Recovery

The previous simulations assume that additional revenues and costs from environmental policies are not passed-through to consumers at the margin, unless specified by the policy design (e.g., for the carbon tax or the RPS policy), but this is not necessarily true in applied settings. Figure 5*b* shows the incidence impacts when retail tariffs are designed to recover or rebate environmental costs through marginal charges. Renewable charges (or marginal carbon tax rebates) attenuate some of the price differences that we observe at the wholesale level and, thus, make policies more similar. In the presence of marginal fees, retail prices decouple from wholesale prices and increase when compared to the baseline. For this reason, all schemes reduce overall demand of electricity, and imply a reduction in consumer surplus. All schemes imply a transfer of surplus from consumers to producers.

The results regarding the welfare impacts look particularly different for the case of the feed-in tariff as seen when comparing to figure 5*a* and 5*b*. The policies no longer generate surplus increases across producers and consumers. If retail prices reflect the cost of renewable subsidies, consumers experience substantial losses. This is because the cost of renewables exceeds the reductions in wholesale prices. The necessary feed-in tariff to achieve a 10% reduction in emissions is also reduced to \$87 (from \$107), as now the demand reduction role plays a substantial role. One can see that the RPS and feed-in tariff regime look much more similar in figure 5*b*, with the RPS policy slightly outperforming the feed-in tariff due to its signaling at the margin. If instead feed-in tariff prices are held at \$107, but final consumers are charged for it, welfare is improved compared to the case without renewable charges; however, it is still substantially inefficient.

When comparing welfare outcomes, the carbon tax is still the most effective option, in spite of the detrimental effects of rebating carbon taxes at the margin. Indeed, because the emissions reductions are held fixed at 10%, the implied solution raises prices to \$43, instead of \$25, and therefore the externality signal is still present. If instead one keeps the carbon tax at \$23, but introduces marginal rebating, then the overall welfare improvement is reduced by 20% as emissions reductions are lowered.

4.3. Efficiency Implications of Alternative Retail Tariffs

How do these alternative retail tariff designs compare from an efficiency point of view? To perform such a comparison I focus on total welfare, which includes the benefits from emissions reductions. For ease of comparison, figure 6 compares each retail tariff design to the baseline case with no environmental policy.

For the case of a carbon tax it is inefficient to rebate carbon at the margin. Therefore, the baseline policy performs best, followed by marginal pricing, which performs similarly to flat prices in spite of introducing rebating, highlighting the value of moving

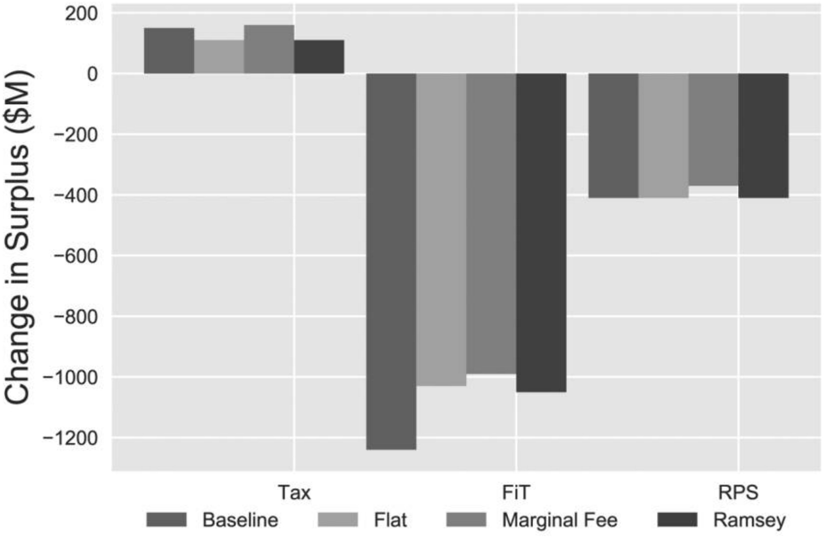

Figure 6. Welfare impacts across alternative retail designs. This figure shows a welfare comparison across retail tariff designs over a set of alternative renewable energy policies. All welfare changes are reported with respect to a scenario with no environmental policy and flat prices. The baseline scenario for each policy considers a target of 10% of emissions reductions, flat prices, and no rebating or environmental charges at the margin.

toward real-time prices in the presence of a carbon tax.[41] For the RPS case on the right of figure 5*a* and 5*b*, the most efficient pricing scheme is also the one with real-time prices and a marginal fee, as one would expect. Importantly, Ramsey prices appear to reduce net welfare, even when compared to flat prices. While Ramsey prices can be justified as a way to improve welfare in the electricity market alone, they do not take into account the emissions externality. By subsidizing industrial and commercial consumers, which are more price sensitive, the emissions reductions coming from demand response are hampered.

With the feed-in tariff, Ramsey prices also perform worse than the other policies that include renewable charges but certainly better than not including any renewable charges at all (baseline). This is due to the fact that prices are distorted in the baseline case: they do not reflect the externality, and wholesale prices are potentially artificially depressed when renewables are at the margin. Thus, even though the flat tariffs and

41. The benefits could be even larger if consumers on real-time prices became more responsive, as found in Allcott (2011).

Ramsey prices have limitations due to their coarseness and second-best nature, their impact on increased retail prices has positive implications for the overall welfare.

The previous results highlight an inherent inefficiency in explicit renewable energy policies without final consumer charges: they do not reflect the cost of the externality in the wholesale price, and they potentially distort the wholesale price further by depressing prices in hours in which renewables are marginal. The carbon tax explicitly prices the pollution externality but does not necessarily incentivize investment in renewables, if that is an explicit goal. The RPS policy, or an explicit renewable policy that ensures cost recovery through the market, falls in between. It increases prices at the margin due to the renewable requirements and it explicitly incentivizes renewables. While the price signal from the renewable target does not correspond to the optimal Pigouvian tax, it helps ameliorate some of the limitations present in the feed-in tariff mechanism. For this reason, in the feed-in tariff all mechanisms, including Ramsey pricing, perform better than the case of lump-sum transfers.[42]

Importantly, the results in figure 6 assume that lump-sum transfers in the baseline are costless. However, one could consider that raising taxes to pay for renewables outside of the electricity market has distortionary effects in other sectors of the economy (Goulder 1995; Goulder et al. 1999). In such a case, passing through the cost of renewables at the margin has two positive effects: it contributes to signaling the environmental costs of electricity consumption and at the same time it allows raising the revenue necessary to pay for the subsidies, avoiding other distortionary taxes.

4.4. Distributional Implications of Alternative Retail Designs

The designs summarized in figure 6 hide important transfers between consumers of different sectors, even more for the case of Ramsey prices, in which residential consumers end up paying a larger share of renewable costs at the margin. Indeed, figure 7 shows the changes in consumer surplus for the feed-in tariff case when Ramsey prices are considered.[43] One can see that the marginal fee and flat pricing regimes have similar implications from a distributional point of view, with the industrial sector suffering the most in relative terms. Ramsey prices, on the contrary, have a substantial impact on the redistribution of surplus across sectors, as they predict substantially lower prices for the more elastic industrial and commercial consumers.[44] Consumers experience the largest losses under such a scenario.

42. If wholesale prices are instead too high due to other reasons, e.g., market power, or retail tariffs are inflated due to other charges, increasing retail prices due to renewable charges might not move the price signal in the right direction.

43. Results are qualitatively similar for the RPS case.

44. Figure A.4 shows similar qualitative results for the case in which the elasticities of residential, commercial and industrial customers are 0.15, 0.20, and 0.30, respectively. Due to the smaller differences in elasticity, the percentage changes in consumer surplus are smaller.

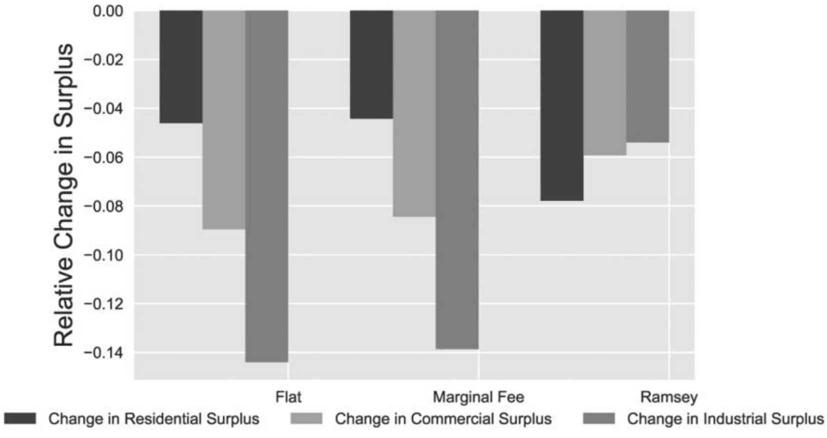

Figure 7. Redistribution across consumer types under alternative pricing rules. This figure shows the changes in consumer surplus across customer classes under a feed-in tariff and alternative retail tariffs, when compared to the case with no environmental policy.

It is hard to justify the rent transfers experienced or imposed under Ramsey pricing, given that, as shown in figure 6, welfare is not necessarily larger than when using simple flat tariffs. What explains such a counterintuitive outcome? How would alternative welfare objectives affect Ramsey prices and thus its distributional implications? Table 7 shows a quantification of optimal Ramsey prices under alternative assumptions and compares them to flat prices. One can see that residential consumers are generally worse off under traditional Ramsey prices. A big driver of this result is the assumption of no environmental considerations in the welfare objective and no leakage in the industrial sector. Under modest feed-in tariffs (panel A), prices are still too low compared to the first-best, and therefore accounting for externalities reverts the results: Ramsey prices should be largest for the most elastic sectors, as these are the ones contributing the most to abatement through demand reductions. In the presence of industrial leakage, then environmental Ramsey prices become largest for the commercial sector, as it is the one with no leakage but still a more elastic demand.

If instead, one assumes that the feed-in tariff is more aggressive (panel B), leading to prices closer to first-best, Ramsey prices perform better than flat tariffs, as flat prices introduce substantial distortions at the margin. One can see that flat prices do indeed lead to large reductions in surplus for the industrial sector, which is inefficient; however, it is substantially attenuated once Ramsey prices are introduced. Taking into account the externality in this case does not change the main ranking of Ramsey prices, although it brings them closer together. Introducing industrial leakage in this context leads again to a reduction in the optimal price for the industrial sector and, therefore, larger differences in welfare impacts between the residential and the industrial sector.

Table 7. Ramsey Prices with Alternative Welfare Assumptions

	Prices			Δ Surplus			
	Res.	Com.	Ind.	Res.	Com.	Ind.	Δ W
	A. Modest Targets (FiT = $107)						
Flat	40.84	40.84	40.84	–.05	–.09	–.14	−1028.86
Ramsey	45.19	38.72	36.92	–.08	–.06	–.05	−1047.02
Ramsey enviro	39.51	41.14	43.14	–.04	–.09	–.19	−1026.54
Ramsey enviro leak	40.86	43.14	34.65	–.05	–.12	–.00	−1044.23
	B. More Aggressive Targets (FiT = $148)						
Flat	59.19	59.19	59.19	–.18	–.33	–.51	−3702.68
Ramsey	76.48	47.50	47.19	–.29	–.18	–.28	−3641.29
Ramsey enviro	69.78	52.42	47.80	–.25	–.25	–.29	−3611.35
Ramsey enviro leak	72.36	52.47	41.73	–.26	–.25	–.16	−3622.08

Note. This table shows results for alternative Ramsey prices when the price of the feed-in tariff is set at $88 which delivers 10% emissions reductions under flat tariffs. Ramsey prices maximize industry welfare; Ramsey enviro consider the externality. Res. = residential; Com. = commercial; Ind. = industrial; FiT = feed-in tariff.

Overall, these results highlight that the existing tension with respect to charging renewable charges to the residential sector is nuanced and the appropriateness of such a scheme will depend on the underlying fundamental assumptions about the optimal first-best environmental goal and the presence of industrial leakage.

5. CONCLUSIONS

In this paper, I study the efficiency and distributional impacts of large-scale renewable energy policies, with special emphasis on how the costs of such policies are passed-through to final consumers. To do so, I build an electricity market model with endogenous investment by natural gas, wind, and solar, which is calibrated using data from the California electricity market. I then consider the interaction between four different environmental policies (feed-in tariff, renewable subsidies, renewable portfolio standards, and carbon taxes) with alternative retail tariff designs (no pass-through, marginal renewable charges, flat tariffs, and Ramsey pricing).

I find that large-scale renewable energy policies are most effective if the costs of the renewable subsidies are passed-through to consumers directly in the electricity market instead of being raised elsewhere in the economy. The rationale for this result is that, in the presence of renewable subsidies, wholesale prices are artificially low and do not reflect the pollution externality. For this same reason, I also find that the Ramsey formula, which is meant to maximize welfare in the electricity market, fails to maximize welfare from a broader environmental point of view, due to the misalignment of price signals and social costs. Therefore, disproportionately imposing renewable charges to residential consumers is not necessarily justified from an optimal taxation perspective in this second-best environment.

While retail tariffs can partially mitigate some of the inefficiencies from renewable subsidies, they are still inferior to a carbon tax. In particular, while renewable charges help signal the higher cost of electricity to final consumers, they do not provide the correct signals to producers. Therefore, the abatement channels under carbon taxes (mainly, new investment in cleaner gas) still remain significantly cheaper than under renewable subsidies (mainly, new investment in wind and solar), absent any other justifications to subsidize renewables.

The model in the paper considers a stylized setting in which the only distortion is the absence of Pigouvian taxes that reflect the social cost of carbon. An interesting avenue for future work would be to consider how the findings of this paper might change in the presence of other distortions, such as market power or the presence of distortionary charges that affect the optimality of retail electricity prices.

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