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Impact of market design on cost-effectiveness of renewable portfolio standards

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A B S T R A C T

A renewable portfolio standard (RPS) is a policy instrument designed to increase production of clean energy technologies by mandating a minimum market share for these technologies. However, the cost-effectiveness of RPS in achieving its goal depends on the market structure, which impacts the level of competition in the market. Here, we analyze the impact of market structure on RPS effectiveness by calculating the amount of subsidies needed to achieve RPS mandates. We identify a critical market share of renewable energy that can be achieved by providing an equal amount of subsidy in both regulated and deregulated markets. We find wide variation in the preferred market structure for state-level RPS policies across the United States. Overall, deregulated markets minimize subsidy requirements for clean energy technologies with lower penetration rates. In contrast, regulated markets minimize subsidy requirements for higher market share mandates. The critical market share can help policymakers design more cost-effective RPS mandates in both regulated and deregulated markets.

1. Introduction

Clean energy technologies play a key role in climate change mitigation policies [1,2]. However, high initial costs of these technologies act as a barrier to their rapid development and deployment [3,4]. Therefore, many governments are offering different policy and financial supports to facilitate the initial commercial adoption of these technologies [5].

There are several policy instruments designed by the governments to motivate and facilitate the deployment of renewable energy technologies. Two of such policy instruments have gained more popularity in different countries over the last few decades. Feed-in Tariff (FiT) is a price-based policy which has been credited for rapid expansion of renewable energy technologies by guaranteeing a specific premium price for electricity generated from renewable energy sources (RES-E) [6]. Despite their relative success in boosting RES-E [7], FiT policies require a long term commitment from the government in the form of price subsidies while imposing increasing fiscal burden to the government budgets as the share of renewable technologies increases over time. The second policy instrument is known as renewable portfolio standards (RPSs) which is a market-based mechanism where the governments set a minimum quantity for the RES-E to be generated and leave it to markets to determine the price [8]. While FiT policies have been successfully implemented in several countries around the world (e.g. for solar energy development in Germany [9]), RPS has gained momentum among the U.S. states since its debut in Iowa in 1983 [10].

RPS policies encourage market competition and allow governments to support RES-E without long term commitments to any specific technology [11]. This has resulted in the emergence of some RES-E technologies as the market leaders with which more expensive renewable technologies have not been able to compete. Therefore, several remedies such as banding and carve-outs have been proposed to diversify the RES-E portfolio [12]. Banding has been used in some European and Asian countries by providing tradable certificate multipliers for less mature, high-cost technologies [13]. Carve-outs on the other hand, are popular policies among the U.S. states where a fixed share of the market have been reserved for certain high-cost renewable technologies.

Nevertheless, the implementation of RPS policies in the U.S. has generated mixed results. RPS policies seem to have had a modest impact on the electricity rates and compliance costs have stayed below 2% of average retail rates [14].

While some studies have also shown a positive impact of RPS on wind energy [15], others have questioned its relative effectiveness compared to FiT policies [16]. Other studies have analyzed the impact of

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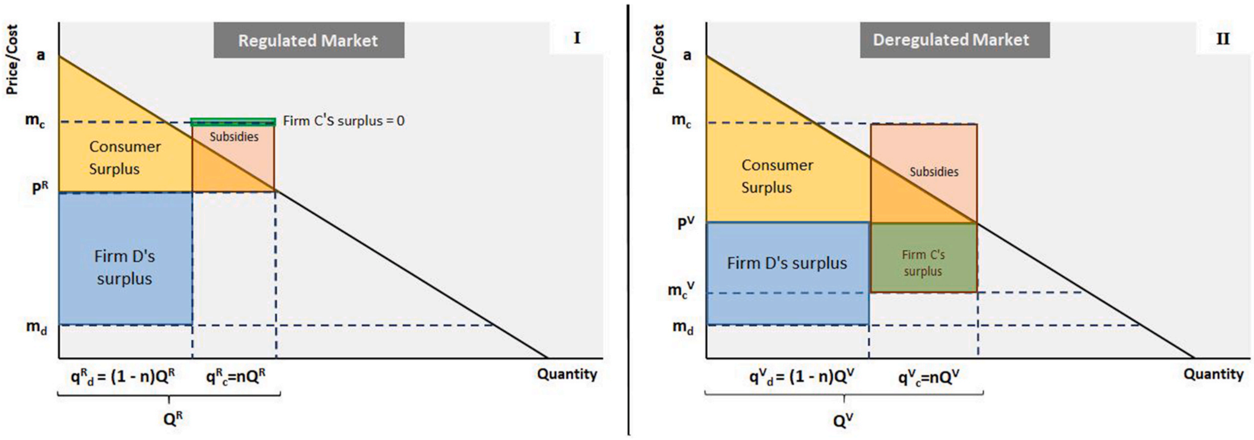


Fig. 1. Optimal quantity and price with subsidy. The monopoly's profit is reduced when the subsidy is offered in a regulated market where the *Clean* producer sells at its production cost (Panel I). Both firms share the market and gain from the deregulated price (Panel II).

RPS on market price of *Clean* energy technologies [17] and have shown that the introduction of RPS might have a negative impact on the total quantity of *Clean* energy consumption [18]. There are other studies on the impact of RPS on energy prices [19], the effectiveness of RPS at the level of utility compliance [20], the stringency and the strength of RPS across states [21], and finally the comparison between RPS and other policy instruments [16,22]. The systematic review of such studies have revealed that overall effectiveness of RPS policies depends heavily on, among other factors, their implementation stringency in each state [23]. In this paper, we consider the role of subsidies as a cost recovery mechanism adopted by state governments to achieve RPS mandates and investigate the role of the state's market structure in determining the size of such subsidies.

Government financial support for achieving RPS mandates generally include research and development funding, demonstration projects financing, and providing deployment subsidies [24,25]. Such investments have driven rapid technological innovation in clean energy technologies in the past [26,27]. For instance, the cost of land-based wind power, utility and distributed photovoltaic (PV) solar power, light emitting diodes (LEDs), and electric vehicles (EVs) in the United States has fallen by 41–94% since 2008, thanks to government subsidies [26,28].

However, governments' interventions are not limited to providing subsidies and financial incentives. They may also include a more fundamental approach to reshape and restructure energy markets [29,30]. In this case, deregulation can bring new competition and choices to the customers while allowing for environmental differentiation and the exploration of an untapped appetite for *Clean* energy consumption [31,32]. Similar to subsidies, deregulation is not a perfect solution. In some cases, it may increase energy prices for consumers [33] or even when prices are lowered by deregulation, it may induce higher consumption of *Dirty* technologies [34].

Therefore, there is a need to investigate the broader impact of energy markets deregulation on the effectiveness of subsidies provided to achieve RPS mandates. Some empirical studies of RPS policies in the U.S. have revealed that deregulated markets have lower percentages of *Clean* energy technologies compared to regulated markets [35]. Here we ratify this empirical finding through a stylized model of electricity markets to provide an analytical assessment of market structure's impact on the required level of subsidies to achieve RPS mandates. In particular, we compare the size of subsidy that guarantees a certain market share for *Clean* energy technologies in both regulated and deregulated markets. We consider which market structure will be better suited for a certain RPS mandate. We show that deregulated markets provide a more attractive environment for developing *Clean* energy technologies with lower penetration rates. In contrast, regulated markets are better suited for *Clean* energy technologies with higher market share mandate. This work informs policy design questions as governments and policymakers consider the continued use, and expansion of, RPS mandates around the world.

Table 1
Variables and parameters used in this paper.

Name	Description	Units
Variables		
P^M	monopolistic price	USD/MWh
Q^M	monopolistic quantity	MWh
P^R	unit price with regulated market subsidies	USD/MWh
Q^R	quantity with regulated market subsidies (Total)	MWh
q_d^R	quantity with regulated market subsidies (*Dirty*)	MWh
q_c^R	quantity with regulated market subsidies (Clean)	MWh
π_d^R	producer surplus with regulated market subsidies (*Dirty*)	USD
π_c^R	producer surplus with regulated market subsidies (*Clean*)	USD
π^R	producer surplus with regulated market subsidies	USD
σ^R	consumer surplus with regulated market subsidies	USD
ω^R	Regulated market subsidies	USD
ψ^R	social welfare with regulated market subsidies	USD
P^V	unit price with deregulated market subsidies	USD/MWh
Q^V	quantity with deregulated market subsidies (Total)	MWh
q_d^V	quantity with deregulated market subsidies (*Dirty*)	MWh
q_c^V	quantity with deregulated market subsidies (*Clean*)	MWh
π_d^V	producer surplus with deregulated market subsidies (*Dirty*)	USD
π_c^V	producer surplus with deregulated market subsidies (*Clean*)	USD
π^V	producer surplus with deregulated market subsidies	USD
σ^V	consumer surplus with deregulated market subsidies	USD
ω^V	cost of deregulated market subsidies	USD
ψ^V	social welfare with deregulated market subsidies	USD
Parameters		
β	price regulation coefficient	USD/USD
a	maximum unit price	USD/MWh
b	slope of the price function	USD/ MWh^2
n	market share of *Clean* energy technology	%
m_d	initial production cost (*Dirty*)	USD/MWh
m_c	initial production cost (*Clean*)	USD/MWh
m_c^V	Cost of *Clean* energy technology after subsidies	USD/MWh

2. Analytical framework

In this section, we develop a stylized model of an electricity market with two representative firms: *Dirty* representing the whole fossil-fuel electricity generation industry, and *Clean* representing the renewable energy technologies as a whole. This simplified assumption enables us to focus on the impact of market structure, and to derive a closed-form solution for the minimum amount of renewable subsidies needed to achieve a certain RPS mandate.

We first consider a regulated monopolistic market with the *Dirty* energy technology, as our baseline case. We then show how subsidies can be utilized to allow a portion of the monopolistic market to be allocated to the *Clean* energy technology. Next, we consider a deregulated market with both firms and show how subsidies in this case can help increase the market share of the *Clean* energy technology. We compare the results of each case with baseline case through four measures of welfare. The first is *Consumer Surplus*, which is defined as the difference between the price that consumers are willing to pay and the actual price they pay. It is the area under the demand curve and above the market price (see Fig. 1). The second measure is *Producer Surplus*. It is defined as the difference between the market price and the cost that producers have to pay.

It is the area under the production cost and above the market price (see Fig. 1). The third measure is the total amount of subsidies, which are provided by governments. Finally, the sum of *Consumer Surplus* and *Producer Surplus*, less the subsidy, measures the social welfare for each scenario.

Table 1 defines all variables and parameters used in this paper. Throughout this paper, subscripts d and c, indicate the properties of *Dirty* and *Clean* technologies respectively.

2.1. Baseline case

In the baseline case, the *Dirty* firm (firm D) initially dominates the market where demand and supply are in equilibrium at a price that is equal or less than the monopolistic price [36,37]. Assuming a linear relationship between price (P) and quantity (Q) we have

$$P = a - bQ \tag{1}$$

where a is the maximum unit price, and b is the slope of the price function. Given the firm's production cost (m_d), the monopolistic price and quantity in this case can be calculated as $P^M = \frac{m_d + a}{2}$ and $Q^M = \frac{a - m_d}{2b}$, respectively.

Throughout our analysis we assume that the production cost of the Clean firm is higher than the monopolistic price of the Dirty firm ($m_c > P^M$). That means, in the absence of subsidies, market mechanisms alone cannot motivate the deployment of the *Clean* energy technology to the level required by RPS mandates. In the next two sections, we consider the minimum required level of such subsidies that guarantees a RPS mandate for the *Clean* energy technology in regulated and deregulated markets.

2.2. Regulated market subsidies

In a regulated monopolistic market, the *Dirty* firm uses a mature *Dirty* energy technology to produce Q^Rquantity of output with the unit price P^R that is regulated and set by the government. The price is regulated at the level between the marginal cost of production (m_d) and the monopolistic price (P^M):

$$P^R = m_d + \beta(a - m_d), \tag{2}$$

The price regulation coefficient β can take the values between zero (production at marginal cost) and 0.5 (unregulated monopolistic market with $P^M$and Q^M). The values of β greater than 0.5 and less than 1 although feasible, are not at the best interest of the firm or the consumer[1]. Therefore, for our analysis we only consider $0 \le \beta \le 0.5$ which means the regulated price is bounded by the production cost and the monopolistic price: $m_d \le P^R \le P^M$. The regulated monopolistic quantity is calculated as:

$$Q^R = \frac{(1 - \beta)(a - m_d)}{b}, \tag{3}$$

After the government intervention, the production cost of the *Dirty* energy technology stays at its level $m_d$but in order to make the production of the *Clean* energy technology feasible, the government pays the difference between the regulated price P^R and the unit cost m_c for the targeted portion of the total supplied quantity Q^R. In this scenario, either the *Clean* producer will sell its product at its unit cost $m_c$and the consumers of this technology receive the price difference ($m_c - P^R$) from the government through subsidies, or alternatively the *Clean* producer will receive the same subsidy as a cost compensation to produce at the cost equal to the regulated market price P^R.

We emphasize that the regulated market in this case remains monopolistic. Because the price is regulated by government, firms are unable to introduce competition into the market, whether they produce the *Clean* or *Dirty* technology. Thus, total quantity is equal to the regulated monopolistic quantity $Q^R$and the equilibrium price is equal to the regulated monopolistic price P^R. However, the *Clean* producer will be allowed to provide n portion (i.e. the RPS mandate) of the total supply while the *Dirty* producer will provide the $1 - n$ portion:

$$q_c^R = nQ^R = \frac{n(1 - \beta)(a - m_d)}{b} \tag{4}$$

and

$$q_d^R = (1 - n)Q^R = \frac{(1 - n)(1 - \beta)(a - m_d)}{b} \tag{5}$$

Panel (I) in Fig. 1 shows the relationship between the two firms' producer surplus and the consumer surplus in the case of regulated market subsidies. The calculations of producer and consumer surpluses, the size of required subsidy and total welfare in regulated markets are presented in the Appendix.

2.3. Deregulated market subsidies

If the market is deregulated, subsidies will be designed to help the *Clean* producer compete with the *Dirty* producer over price and quantity. In this case, the subsidies will reduce the production cost of the *Clean* energy technology from m_c to a lower level m_c^Vthat can guarantee the market share n (i.e. RPS mandate). In contrast to the regulated market, the price in this setting is not regulated and will be set by the market mechanisms. The market price in deregulated setting is expected to fall following the introduction of the *Clean* energy technology [38] [2]. In a deregulated market structure with two producers, each firm decides about its level of output taking into account the optimal level of output from the other firm (Cournot competition). As in the case of the regulated market, the deregulated price (P^V) is a linear function of total

[1] In the monopolistic market, producer surplus is maximized at the value of β equal to 0.5. The values greater than 0.5 and less than 1 reduce both producer surplus and consumer surplus compared to the optimal monopolistic case.

[2] Some studies also have shown that the introduction of intermittent technologies into the market can amplify price volatility [39].

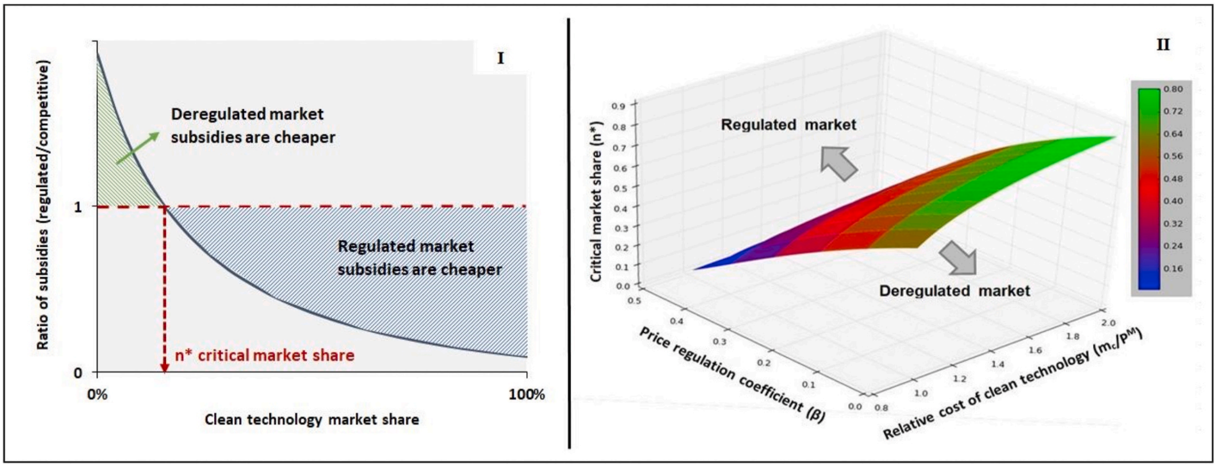


Fig. 2. Ratio of regulated subsidies to deregulated subsidies as a function of clean technology market share (Panel I). The critical market share (n^*) indicates the point that the ratio of subsidies is one. For given market conditions, the critical market share increases as the relative cost of *Clean* energy technology (m_c) compared to the monopolistic price (P^M) increases, and it decreases as price regulation coefficient (β) increases (Panel II).

output:

$$P^V = a - b\left(q_d^V + q_c^V\right), \tag{6}$$

where q_d^V and q_c^V are the supplies of *Dirty* and *Clean* technologies, respectively. In order to find the optimal quantities of both technologies, we solve the first order conditions of profit maximization problem for both firms simultaneously:

$$q_c^V = \frac{a + m_d - 2m_c^V}{3b} \tag{7}$$

and

$$q_d^V = \frac{a - 2m_d + m_c^V}{3b} \tag{8}$$

We note that the reduced cost of *Clean* energy technology m_c^V depends on the desired market share that the government would like to allocate to *Clean* technology. The market share n provided by *Clean* energy is:

$$n = \frac{q_c^V}{q_d^V + q_c^V} = \frac{a + m_d - 2m_c^V}{2a - m_d - m_c^V} \rightarrow m_c^V = \frac{(1-2n)a + (1+n)m_d}{2-n} \tag{9}$$

We can rewrite equations (7) and (8) given the value of the reduced cost:

$$q_c^V = \frac{a + m_d - 2m_c^V}{3b} = \frac{n(a - m_d)}{b(2-n)} \tag{10}$$

and

$$q_d^V = \frac{a - 2m_d + m_c^V}{3b} = \frac{(1-n)(a - m_d)}{b(2-n)} \tag{11}$$

Total quantity and the equilibrium price in this case will be:

$$Q^V = q_d^V + q_c^V = \frac{2a - m_d - m_c^V}{3b} = \frac{a - m_d}{b(2-n)} \tag{12}$$

and

$$P^V = \frac{a + m_d + m_c^V}{3b} = \frac{a(1-n) + m_d}{2-n} \tag{13}$$

Panel (II) in Fig. 1 shows the relationship between the two firms' producer surplus and the consumer surplus in the case of production subsidies. The calculations of producer and consumer surpluses, the size of required subsidy and total welfare in deregulated markets are presented in the Appendix.

2.4. Comparison of subsidies

In the last two sections, we provided analytical solutions for the minimum level of subsidies in each market setting that guarantees the RPS mandate of n. In order to compare the results of regulated and deregulated markets, we first need to find an equilibrium where providing equal amount of subsidy can deliver the same RPS mandate in each market. Proposition 1 guarantees the existence of such equilibrium.

Proposition 1. *In a regulated market defined by Equations (2)–(5) and a deregulated market defined by Equations (6)–(13), there exists a critical market share of Clean energy technology with $m_c \geq P^M$, that can be achieved by allocating equal amount of subsidies in regulated and deregulated markets.*

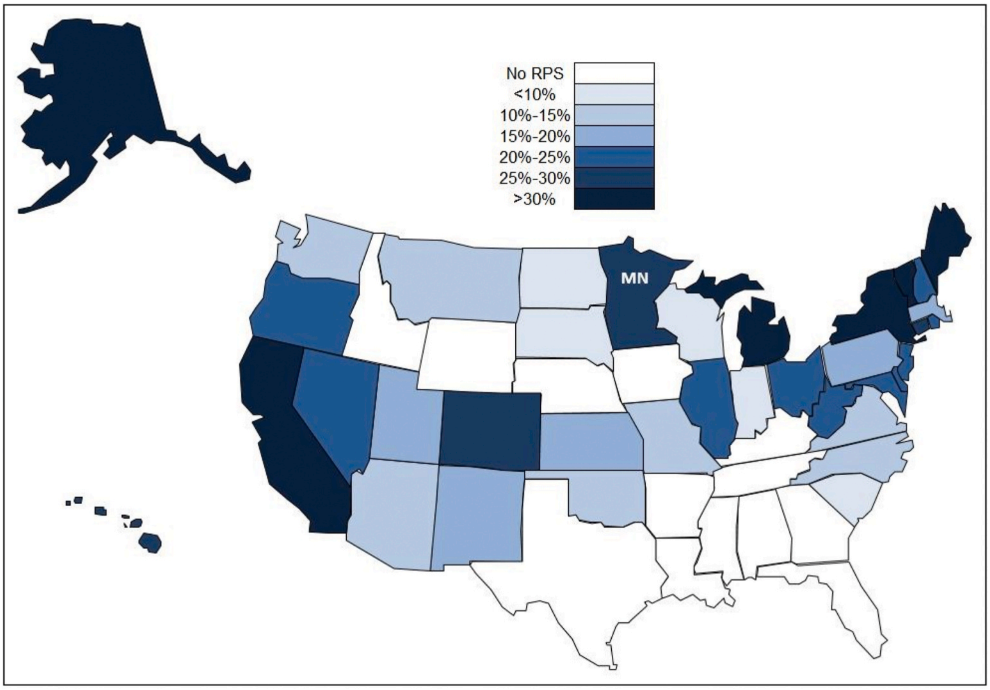
$$\exists n^* \in [0,1] : f(n^*) = \frac{\omega^R}{\omega^V} = 1$$

where function $f(n)$ is the ratio of subsidies needed to achieve the market share n in regulated to deregulated markets. The Proof of this proposition is provided in the Appendix where we derive the explicit form of function$f(n)$ as

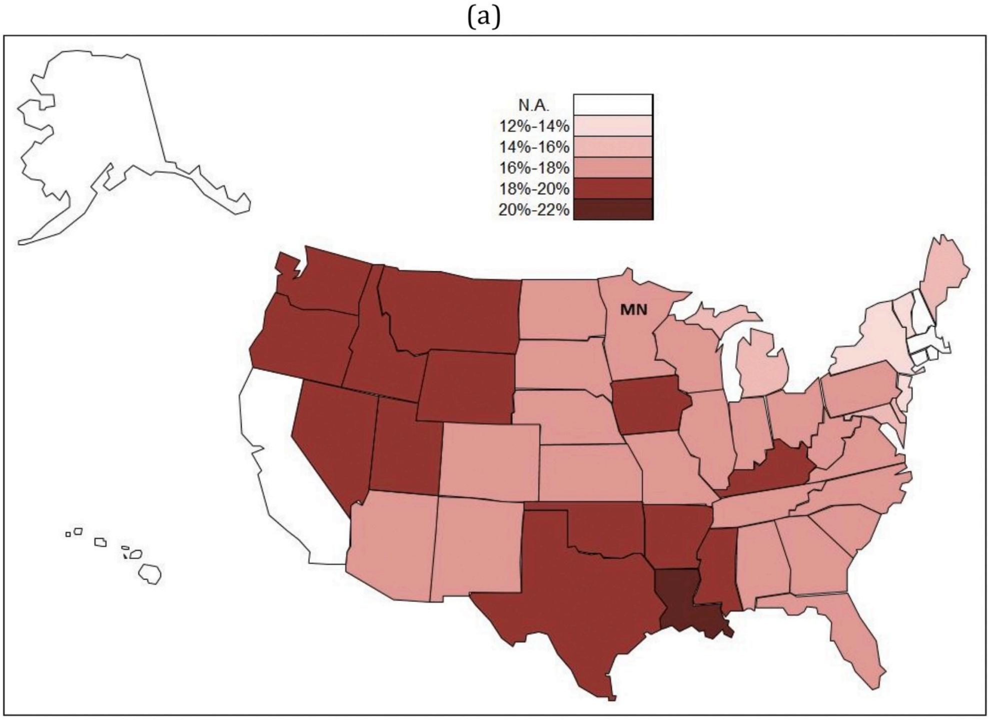
$$f(n) = \frac{(1-\beta)(B - \beta A)(2-n)^2}{(2-n)B - 2(2-n) + 3A}$$

where $A = a - m_d$ and $B = m_c - m_d$. Fig. 2 shows a schematic representation of this function and its relationship with the critical market value n^*. As this graph shows, achieving an RPS mandate less than n^*requires less subsidies in deregulated markets than in regulated markets (Panel I in Fig. 2). In contrast, achieving an RPS mandate greater than n^* requires more subsidies in deregulated markets than in regulated markets.

Panel II in Fig. 2 shows the relationship between the critical market share n^* and the initial cost of *Clean* energy technology and the price regulation coefficient in regulated markets. For any given set of market conditions (a, m_d, and β), the critical market share increases (decreases) as the cost of the *Clean* energy technology (m_c) increases (decreases). In the extreme case, where the cost of the *Clean* energy technology approaches the monopolistic price ($m_c \rightarrow P^M$), the critical market share approaches zero. We demonstrate the implications of these results through a numerical example in the electricity markets in the United States.



(a)



(b)

Fig. 3. RPS and critical market share in the United States: (a) state level RPS mandates for year 2025 compiled from Ref. [41], (b) critical market share (n^*)in the U.S. electricity market shown only for the states with $m_c > P^M$as stated in Theorem 1.

3. Electricity markets in the U.S

RPS mandates have been implemented in both regulated and deregulated electricity markets in the United States. Fig. 3a shows the range of RPS mandates for year 2025 in 37 states ranging from 2% in South Carolina to 55% in Vermont. Here we consider the case of electricity market in Minnesota (MN) as an example of a regulated market where the state has adopted an RPS mandate to achieve 26.5% market share for renewable energies by 2025 [40].

In 2016, the average price of electricity in MN was about 10 Cents/KWh or 100 USD/MWh [42]. The average cost of generating electricity in the U.S. in 2016 was about $m_d = 36USD/MWh$ for fossil fuel technologies [43]. Total electricity generated in MN in 2016 amounted for about 59.48 TWh. To calibrate our simple model, we assume that the electricity market in MN in 2016 was closely following a regulated monopolistic market structure with $\beta = 0.4$ and therefore we are able to

Table 2
Optimal quantities and price under two market conditions in Minnesota: regulated and deregulated. To ensure a fixed market share (26.5% in this example), the subsidy brings the price of *Clean* energy technology (biofuel) from $m_c = 150$ down to the regulated price of $P^R = 100$ when the market is regulated. In the hypothetical case of deregulation, the subsidy would reduce the cost of production from $m_c = 150$ to $m_c^V = 79.34$ so it could compete with *Dirty* technologies (fossil fuel).

		Regulated market	Deregulated market
Clean firm	**Cost (USD/MWh)**	150.00	79.34
	Quantity (TWh)	15.76	15.14
	Producer surplus (millions USD)	0.00	370.03
Dirty firm	**Cost (USD/MWh)**	36.00	36.00
	Quantity (TWh)	43.72	42.00
	Producer surplus (millions USD)	2797.94	2846.53
Market	**Price (USD/MWh)**	100.00	103.78
	Consumer surplus (millions USD)	2855.04	2634.58
	Subsidies (millions USD)	788.11	1069.85
Social welfare (millions USD)		4864.87	4781.28

derive the maximum price a and the slope of price function b from the following equations:

$$P = m_d + \beta(a - m_d) \Rightarrow a = m_d + \frac{P - m_d}{\beta} = 36 + \frac{100 - 36}{0.4} = 196USD \Big/ Mwh$$

$$P = a - bQ \Rightarrow b = \frac{a - P}{Q} = \frac{196 - 100}{59.48 \times 10^6} = 1.61 \times 10^{-6}$$

Further, we assume that the marginal cost of the costly *Clean* technology is $m_c = 150USD/MWh$ that is in the range of the levelized cost of biomass electricity [44]. For our simplified market analysis, we choose biomass technologies as it competes most similarly to fossil fuel technologies. Biomass technologies have similar flexibility characteristics to fossil fuel technologies [45]. Because of such higher initial cost, a subsidy is required to ensure that certain market share is guaranteed for *Clean* energy technologies. For this example, we assume the desired market share is $n = 26.5\%$ that matches MN's renewable mandate. Given the maximum price, the generation costs of both types of technologies, and assuming the regulation coefficient $\beta = 0.4$, we calculate the critical market share to be $n^* = 16.2\%$ which is less than the RPS mandate. Table 2 compares the welfare calculations for achieving the MN's renewable mandate ($n = 26.5\%$) in both regulated and deregulated markets. Comparing the two cases shows that in the deregulated market, the required subsidy and producer surplus are higher while in the regulated market, consumer surplus and social welfare are higher.

As Panel I in Fig. 4 illustrates, when the market share is growing, the consumer and producer surpluses are decreasing while the social welfare stays almost equal in both markets.

Panel II in Fig. 4 shows when the market share of the *Clean* energy technology is relatively small—less than $n^* = 16.2\%$ in the example of Minnesota— achieving the target market share in deregulated markets are cheaper than in regulated markets. On the other hand, for higher shares of renewable such as the 26.5% RPS, the ratio of subsidies in regulated to deregulated markets drops to about 0.74. That is, achieving the RPS mandate is 26% cheaper in regulated markets than in deregulated markets. This will have a large impact on the deregulation policy and its long term impact on *Clean* energy technologies. Deregulation helps bring down the market price and provide a greater total quantity supplied to the market, however it will cost about 26% more in terms of subsidies. Fig. 3b shows the range of critical market share where the size of subsidy is equal in regulated and deregulated markets. The results are shown for 42 states ranging from 13% in Vermont, New York, and New Jersey to 20% in Louisiana. Minnesota currently has a regulated electricity market with a relatively low critical market share of 16.2%.

As shown in Table 2, achieving 26.5% RPS (which is greater than the critical market share of $n^* = 16.2\%$) will be more effective in the current regulated market if other market parameters remain unchanged. As stated previously, as a general rule, achieving RPS mandates less than the critical market share is more effective in deregulated markets. On contrary, achieving RPS mandates greater than the critical market share is more effective in regulated markets.

Fig. 5a shows the current state of deregulation of electricity markets in the United States. Currently 17 states (and the District of Columbia) have deregulated their electricity markets to some extent [46]. Based on RPS mandates from Fig. 3a and the critical market share from Fig. 3b, we can show where deregulation is more cost-effective. Fig. 5b shows for each state whether achieving their RPS mandate is more cost-effective in regulated or deregulated market. Comparing Fig. 5a and 5b reveals potential positive impacts of deregulation on achieving RPS mandates for some states including Arizona, Indiana, Missouri, Montana, North Carolina, North Dakota, Oklahoma, South Carolina, South Dakota, Washington, and Wisconsin. On the other hand, some states with deregulated markets would have lower overall subsidies for achieving their RPS mandates under regulated markets. These states include Delaware, Illinois, Maryland, Maine, Michigan, New jersey, New York, Ohio, Oregon, and Pennsylvania. Virginia is the only states with a deregulated market that can achieve its RPS most cost-effectively

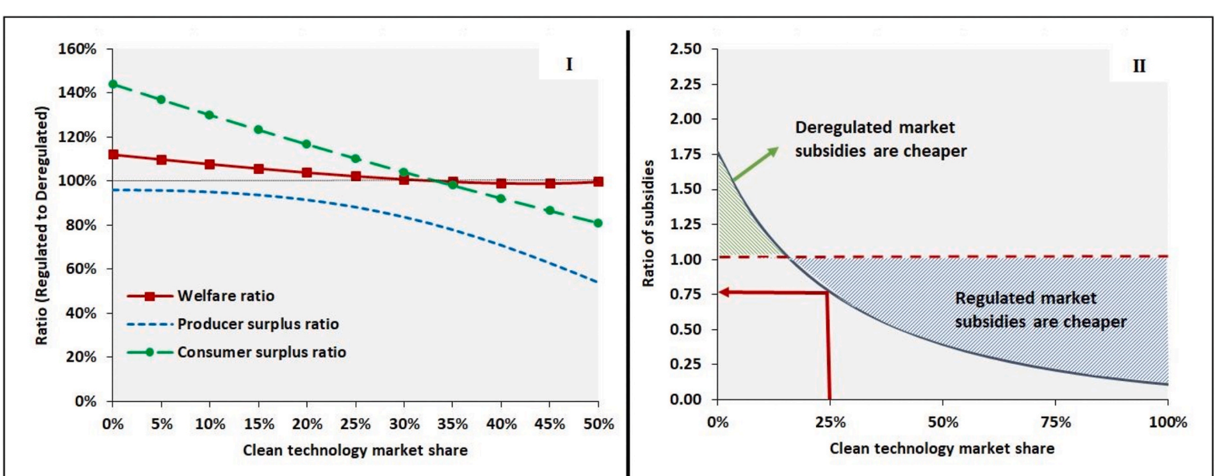
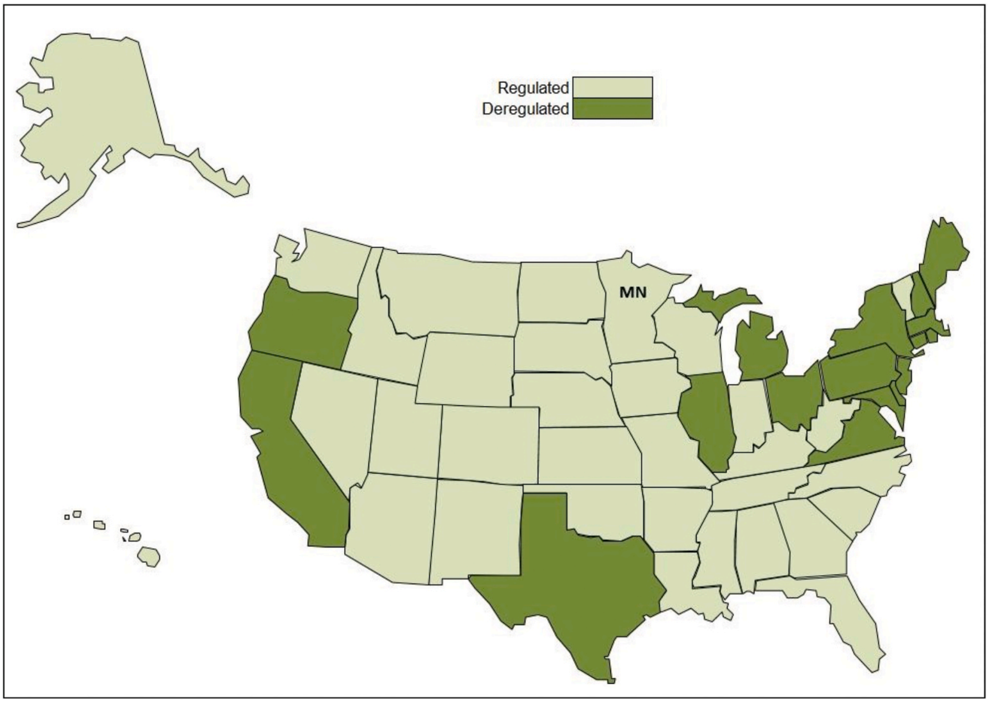


Fig. 4. Producer surplus, Consumer surplus, and Welfare ratios as functions of *Clean* energy technology market share. As the market share increases, both consumer and producer surpluses decreases while social welfare reduces slightly.



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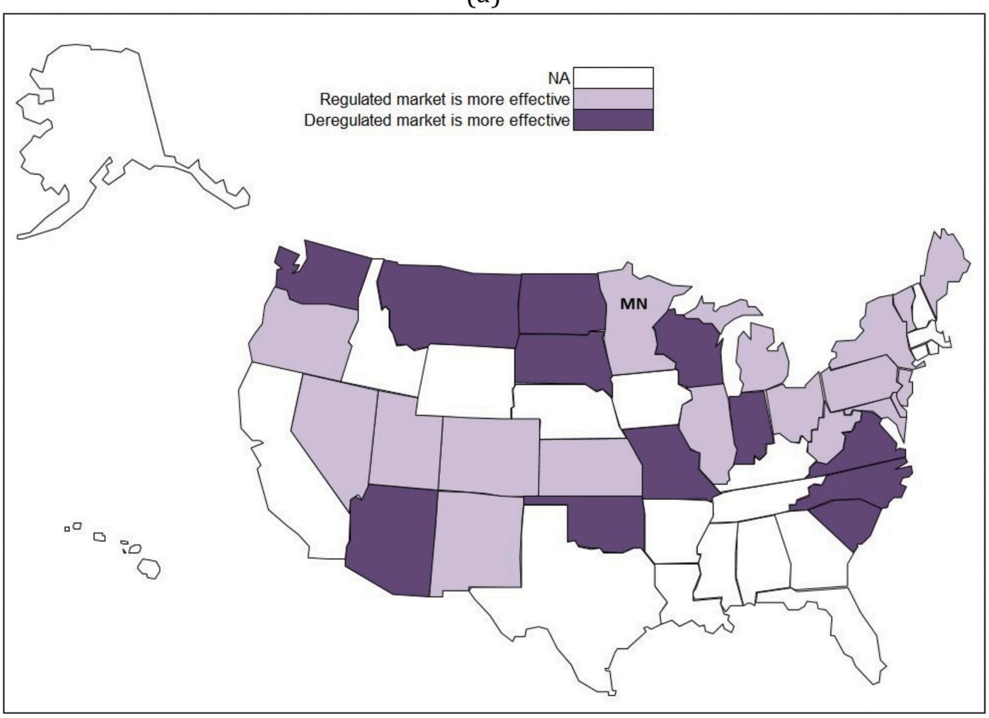

(b)

Fig. 5. RPS and market structures in the United States: (a) deregulated and regulated electricity markets, (b) effectiveness of RPS in regulated and deregulated markets by comparing RPS and critical market share.

through deregulation. In other states with regulated markets including Colorado, Kansas, Minnesota, New Mexico, Nevada, Utah, Vermont, and West Virginia, achieving RPS is more cost-effective under current regulations. Further state-wide analysis is provided in Table C3in Appendix C.

4. Conclusions

Renewable Portfolio Standards are powerful tools to incentivize the deployment of *Clean* energy technologies. In this paper, we compare RPS policies in two types of markets, regulated and deregulated. We use a stylized model of electricity markets to quantify the impact of market structure on the effectiveness of RPS programs. We compare subsidies in two market structures and identify a critical market share that can be achieved by allocating equal amount of subsidy in both market structures. For RPS mandates smaller than the critical value, the benefits of competition favor allocating subsidies in deregulated markets. For RPS mandates above the critical market share, smaller subsidies can achieve higher market share in regulated markets.

As we show in Fig. 2, the critical market share depends only on the cost ratio of energy technologies. For technologies with lower relative cost, deregulated markets are preferred when the target market share is relatively small. However, regulated market subsidies are more effective with a relatively high cost and high target market share. In other words, deregulation helps relatively cheap *Clean* energy technologies to achieve relatively small market share targets.

Our results should be treated with some caution. First, our classification of regulated and deregulated markets is not absolute. Many of state electricity markets in the U.S., for example, are restructured rather than fully liberated and deregulated. Second, we consider a static market without technological innovation [47]. As *Clean* energy technologies have observed rapid price reductions as deployment has increased, this simplification may overestimate subsidy costs and welfare losses [48] for deployment subsidies. Our analysis instead focuses on short-term impacts of market deregulation, and may not be applicable to larger or long-term subsidy programs. Third, we have only focused on the role of subsidies while RPS mandates are usually satisfied through both providing subsidies for *Clean* energy technologies and imposing taxes on *Dirty* energy technologies. Finally, we have considered only biomass as a representative of *Clean* energy technologies. In fact, there are many Other renewable technologies with lower costs and higher market share potential. Our hope is that this analysis paves the way for future research in this field.

4.1. Policy implications

Our analysis has several implications for policy design. First, we find that in both regulated and deregulated markets, subsidies can be designed to guarantee a range of market shares for *Clean* technologies. While market design affects the cost-effectiveness of a RPS, it does not impact the ability of RPS policies to achieve their goals. As a result, policymakers will likely want to consider other constraints, such as political economy or budget limitations, when designing subsidies [49].

Second, regulated markets may enable lower-cost RPS policies as several states contemplate 100% clean energy standards. At least 10 U.S. states and territories have set 100% clean energy standards as of 2020. As mentioned above, larger subsidies are generally needed to achieve higher market shares in deregulated markets compared to regulated markets. Similarly, all US states appear to have a critical market share under 20% for biopower technologies (Table C3). Policymakers designing 100% clean energy standards may want to consider the advantages of regulated markets in maximizing welfare.

Finally, we are not able to derive a critical market share for several states, as the basic underlying assumption of our model ($m_c \geq P^M$) does not hold in this case. For these States such as California, the price of electricity is higher than the cost of *Clean* energy technologies and therefore the government intervention in the form of providing direct subsidies is not justified. In this case, the governments may choose alternative supporting policies such as carbon pricing to promote *Clean* energy technologies [50].

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix F. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.rser.2020.110397.

Appendix A. Welfare calculations

Appendix A.1. Regulated market

The producer surplus for the *Clean* producer (π_c^R) is zero since this producer sells at its cost:

$$\pi_c^R = q_c^R(m_c - m_c) \;= 0 \tag{A.1}$$

In contrast, the producer surplus of the *Dirty* producer (π_d^S) is nonzero:

$$\pi_d^R = q_d^R\left(P^R - m_d\right) = \frac{(1-n)\beta(1-\beta)(a-m_d)^2}{b} \tag{A.2}$$

Total producer surplus is the sum of the two firms' surpluses:

$$\pi^R = \pi_c^R + \pi_d^R = \frac{(1-n)\beta(1-\beta)(a-m_d)^2}{b} \tag{A.3}$$

The consumer surplus (σ^R) can be calculated as:

$$\sigma^R = \frac{Q^R\left(a-P^R\right)}{2} = \frac{(1-\beta)^2(a-m_d)^2}{2b} \tag{A.4}$$

The amount of regulated market subsidies is:

$$\omega^R = q_c^R\left(m_c - P^R\right) = \left(\frac{n(1-\beta)(a-m_d)}{b}\right)(m_c - m_d - \beta(a-m_d)) \tag{A.5}$$

$$= \frac{n(1-\beta)(a-m_d)(m_c - m_d - \beta(a-m_d))}{b}$$

The social welfare is the sum of consumer and producer surpluses minus subsidy Cost:

$$\psi^R = \pi^R + \sigma^R - \omega^R$$

$$\psi^R = \frac{(1-\beta)(a-m_d)((1+\beta)(a-m_d) - 2n(m_c - m_d))}{2b} \tag{A.6}$$

Appendix A.2. Deregulated market

Consumer surplus and overall economic welfare improve in deregulated market. The producer surplus for *Clean* producer (π_c^V) is:

$$\pi_c^V = \left(P^V - m_c^V\right)q_c^V = \frac{n^2(a-m_d)^2}{b(2-n)^2} \tag{A.7}$$

The producer surplus of the *Dirty* producer is:

$$\pi_d^V = \left(P^V - m_d\right)q_d^V = \frac{(1-n)^2(a-m_d)^2}{b(2-n)^2} \tag{A.8}$$

Total producer surplus is the sum of the two firms' surpluses:

$$\pi^V = \pi_c^V + \pi_d^V = \frac{\left[n^2 + (1-n)^2\right](a-m_d)^2}{b(2-n)^2} \tag{A.9}$$

As the deregulated price is less than the monopolistic price, the consumer surplus (σ^V) increases compared to the monopolistic market:

$$\sigma^V = \frac{\left(a - P^V\right)Q^V}{2} = \frac{(a-m_d)^2}{2b(2-n)^2} \tag{A.10}$$

The size of deregulated market subsidies is:

$$\omega^V = q_c^R\left(m_c - m_c^V\right) = \frac{n(a-m_d)}{b(2-n)}\left(m_c - \frac{(1-2n)a + (1+n)m_d}{2-n}\right) \tag{A.11}$$

$$= \frac{n(a-m_d)((2-n)(m_c-m_d) - 2(2-n)(a-m_d) + 3(a-m_d))}{b(2-n)^2}$$

Social welfare is the sum of consumer and producer surpluses minus the subsidy:

$$\psi^V = \pi^V + \sigma^V - \omega^V$$

$$= \frac{(a-m_d)((3-2n)(a-m_d) - 2n(2-n)(m_c-m_d))}{2b(2-n)^2} \tag{A.12}$$

Appendix B. Proof of the Proposition 1

Proposition 1 In a regulated market defined by Equations (2)–(5) and a deregulated market defined by Equations (6)–(13), there exists a critical market share of Clean energy technology, $0 \le n^* \le 1$, that can be achieved by allocating equal amount of subsidies in regulated and deregulated markets.

Proof We define the function $f(n)$ to be the ratio of subsidies needed to achieve the market share $n$in regulated to deregulated markets. We set $f(n^*) = 1$ in order to find the critical market share that requires the same amount of subsidies in both regulated and deregulated markets. We prove that there exists a feasible solution to this equation. We denote by $A = a - m_d$ and $B = m_c - m_d$.

Subtracting Equation A.11 from Equation A.5, gives us:

$$f(n^*) = \frac{\omega^R}{\omega^V} = 1$$

$$f(n^*) = \frac{n^*(1-\beta)A(B-\beta A)}{b} \Bigg/ \frac{nA((2-n^*)B - 2(2-n^*)A + 3A)}{(2-n^*)^2 b} = 1$$

$$f(n^*) = \frac{Abn^*(1-\beta)(B-\beta A)(2-n^*)^2}{Abn((2-n^*)B - 2(2-n^*)A + 3A)} = 1$$

$$\rightarrow n^*\left((1-\beta)(B-\beta A)m^2+(2A-B)m-3A\right)=0$$

where $m = 2 - n^*$ and $1 \leq m \leq 2$.

The equation above has one trivial solution ($n^* = 0$). This is the case where no subsidies are provided. The other solution comes from finding the roots of the quadratic function inside the parenthesis in the nominator of the fraction:

$$(1-\beta)(B-\beta A)m^2+(2A-B)m-3A=0,$$

Forming the discriminant of the quadratic equation, we will have:

$$\Delta=(2A-B)^2+12(1-\beta)A(B-\beta A)$$

In order for $n^*$to exist, Δ must be non-negative. Therefore, we need to have $B-\beta A \geq 0$which gives us

$$\frac{A}{B}\leq\frac{1}{\beta}\rightarrow m_c \geq m_d+\beta(a-m_d)\rightarrow m_c \geq P^R.$$

which holds because of our assumption about the cost of the *Clean* energy technology ($m_c \geq P^M \geq P^R$) and the price regulation coefficient ($0 \leq \beta \leq 0.5$).

In order to have a feasible n^* we require:

$$0 \leq n^* \leq 1 \rightarrow 1 \leq m^* \leq 2$$

We investigate each part of this chain of inequations separately:

- lower-bound condition ($0 \leq n^* \rightarrow m^* \leq 2$):

$$\frac{-(2A-B)\pm\sqrt{(2A-B)^2+12(1-\beta)A(B-\beta A)}}{2(1-\beta)(B-\beta A)}\leq 2$$

$$(2A-B)^2+12(1-\beta)A(B-\beta A)\leq[4(1-\beta)(B-\beta A)+(2A-B)]^2$$

$$3A \leq 4(1-\beta)(B-\beta A)+2(2A-B)$$

$$(2-4(1-\beta))B \leq (1-4\beta(1-\beta))A$$

$$\frac{2-4(1-\beta)}{(2\beta-1)^2}\leq^{**}0\leq^{*}\frac{A}{B}$$

* since A and B are positive, this inequality always holds.
** since $0 \leq \beta \leq 0.5$, this inequality always holds.

- upper-bound condition ($n^* \leq 1 \rightarrow 1 \leq m^*$):

$$1 \leq \frac{-(2A-B)\pm\sqrt{(2A-B)^2+12(1-\beta)A(B-\beta A)}}{2(1-\beta)(B-\beta A)}$$

$$[2(1-\beta)(B-\beta A)+(2A-B)]^2 \leq (2A-B)^2+12(1-\beta)A(B-\beta A)$$

$$(1-\beta)(B-\beta A)+(2A-B)\leq 3A$$

$$\frac{-\beta}{1+\beta(1-\beta)}\leq^{*}\frac{A}{B}$$

* which already holds since A and B are positive.

Therefore, all the conditions for the existence of the critical market share n^* are satisfied.

Appendix C. U.S. electricity market and state RPS mandates

Table C3 provides data on electricity generation and its average prices for all 50 states [42]. We calculate the maximum price $a$and the slope of price function $b$from the following equations:

$$P=m_d+\beta(a-m_d)\Rightarrow a=m_d+\frac{P-m_d}{\beta}$$

$$P=a-bQ\Rightarrow b=\frac{a-P}{Q}$$

Critical market share can be then found by equating equations A.6 and A.12.

The RPS mandates are obtained from Ref. [41].

Table C.3
Market price and supplied quantities of electricity for all 50 states in 2016. Critical market share is calculated for the markets that satisfy the condition stated in Theorem 1.

Year	State	Price ($/MWh)	Quantity (MWh)	A	b	n*	2025 RPS	Deregulated
2016	AK	179	6335034	394.3	3.39304E-05	–	50.0%	No
2016	AL	96	142385098	185.0	6.27875E-07	16.7%	–	No
2016	AR	81	60445059	149.3	1.12416E-06	18.6%	–	No
2016	AZ	103	108763449	204.3	9.28161E-07	15.9%	15.0%	No
2016	CA	152	196963215	326.8	8.85698E-07	–	40.0%	Yes
2016	CO	98	54418480	191.8	1.71725E-06	16.4%	30.0%	No
2016	CT	172	36496560	377.0	5.60601E-06	–	27.0%	Yes
2016	DC	117	76474	239.3	0.00159466	14.6%	20.0%	Yes
2016	DE	111	8731261	223.3	1.28676E-05	15.1%	25.0%	Yes
2016	FL	99	238262150	193.8	3.97252E-07	16.3%	–	No
2016	GA	96	133380416	185.8	6.73637E-07	16.6%	–	No
2016	HI	239	9948845	542.8	3.05613E-05	–	30.0%	No
2016	IA	86	54392507	159.8	1.36508E-06	18.0%	–	No
2016	ID	81	15660938	148.0	4.29093E-06	18.7%	–	No
2016	IL	94	187289131	180.5	4.62921E-07	16.9%	25.0%	Yes
2016	IN	92	101759059	176.5	8.28427E-07	17.1%	10.0%	No
2016	KS	105	47599991	208.3	2.17122E-06	15.7%	20.0%	No
2016	KY	84	80273501	156.5	9.00671E-07	18.2%	–	No
2016	LA	75	107268804	132.5	5.39766E-07	19.7%	–	No
2016	MA	165	31955022	358.0	6.046E-06	–	20.0%	Yes
2016	MD	122	37166687	251.3	3.47489E-06	14.2%	25.0%	Yes
2016	ME	128	11514427	266.0	1.1985E-05	13.8%	40.0%	Yes
2016	MI	111	112121790	222.3	9.96684E-07	15.2%	35.0%	Yes
2016	MN	100	59478753	195.8	1.6115E-06	16.2%	26.5%	No
2016	MO	97	78611513	189.5	1.17158E-06	16.5%	15.0%	No
2016	MS	87	62881295	162.8	1.20942E-06	17.8%	–	No
2016	MT	88	27783529	167.0	2.82901E-06	17.6%	15.0%	No
2016	NC	92	130779157	176.0	6.42304E-07	17.1%	12.5%	No
2016	ND	89	37856452	169.5	2.11589E-06	17.4%	10.0%	No
2016	NE	91	36524869	172.3	2.2382E-06	17.3%	–	No
2016	NH	157	19282493	337.5	9.38157E-06	–	24.8%	Yes
2016	NJ	134	77611403	280.5	1.89019E-06	13.4%	24.5%	Yes
2016	NM	91	32912045	174.0	2.5158E-06	17.2%	20.0%	No
2016	NV	84	39787005	155.8	1.80587E-06	18.2%	25.0%	No
2016	NY	145	134417107	307.8	1.21302E-06	12.8%	50.0%	Yes
2016	OH	98	118922078	192.0	7.8707E-07	16.4%	25.0%	Yes
2016	OK	78	78655007	141.8	8.06687E-07	19.1%	15.0%	No
2016	OR	88	60182013	166.8	1.30355E-06	17.6%	25.0%	Yes
2016	PA	102	215066509	200.8	4.59625E-07	16.0%	18.0%	Yes
2016	RI	163	6564885	353.0	2.89723E-05	–	23.5%	Yes
2016	SC	98	96985764	190.8	9.57357E-07	16.4%	2.0%	No
2016	SD	98	11524184	191.8	8.10903E-06	16.4%	10.0%	No
2016	TN	92	79340633	176.8	1.0644E-06	17.1%	–	No
2016	TX	84	454047591	156.8	1.59565E-07	18.1%	–	Yes
2016	UT	87	38133928	164.0	2.01395E-06	17.7%	20.0%	No
2016	VA	91	92554876	173.3	8.89742E-07	17.2%	15.0%	Yes
2016	VT	145	1911207	307.5	8.52341E-05	12.8%	55.0%	No
2016	WA	77	114086582	138.0	5.36435E-07	19.3%	15.0%	No
2016	WI	107	64966611	212.8	1.63238E-06	15.5%	10.0%	No
2016	WV	90	75942968	170.5	1.06264E-06	17.4%	25.0%	No
2016	WY	82	46656630	150.8	1.47567E-06	18.5%	–	No

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