Netw Spat Econ (2013) 13:149–181
DOI 10.1007/s11067-012-9176-0

Renewable Portfolio Standards in the Presence of Green Consumers and Emissions Trading

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Published online: 22 May 2012

Abstract Greenhouse gas (GHG) emissions trading, green pricing programs and renewable portfolio standards (RPS) are three concurrent policies implemented in the United States to reduce reliance on fossil fuel and GHG emissions. Despite their differences in policy targets, they are closely related and integrated with competitive electric markets. This paper examines the interactions among these three policies by considering two aspects of the RPS policy design: double-counting and bundling. Whereas the former grants utilities using the same MWh of renewable energy to meet RPS and to sell as green power, the latter allows them to bundle the renewable energy credits/certificates (RECs) with non-renewable electricity and sell as green power. This paper studies the policy designs by formulating each policy combination as a market model, which treats electricity as a differentiated product. We derive the conditions under which the REC price serves as the upper bound of the green premium or vice versa. The theoretical analysis shows that the bundling could be redundant in the presence of double counting. The policies that allow for double-counting appear to be a better choice, since they result in a higher social surplus. Most surplus gains are due to consumers surplus from green power sales. The framework we develop in this paper is capable

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of incorporating other detailed policy designs in the analysis such as strategic reserve and offset.

Keywords Renewable portfolio standards · Green pricing programs · Emission trading programs · Electricity market

1 Introduction

Choices of policy instruments on emissions reduction have a profound impact on regulated industries and the environment. A good instrument provides incentives and flexibilities to meet the reduction target at the least costs, preserving economic efficiency, while an inappropriate instrument possibly intervenes with existing policies or market conditions, creating loopholes or difficulties for compliance. As climate change becomes evident, numerous resources and policies have been devoted to controlling greenhouse gas emissions (GHG) from the power sector and other energy-intensive sectors.[1] GHG emissions cap-and-trade (C&T), green pricing programs and the renewable portfolio standard (RPS) are three concurrent policies/programs that are implemented in several eastern states in the United States to reduce reliance on fossil-fueled energy. These three policies are all markets-based instruments but distinct in significant ways. C&T programs first establish a cap on total regional emissions and then allocate permits to affected facilities by means of grandfathering, auctions, etc. One unit of permit allows its holder to emit a fixed amount of pollutant, and permits can be traded in secondary markets. The owners of polluting facilities can reduce pollution through operational or equipment upgrades, or purchase permits from other companies who have excess permits. Excess permits can be sold or banked for future use. RPS mandates a certain percent (or a MWh amount in some states) of electricity generation to be from renewable sources. The last of the three policies is the voluntary green pricing programs that are offered by utilities or independent marketers to their consumers who are willing to pay a "green premium" to ensure their consumed electricity is from renewables. The point-of-regulation under the RPS is generally on load serving entities (LSEs). In some states, there is more than one way of meeting the RPS requirements: self-generation, procuring power from renewable sources via bilateral contracts and purchasing renewable energy credits/Certificates (RECs) from secondary markets. Thus, the RPS REC is the analog of the allowances or permits in a C&T program.

On June 26, 2009, the United States House of Representatives passed the American Clean Energy and Security Act of 2009 (ACESA) (Committe on Energy and Commerce 2008). The "Clean Energy Jobs and American Power

[1] In the United States, the electric power sector emits three-quarters of SO_2 emissions, one-fifth of NOx emissions, one-third of mercury emissions, and two-fifths of GHG, with the latter fraction anticipated to rise significantly in the next two decades.

Act" (also known as the Kerry-Boxer Bill) was subsequently introduced to the Senate on September 30, 2009. Both detail a suite of policies to reduce GHG emissions and create job opportunities.[2] Although three policies (i.e., RPS, green pricing and GHG C&T) are currently co-existing only in some eastern states in the United States, their joint implementation is expected in many more states in the foreseeable future.

The literature concerning the interactions of green pricing programs, RPS and C&T programs can be broadly divided into two focuses: qualitative and quantitative. Bird and Lokey (2007) and Bird et al. (2008) summarized key issues of how renewable energy markets might interact with carbon regulation, including the implications for emissions benefits claims, voluntary market demand and the use of RECs in multiple markets (e.g., double-counting). Mozumder and Marathe (2004) gave an overview of RPS and discussed the benefits of an integrated RECs market. Gillenwater (2008a, b) explained various challenges when using RECs to offset pollution emissions (e.g., additionality). Holt and Wiser (2007) summarized the treatment of renewable energy attributes in state RPS rules and addressed a number of crucial issues for implementing successful policies. Several studies examined the RECs and/or the emissions markets quantitatively. Amundsen and Mortensen (2001) applied a simple static model to examine change in the RPS requirement and a C&T program on the short- and long-run outcomes in the emerging Danish green certificates markets based on comparative statics principles. Jensen and Skytte (2002) used a similar setup (but excluding emission markets) and found increasing RPS would raise REC price. However, the impact on consumers price was ambiguous due to a decline in conventional electricity demand that drives down the wholesale electricity price. Hindsberger et al. (2003) examined the long run implications of co-existence of emissions and RECs markets in the Baltic Sea region. The paper concluded that C&T and RPS can effectively increase renewables deployment. Yet the issue of how the prices of the emissions allowances might interact with RECs prices was not addressed. Linares et al. (2008) analyzed the emissions and renewable policies in the context of the Spanish market by using graphic and simulation approaches. The main conclusion is that a certain coordination is necessary in order to meet respective policy targets without sacrificing consumers' benefits. Finally, a recent paper by Tsao et al. (2011) found that when a C&T coexisted with an RPS, lowering the C&T cap might penalize renewable units, and increasing the RPS level could sometimes benefit coal and oil and make natural gas units less attractive.

Process-based models that incorporate transmission networks have been applied to examine issues related to electricity markets that is comprised of producers with heterogeneous production technologies and emissions rates

[2] ACESA includes (i) a clean energy provision to promote renewable energy through RPS, low-carbon transportation fuel, clean electric vehicles, smart grid technology etc., (ii) an energy efficiency provision to increase energy efficiency across economy sectors and (iii) a global warming provision to develop federal C&T programs to regulate GHG emissions.

(Wei and Smeers 1999; Metzler et al. 2003; Hobbs 2001; Bushnell 2003; Yao et al. 2008; Chen and Hobbs 2005). Supply curves in these models were represented by step functions in contrast to other models with smooth function representations that require an interior solution assumption when deriving first-order optimality conditions. The strength of these models is readily available theories concerning the existence and uniqueness of the solutions as well as the availability of efficient algorithms to solve them. Wei and Smeers (1999) studied the market power in electricity markets when transmission prices are regulated. Yao et al. (2008) examined the generators' market power in a two-settlement system (e.g., day-ahead and spot market). Hobbs (2001) established the equivalence of the bilateral and the pooled-type power market. Chen and Hobbs (2005) studied how generators might enhance their market power in the electricity market by manipulating the NO_x allowances market. Bushnell (2003) formulated the hydrothermal scheduling problem under the Cournot assumption. When applied to the western United States power system, the results indicated that some firms find it profitable to allocate a considerable amount of hydro-production to the off-peak periods. This is in contrast to the general wisdom that hydro should produce in the peak periods to take advantage of higher electricity prices. As the GHG emissions rate is unlikely to be monotonic, we opt to use this approach to model policy interactions.

This paper extends the existing work by simultaneously considering the green pricing programs, RPS and a GHG C&T program in the models. We infer from our models in Section 3 concerning the relationship between the green premium and REC prices as well as identify what might be redundant when some designs in the RPS programs (e.g., double counting and bundling) that aim at reducing compliance costs. Electricity is treated as differentiated products in our model, as opposed to homogeneous commodities in other studies. We explicitly model the joint optimization problem faced by LSEs and consumers, which is to maximize the consumer value minus the costs of procuring electricity (i.e., the payments to generators). This is contrary to the previous studies in which the consumers and the LSEs are represented by inverse demand curves. Besides incorporating transmission constraints that are overlooked in many other studies, we also explicitly model various institutional aspects of the regulation that allow the point-of-regulation to be varied by policies.[3] We limit our analysis to the short-run since we are mainly interested in how different prices interact and how firms with different generation mixes respond to multiple policies. As discussed later, the framework is readily tailored to other policy features (e.g., offset and strategic reserve) or extended to other long-run analysis.

[3] Consistent with the actual policies, the point-of-regulation for RPS and GHG C&T is on LSE and producers, respectively. Several GHG C&T programs, which differ by their point-of-regulation, were considered by California when implementing AB32 (e.g., source-based, load-based and first-jurisdictional approaches.) The motivation of the second and the third programs is to prevent the incidents of emissions leakage (Chen et al. 2011). These design features can be easily incorporated in the current models, but their interaction of the RPS and green pricing programs are beyond the scope of this paper.

The results from our analyses show that the double-counting and bundling render an easier solution for LSEs to meet their RPS target and also provide an effective arbitrage opportunity between the RECs and green premiums. As detailed in the five propositions in Section 3.3, under certain conditions, the REC price serves as an upper bound to the green premium; under other conditions, it becomes the lower bound. Moreover, if the double-counting is not allowed, then the "no bundling" requirement appears to be redundant. In general, policies that allow more flexibility lead to a higher social surplus, due to the increase of consumers surplus from green power sales and the pass-through of the lower RPS compliance costs to consumers. Finally, a tighter emissions cap results in a lower REC price due to demand response and a positive effect on green energy sales.

The remainder of this paper is organized as follows. Section 2 contains background on the current state of the GHG C&T, green pricing programs and RPS in the United States. In Section 3, we introduce the mathematical formulation of the models, together with their theoretical properties. Then in Section 4, we present the setup of our case study, including the generation mixes, transmission network and the policy assumptions. In Section 5 we provide some closing comments.

2 Background

GHG C&T programs have received considerable popularity recently. Although emissions trading is not a new concept, the economic impact of GHG policies is expected to be more far-reaching than the previous programs that target other pollutants (e.g., SO_2 and NO_x). This is in part because facilities regardless of their technologies would incur substantial emissions costs. The pioneer EU ETS (European Union Emissions Trading Scheme), which began in 2005 and then expanded to 27 EU member countries in 2007, has produced the number of encouraging results (Convery and Redmond 2007). The basic principle of a C&T program is that a fixed number of emissions allowances are distributed to the emissions sources (e.g., power generators), and these facilities need to have sufficient allowances or permits to cover their annual emissions by the end of the compliance cycle. The emissions allowances may be traded in secondary markets.

In the United States, due to the lack of federal leadership,[4] a number of states have taken actions to control GHG emissions. The programs in the eastern, midwestern and western states are called RGGI (Regional Greenhouse

[4]Although the recent setback of the Obama Administration in the midterm election may slowdown the development of a comprehensive federal climate or energy policy, the EPA (Environmental Protection Agency) has undertaken a strong leadership in regulating GHG emissions through the New Source Review (NSR) rules under the Clean Air Act. Unlike the fact that NSR has little impacts on existing facilities in regulating SO2 emissions, NSR for GHG or CO_2 is expected to have significant financial impacts on the power sector (Burtraw et al. 2004).

Gas Initiative 2011), MGGA (Midwestern Greenhouse Gas Reduction Accord 2011) and WCI (Western Climate Initiative 2011), respectively. RGGI's compliance schedule set forth that the CO_2 emissions will be capped at the current level during 2009–2015, followed by a gradual decline to 10 percent below the current level by 2019. Fossil-fueled generating units (e.g., gas, oil and coal) with a name capacity greater than or equal to 25 MW fall under the cap. A total of 77.8 millions tons of CO_2 permits have been sold in three runs of auctions (sealed bid, first price) conducted by RGGI since September 2008. The permit price ranges from \$3.0 to \$3.5/ton (Regional Greenhouse Gas Initiative 2009). MGGA constitutes nine midwestern states and two Canadian provinces. The program aims to establish a multi-sector C&T program to reduce GHG emissions. Among the WCI states, California is the first one to adopt legislation limiting GHGs (including six species). On September 27, 2006, the state of California passed a comprehensive bill—AB32, "The Global Warming Solutions Act"—that aims at reducing in-state GHG emissions from various sectors to the 1990 level by 2020, which is equivalent to a 25% decline compared to the business-as-usual case (California Air Resources Board 2008). AB32 is the first climate change legislation in the United States that regulates most polluting sectors in an economy. Led by the California Energy Commission (CEC) and the California Air Resources Board (CARB) in consultation with other agencies, a state-wide emissions cap is expected to be in effect by 2013. This is expected to be accomplished with a suite of instruments such as a low carbon fuel standard for vehicles that would reduce GHGs of transportation fuels by at least 10% by 2020 (California Air Resources Board 2007).

In parallel with the GHG C&T program are the RPS and green pricing programs. Whereas the RPS is a mandatory requirement, the green pricing programs are voluntary. Depending on whether the programs are offered by regulated utilities or by independent marketers, these voluntary programs are referred to as green pricing and green power marketing, respectively (US Department of Energy 2008). In this paper, we will refer to them collectively as "green pricing programs." As of 2010, a total of thirty-four and forty states together with the District of Columbia have RPS and green pricing programs, respectively. The eligible sources, the targeting year and the level of the RPS requirement vary by states, reflecting the aggressiveness of the state policies and the types of renewable sources that states possess (Bird and Lokey 2007). For example, whereas hydropower with a capacity greater than 25 MW does not qualify in most states, it is eligible under Maine's RPS program. California has a binding RPS of 33% by 2020, compared to Arizona's goal of 15% by 2025. Some RPSs have tier structures, which would favor certain technologies: class I technologies under the New Jersey RPS include solar, wind, tidal wave, geothermal, etc. (Database of State Incentives for Renewable and Efficiency 2008). In some states, the RPS is a non-binding policy (e.g., North Dakota, 10% by 2015.) The REC prices have varied significantly by states (Wiser and Barbose 2007), reflecting all the factors discussed above.

The premium of the utilities' green pricing programs ranges from \$1 to \$176/MWh with a national average of \$21/MWh (Bird and Lokey 2007). The premium of the programs offered by the independent marketers in the deregulated markets ranges between \$1 to \$25/MWh. In some states, the green pricing programs providers are allowed to bundle power generated from fossil-fueled sources with RECs and sell as green power (Bird and Lokey 2007). This provides a direct arbitrage opportunity between REC and green power. However, there is no theoretical and empirical study examining their interactions.

We study the RPS and green pricing programs considering a combination of two policy/program features:

- Double-counting:[5] If double-counting is allowed, the same MWh of procured renewable power can be used to meet RPS and sell to consumers as green power. Double-counting is allowed only in Texas, Arizona and Wisconsin (Holt and Wiser 2007).
- Bundling: If bundling is allowed, LSEs can purchase RECs from secondary markets and sell to consumers as green power by bundling them with ordinary power. The reverse "*un-bundling*" is allowed in most states since RECs represent the "green-ness" of renewable energy (Holt and Wiser 2007). In current markets, bundling is allowed in some but not all of the markets in the United States (Bird and Lokey 2007).

Depending on whether double-counting and bundling are allowed, we define four cases for in-depth analysis:

Case 1: Both double-counting and bundling are allowed.
Case 2: Double-counting is allowed but bundling is not.
Case 3: Bundling is allowed but double-counting is not.
Case 4: Neither double-counting nor bundling is allowed.

3 Model

In this section, we formulate the four cases described in Section 2 as separate market models and derive their market equilibrium conditions. The models are variants of Hobbs (2001) and Chen and Hobbs (2005), elaborated to account for the three environmental policies.[6] One key feature of these models is that sales of electricity from a source to a destination is modeled as re-routing through a hub. This approach has significant implications concerning transmission charges, and we will elaborate on it further in the relevant sections.

[5]The term "*double-counting*" has also been defined differently in references (Bird and Lokey (2007); Holt and Wiser (2007)) as the same MWh of green energy being used to meet RPS in more than one state.

[6]Similar models based on complementarily formulations include electricity markets (Leuthold et al. 2010; Smeers 2003a, b) and gas markets (Gabriel et al. 2003).

A theoretical analysis of the mathematical properties of the models, including the uniqueness and the existence of equilibria, can be found in Metzler et al. (2003). In Section 3.1, we introduce the notations used in the models; the optimization models for market participants are presented in Section 3.2, and we derive propositions regarding the properties of the market equilibria in Section 3.3.

3.1 Notations

We use upper-case, lower-case, and the Greek lower-case letters for parameters/sets, variables/indices, and dual variables, respectively.

Sets and Indices

I	Set of zones
H	Set of generating units
K	Set of flowgates or transmission lines
F	Set of power producers
$i, j \in I$	Zone or LSE i, j
$f \in F$	Power producer f
$H_{\text{if}}(H_{\text{if}}^{\text{G}}$ or $H_{\text{if}}^{\text{O}})$	Sets of all (green or ordinary) generators owned by firm f located at zone i
$h \in H$	Generator h
$k \in K$	Flowgate or transmission link k

Parameters

$P_j^0(Q_j^0)$	Price (quantity) intercept of the inverse demand function at zone j [\$/MWh (MWh)]
$P_j^{\text{G}}(Q_j^{\text{G}})$	Price (quantity) intercept of the inverse demand function for green premium j [\$/MWh (MWh)]
K_f	Initial free allocation of GHG allowances to firm f [tons]
E_{fih}	Emission rate of generator (f, i, h) [tons/MWh]
$\overline{E}$	System-wide GHG cap [tons]
R	RPS requirement [unitless]
X_{fih}	Capacity of generator (f, i, h) [MW]
C_{fih}	Unit production cost of generator (f, i, h) [\$/MWh]
$PTDF_{ki}$	The (k, i)-th element of the power transmission distribution factor matrix
T_k	Thermal capacity of flowgate or transmission link k [MW].

Variables

z_{fihj}	LSE j's purchase of power from generator (f, i, h) [MWh]
z_j^{G}	LSE j's total purchase of green power [MWh]: $z_j^{\text{G}} = \sum_{f,i,h \in H_{\text{if}}^{\text{G}}} z_{fihj}$
z_j^{O}	LSE j's total purchase of ordinary power [MWh]: $z_j^{\text{O}} = \sum_{f,i,h \in H_{\text{if}}^{\text{O}}} z_{fihj}$
s_j^{O} (s_j^{G})	LSE j's total sales to consumers of ordinary (green) power [MWh]

s_j^{REC}	LSE j's REC sales (positive) or purchase (negative) [MWh]
x_{fihj}	Power produced by generator (f, i, h) and sold to LSE j [MWh]
y_i	MWs transmitted from the hub to zone i (positive) or vice versa (negative) [MW]
w_i	Transmission fees associated with y_i [$/MW]
p_j^E	Price of electricity at zone j [$/MWh]
p_{fihj}	Price of electricity produced by generator (f, i, h) and sold to LSE j [$/MWh]
p^{GHG}	GHG permit price [$/ton]
p^{REC}	REC price [$/MWh]
p_j^{G}	Green premium in addition to p_j^E [$/MWh]

3.2 Optimization models for market participants

Consumers Consumers' willingness-to-pay for electricity is described by the inverse demand function:

$$p_j^E = P_j^0 - \frac{P_j^0}{Q_j^0}\left(s_j^{\mathrm{O}} + s_j^{\mathrm{G}}\right), \tag{1}$$

where superscripts O and G indicate ordinary and green/renewable electricity, respectively. We assume that there is another segment of consumers who are willing to pay a green premium, p_j^{G}, in addition to p_j^E to support energy generated from renewable sources. The marginal benefit of green power is characterized by the inverse demand curves with choke price (P_j^{G}) and quantity (Q_j^{G}), respectively. Choke price is likely location-specific, endogenously determined by education, income and other social-economic factors.[7] The amount of green premium is therefore a function of sales of green electricity and can be expressed as follows:[8]

$$p_j^{\mathrm{G}} = P_j^{\mathrm{G}} - \frac{P_j^{\mathrm{G}}}{Q_j^{\mathrm{G}}} s_j^{\mathrm{G}}. \tag{2}$$

[7] These parameters are defined in the numerical section mainly for illustrative purposes with partial reference to the actual market data. In reality, the endogeneity between prices and quantities makes the identification very difficult in most cases. A typical approach is to identify some exogenous shocks, demand (cost) shifters, that are perpendicular or unrelated to the supply (demand) conditions and use them as instrument variables in the analysis. A classic example is to estimate the demand of fish consumption in fish markets (Angrist et al. 2000). The paper illustrated using the weather conditions as an instrument variable for cost shifters since the fish demand in the market is unlikely to be affected by the bad weather conditions hundred or thousands of miles away.

[8] Of course, the green premium could also depend on the prices of ordinary electricity or the total consumptions. However, under these cases, the inverse demand function could be nonlinear, and the nice properties associated with LCPs cannot be applied. We thank one referee for noting this.

Load Serving Entities We assume that LSEs, one in each zone, procure electricity on behalf of consumers via bilateral contracts with generators.[9] Hence, LSE j maximizes zone j's consumers surplus, which is defined as consumer willingness-to-pay (areas under demand curves (1) and (2)) minus payments to power suppliers and RECs.[10] The optimization problem faced by LSE j is the following:

$$\max_{z,s^{\mathrm{G}},s^{\mathrm{O}},s^{\mathrm{REC}}} \quad P_j^0\left(s_j^{\mathrm{O}}+s_j^{\mathrm{G}}\right)-\frac{P_j^0}{2Q_j^0}\left(s_j^{\mathrm{O}}+s_j^{\mathrm{G}}\right)^2 \tag{3}$$

$$+P_j^{\mathrm{G}}s_j^{\mathrm{G}}-\frac{P_j^{\mathrm{G}}}{2Q_j^{\mathrm{G}}}\left(s_j^{\mathrm{G}}\right)^2$$

$$-\sum\nolimits_{f,i,h\in H_{\mathrm{if}}} p_{\mathrm{fihj}}z_{fihj}$$

$$+p^{\mathrm{REC}}s_j^{\mathrm{REC}}$$

$$\text{s. t.} \qquad z_j^{\mathrm{G}}+z_j^{\mathrm{O}}=s_j^{\mathrm{O}}+s_j^{\mathrm{G}}, \qquad (\theta_j) \tag{4}$$

$$s_j^{\mathrm{REC}}\le z_j^{\mathrm{G}}-R\left(z_j^{\mathrm{G}}+z_j^{\mathrm{O}}\right), \qquad (\phi_j) \tag{5}$$

$$f_j\left(s_j^{\mathrm{G}}, z_{fihj}, s^{\mathrm{REC}}, R\right)\le 0 \tag{6}$$

$$z_j^{\mathrm{G}}=\sum\nolimits_{f,i,h\in H_{\mathrm{if}}^{\mathrm{G}}} z_{fihj} \qquad \left(\omega_j^{\mathrm{G}}\right) \tag{7}$$

$$z_j^{\mathrm{O}}=\sum\nolimits_{f,i,h\in H_{\mathrm{if}}^{\mathrm{O}}} z_{fihj} \qquad \left(\omega_j^{\mathrm{O}}\right) \tag{8}$$

$$z_{fihj}, s_j^{\mathrm{G}}, s_j^{\mathrm{O}}, z_j^{\mathrm{O}}, z_j^{\mathrm{G}}\ge 0;\ s_j^{\mathrm{REC}} \text{ free.} \tag{9}$$

The first two terms in the objective function (Eq. (3)) are consumer willingness-to-pay for electricity consumption $\int_0^{s_j^{\mathrm{G}}+s_j^{\mathrm{O}}}(P_j^0-\frac{P_j^0}{Q_j^0}q)dq$ and the "green-ness" attribute $\int_0^{s_j^{\mathrm{G}}}(P_j^{\mathrm{G}}-\frac{P_j^{\mathrm{G}}}{Q_j^{\mathrm{G}}}q)dq$, respectively. The third term is payment to generators, and the fourth represents the revenue from the REC sales. A positive (negative) s_j^{REC} means sales to (purchase from) the REC market.

[9]This formulation is also used for modeling the economic and emissions implications of the load-based emissions trading program under the California AB32 (Chen et al. 2011). When (i) modeling electricity as homogeneous products (no green premium) and (ii) without considering RPS and C&T policies, the lines 2 and 4 in Eq. (9) and the Constraints (5) and (6) will be omitted. After substitutions of z variables for s variables, the first-order condition with respect to z becomes $0\le \perp p_{\mathrm{fihj}}-(P_j^0-(P_j^0/Q_j^0)(z_j^{\mathrm{O}}+z_j^{\mathrm{G}})\ge 0$, where the second term to the right of $\perp$ defines the marginal benefit. This condition states that consumption in j will be up to the level when $p_{\mathrm{fihj}}=$ marginal benefit, a standard result from the consumers theory.

[10]In a sense, we model the consumers and LSE jointly. The first three lines in the objective function (Eq. (3)) could be expanded to "consumers' willingness-to-pay" —"consumers' payments to the LSE" + "payments received by the LSE from consumers"—"payments to producers by the LSE." The middle two terms are cancelled out because they become an internal wealth transfer between consumers and the LSE when modeling the consumers and LSE as a single entity.

Constraint (4) requires the balance between total sales and total procurement. Constraint (5) restricts the REC sales within the difference between green procurement and RPS requirement. That is, an LSE cannot sell more RECs than it possesses. Finally, Constraint (6) is case-dependent, and we elaborate it as follows:

Case 1 In this case, Constraint (6) becomes

$$s_j^{\mathrm{G}} \leq z_j^{\mathrm{G}} + \left[z_j^{\mathrm{G}} - s_j^{\mathrm{REC}} - R\left(z_j^{\mathrm{G}} + z_j^{\mathrm{O}}\right)\right] \qquad (\tau_j) \tag{10}$$

$$s_j^{\mathrm{G}} \leq R\left(z_j^{\mathrm{G}} + z_j^{\mathrm{O}}\right) + \left[z_j^{\mathrm{G}} - s_j^{\mathrm{REC}} - R\left(z_j^{\mathrm{G}} + z_j^{\mathrm{O}}\right)\right] \qquad (\delta_j). \tag{11}$$

These two constraints are equivalent to

$$s_j^{\mathrm{G}} \leq \min\left\{z_j^{\mathrm{G}}, R\left(z_j^{\mathrm{O}} + z_j^{\mathrm{G}}\right)\right\} + z_j^{\mathrm{G}} - s_j^{\mathrm{REC}} - R\left(z_j^{\mathrm{O}} + z_j^{\mathrm{G}}\right). \tag{12}$$

Here, the term with the min operator is the amount of green power eligible for double-counting, and the terms $z_j^{\mathrm{G}} - s_j^{\mathrm{REC}} - R(z_j^{\mathrm{O}} + z_j^{\mathrm{G}})$ are the green power procurement less REC sales and RPS requirement. Therefore, the right-hand-side of Eq. (12) is the amount of green power eligible to receive green premium. For instance, if $z_j^{\mathrm{G}} = 10$ MWh and $R(z_j^{\mathrm{O}} + z_j^{\mathrm{G}}) = 8$ MWh, then 8 MWh can be used to meet RPS and sold as green power, but the other 2 MWh green power can be sold either as green power or into the REC market but not both. In the presence of an arbitrage opportunity ($p_j^E > p^{\mathrm{REC}}$), LSE could also purchase RECs, bundle them with ordinary power, and sell it as green power.

Case 2 In this case, Constraint (6) becomes:

Constraints (10) and (11)

$$s_j^{\mathrm{G}} \leq z_j^{\mathrm{G}} \qquad (\kappa_j) \tag{13}$$

Constraints (10) and (11) remain unchanged since double-counting is allowed. Constraint (13) requires that green power sales be bounded by green power procurement, since bundling is not allowed. So, if $z_j^{\mathrm{G}} = 10$ and $R(z_j^{\mathrm{O}} + z_j^{\mathrm{G}}) = 8$, the result is the same with Case 1 except that s_j^{G} is bounded from above at 10 MWh.

Case 3 In this case, Constraint (6) becomes:

$$s_j^{\mathrm{G}} \leq z_j^{\mathrm{G}} - s_j^{\mathrm{REC}} - R\left(z_j^{\mathrm{O}} + z_j^{\mathrm{G}}\right) \qquad (\gamma_j) \tag{14}$$

The difference between Constraint (14) and (12) is that the extra amount of double-counted green power sales, $\min\{z_j^{\mathrm{G}}, R(z_j^{\mathrm{O}} + z_j^{\mathrm{G}})\}$, is not allowed in Case 3. So, if $z_j^{\mathrm{G}} = 10$ and $R(z_j^{\mathrm{O}} + z_j^{\mathrm{G}}) = 8$, then LSE can only sell at most 2 MWh of its procured green power plus REC-bundled ordinary power.

Case 4 In this case, Constraint (6) becomes Constraints (13) and (14). So, if $z_j^{\mathrm{G}} = 10$ and $R(z_j^{\mathrm{O}} + z_j^{\mathrm{G}}) = 8$, then LSE can sell at most 2 MWh of its procured green power minus sales to the REC market.

Producers Producers are assumed to be price-takers with respect to p_{fihj} and w_i, who maximize profits subject to GHG regulation. Producer f's profit maximization problem is as follows:[11]

$$\max_x \quad \sum_{i,j,h\in H_{\mathrm{if}}} p_{\mathrm{fihj}} x_{\mathrm{fihj}} \tag{15}$$

$$- \sum_{i,h\in H_{\mathrm{if}},j} C_{\mathrm{fih}} x_{\mathrm{fihj}}$$

$$- \sum_{i,h\in H_{\mathrm{if}},j} (w_j - w_i) x_{\mathrm{fihj}}$$

$$- p^{\mathrm{GHG}} \left(\sum_{i,h\in H_{\mathrm{if}},j} E_{\mathrm{fih}} x_{\mathrm{fihj}} - K_f \right)$$

$$\text{s.t.} \quad \forall i, j, h \quad \sum_j x_{\mathrm{fihj}} \le X_{\mathrm{fih}} \qquad (\rho_{\mathrm{fih}}) \tag{16}$$

$$\forall i, j, h \quad x_{\mathrm{fihj}} \ge 0. \tag{17}$$

The four terms in the objective function (Eq. (15)) are sales revenue, production costs, transmission payments and emissions allowances payment, respectively. In the last term, if $\sum_{i,h\in H_{\mathrm{if}},j} E_{\mathrm{fih}} x_{\mathrm{fihj}} - K_f \ge 0$, then producer f produces more than its tolerated emissions K_f and has to buy extra emissions allowances; on the contrary, if $\sum_{i,h\in H_{\mathrm{if}},j} E_{\mathrm{fih}} x_{\mathrm{fihj}} - K_f \le 0$, then the producer does not reach its maximum emissions and is assumed to sell its extra allowance to others at the price p^{GHG}.

The way we model the transmission charge requires some explanations. The transmission charge w_i is defined as the per MW price of delivering power from the hub to location i. This can be positive or negative; it is positive if moving 1 MW from the hub to i worsens congestion, while it is negative if moving power in that direction instead relieves congestion (so-called counterflow). A negative flow from the hub to i (that is, a delivery in the opposite direction) instead is paid that amount by the grid, as economically and physically it has precisely the opposite effect upon system costs. To ship power produced in i to j, the net transmission charge per MW is equal to w_i (revenue received by providing counterflow from i to the hub) minus w_j (payments to ship power from the hub to j).

[11] Of course, the power market could be dominated by a few producers (Bushnell et al. 2008), and a oligopoly formulation could be an alternative representation to the market conditions. However, the price-taking assumptions concerning the producers behavior allow us to isolate and understand the interactions among the three policies. For example, had market power in electricity markets been considered, we might find it difficult to disentangle the effects of bounding or double-counting from strategic manipulation. One possible extension is to model LSEs with market power by formulating their objective functions as “consumers’ payments to the LSE” minus “payments received by the LSE from consumers.” We leave these considerations to future research.

ISO The system operator is assumed to be a price-taker with respect to w_i as it maximizes the value of the transmission network, which is equal to the summation of the product of injection/withdrawal (y_i) and transmission charge (w_i) over i. We use the same formulation as in Metzler et al. (2003); Hobbs (2001); Yao et al. (2008); Chen and Hobbs (2005). More sophisticated formulations that allow for transmission losses or phase shifters can be found in Chen et al. (2006); Hobbs et al. (2008).

$$\max_{y} \quad \sum_i w_i y_i \tag{18}$$

$$\text{s.t.}\ \forall k \in K \quad -T_k \le \sum_i PTDF_{\text{ki}} y_i \le T_k \quad (\lambda_k^-, \lambda_k^+) \tag{19}$$

$$y_i, \text{free},$$

where variables λ_k^- and λ_k^+ correspond to the dual variables of the lower and upper transmission capacity constraints, respectively. PTDF stands for power transfer and distribute factor, which describes the linear relationship between power flows in the network and power injections/withdrawals at different locations. It is derived from the Kirchoff's Current and Voltage Laws assuming no resistance losses (Schweppe et al. 1988).

Market Clearing Conditions In addition to Eqs. (1) and (2), the other market clearing conditions, one for each commodity, that determine p^{REC}, p^{GHG}, w_i and p_{fihj} are listed in Eqs. (20)–(23). These conditions, not first-order-conditions (FOCs) from any optimization problems, are to determine the prices of commodities (RECs, allowances and transmission charges) and are essential to solve the models.

$$0 \le p^{\text{REC}} \perp \sum_j s_j^{\text{REC}} \ge 0 \tag{20}$$

$$0 \le p^{\text{GHG}} \perp \overline{E} - \sum_{f,i,h \in H_{\text{if}},j} E_{\text{fih}} x_{\text{fihj}} \ge 0 \tag{21}$$

$$\forall i \quad w_i \text{ free} \perp \sum_{f,h \in H_{\text{if}},j} x_{\text{fihj}} - s_i^{\text{O}} - s_i^{\text{G}} + y_i = 0 \tag{22}$$

$$\forall f, i, h \in H_{\text{if}}, j \quad p_{\text{fihj}} \text{ free} \perp z_{fihj} = x_{\text{fihj}}. \tag{23}$$

The symbol '$\perp$' indicates the complementarity of two vectors, thus $x \perp y$ means that $x^\top y = 0$. Conditions (20) and (21) state that if there are surplus RECs and GHG allowances in the markets, then p^{REC} and p^{GHG} are zero, respectively. When there is no surplus allowance available, p^{REC} and p^{GHG} will reflect their scarcity rent in the markets. In this case, Eqs. (20)–(21) can be replaced by the expressions to the right of the complementarity sign ($\perp$) by changing the inequality to an equality. Condition (22) is the network conservation constraint, and Eq. (23) equates power purchase with sales. We use $\overline{E} = \sum_f K_f$ to represent the summation of all power producers' initial allowances, but this value may not be equal to the system's cap. Most GHG cap-and-trade programs reserve some allowances for new entries or other purposes (European Union 2008), which should be excluded from $\overline{E}$ in our model. Finally, because the paper does not examine the market power, the dual variable p_{fihj} in Eq. (23) defines the prices paid by the LSEs to the producers for acquiring z_{fihj}.

As an indicator of the economic efficiency of the market equilibrium under the environmental policy intervention, we define social surplus as the summation of all decision makers' (LSEs, producers and ISO) objective functions, which is equivalent to the consumer willingness-to-pay less generation cost:

$$\Pi = \sum_j \left[P_j^0 \left(s_j^{\mathrm{G}} + s_j^{\mathrm{O}} \right) - \frac{P_j^0}{2Q_j^0} \left(s_j^{\mathrm{G}} + s_j^{\mathrm{O}} \right)^2 \right] + \sum_j \left[P_j^{\mathrm{G}} s_j^{\mathrm{G}} - \frac{P_j^{\mathrm{G}}}{2Q_j^{\mathrm{G}}} \left(s_j^{\mathrm{G}} \right)^2 \right] - \sum_{f,i,h \in H_{\mathrm{if}},j} C_{\mathrm{fih}} x_{\mathrm{fihj}}. \tag{24}$$

In Appendix B, we construct four quadratic programs, one for each case, such that the optimal solution to each quadratic program yields the market equilibrium solution for the corresponding model in Section 3. We show that all four quadratic programs maximize the same concave social surplus function (Eq. (24)) but are subject to different sets of constraints for different cases.

3.3 Analytical results

This section summarizes the major conclusions of our analytical analysis in the following propositions. The proofs are presented in Appendix B.

Proposition 1 *When bundling is allowed (Cases* 1 *and* 3*), if some LSE j sells the ordinary power ($s_j^O > 0$), then the REC price serves as an upper bound of the green premium: $p^{REC} \geq p_j^G$. Furthermore, if LSE j also exercises bundling strategy, then $p^{REC} = p_j^G$.*

Remark 1 The green premium reflects consumers' additional willingness-to-pay for green energy beyond ordinary energy price, and the REC price indicates the additional cost of procuring renewable energy beyond ordinary energy under the RPS requirement. When bundling is allowed, any positive difference between p_j^{G} and p^{REC} would be subject to arbitrage by LSEs who sell ordinary power (i.e., capable of bundling). As a result, $p^{\mathrm{REC}} \geq p_j^{\mathrm{G}}$ is expected under market equilibrium. On the other hand, for any LSE to find bundling worth exercising, $p^{\mathrm{REC}} \leq p_j^{\mathrm{G}}$ should be satisfied. Therefore, $p^{\mathrm{REC}} = p_j^{\mathrm{G}}$.

Proposition 2 *When bundling is not allowed (Cases* 2 *and* 4*), if some LSE j sells RECs ($s_j^{REC} > 0$), then the REC price serves as an upper bound of the green premium: $p^{REC} \geq p_j^G$. Furthermore, if LSE j also sells more green power than its RPS requirement ($s_j^G > R(z_j^O + z_j^G)$) in Case* 2*, or if LSE j sells green power ($s_j^G > 0$) in Case* 4*, then $p^{REC} = p_j^G$.*

Remark 2 When bundling is not allowed but some LSE still sells RECs, it must come from extra green procurement, the opportunity cost of which is p_j^{G}. Therefore $p^{\mathrm{REC}} \geq p_j^{\mathrm{G}}$ is intuitive. In Case 4, from the LSE's perspective, as the difference in green and ordinary power sales is gauged by the green premium, an LSE would compare the value of the green premium to the situation as foregoing the opportunity of selling power and using it to meet the RPS requirement. Thus, the green premium also effectively serves as an upper bound of REC prices. In Case 2, the condition is more strict because a certain number of RECs can be double-counted.

Proposition 3 *For any bundling equilibrium in Case* 1*, there exists a non-bundling equilibrium in Case* 2 *with the same* p_j^G *and* Π*. If some LSE j both exercises bundling and sells ordinary power in Case* 1*, then the* p^{REC} *in Case* 2 *is no higher than that in Case* 1.

Remark 3 Suppose a Case 1 solution, denoted by $(s_j^{\mathrm{G}}, s_j^{\mathrm{O}}, z_j^{\mathrm{G}}, z_j^{\mathrm{O}}, s_j^{\mathrm{REC}})$, involves bundling. Then we can construct a non-bundling Case 2 equilibrium by simply exchanging green and ordinary power procurement among different LSEs. As a result, the non-bundling Constraint (13) is satisfied for all LSEs, whereas the power production for all producers and sales for all LSEs are unchanged. As a result, the new equilibrium will result in the same overall generation portfolio, green premium p_j^{G} and social surplus Π, but a lower p^{REC} due to reduced demand in the REC market.

Proposition 4 *For any bundling equilibrium in Case* 3*, there exists a non-bundling equilibrium in Case* 4 *with the same* p_j^G *and* Π*. If some LSE j sells both green and ordinary power in Case* 3*, then the* p^{REC} *in Case* 4 *is no higher than that in Case* 3.

Remark 4 This result is similar with Proposition 3.

Proposition 5 *The social surplus under equilibria of the four cases satisfies the following relationship:* $\Pi_1 = \Pi_2 \geq \Pi_3 = \Pi_4$*, in which* Π_i *denotes the social surplus under market equilibrium in Case i.*

Remark 5 The proposition reveals that a less restricted policy results in a higher value of social surplus than a more restricted one and that the non-bundling regulation is redundant.

4 A numerical example

4.1 Setup

To examine the interactions of the RPS and green pricing programs, we present a case study of a simple hypothetical example. Consider a three-zone

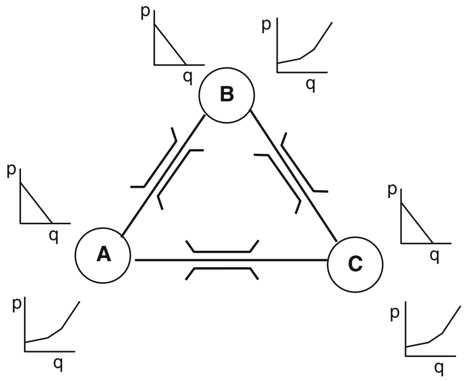

Fig. 1 Hypothetical three-zone network

($I = \{A,B,C\}$) network connected by three transmission lines with fixed capacities (Fig. 1). The flow in the network is modeled by the linearized DC flow that ignores reactive power and resistance losses (Schweppe et al. 1988). Such an approach is commonly used in economic and policy analysis in the electricity sector. A demand elasticity of −0.2 is calibrated with a pair of reference quantity and price based on a least-cost linear program.[12] Although short-run demand is nearly inelastic, this level of elasticity is within empirical estimates (Azevedo et al. 2011; Espey and Espey 2004). Other sources of demand elasticities could be from price-responsive imports or fringes (Bushnell et al. 2008). We assume that a number of generating units ($H = \{1, 2, ..., 10\}$) are owned by producers ($F = \{1, 2, 3\}$) and located at three zones. Their characteristics, including locations, fuel costs, emissions rate, etc., are summarized in Appendix D. We allow producers to own generating assets in different locations. Consumers reside in each zone with their willingness-to-pay represented by linear inverse demand curves. A GHG emissions cap of 500 tons is imposed at all locations. For simplicity, we model the markets for a single time period. As a comparison, we simulate each case at two levels of RPS (10% and 20%) and emissions cap (300 and 500 tons).

An equilibrium market model comprises Eqs. (1) and (2), the Karush-Kuhn-Tucker (KKT) conditions of all market participants' optimization problems (see Appendix A) and the market clearing Conditions 20–23. The resulting complementarity problem can then be implemented in GAMS and solved numerically with the complementarity solver PATH (Ferris and Munson 2000).

[12]We solve a linear program (LP) that minimizes the production cost subject to fixed demand to get the reference prices or the dual variables of nodal demand constraints. This is equivalent to the perfect competition assumption. We then construct the inverse demand curves with the assumed elasticity. Given that the demand is linear in the model, the demand elasticity will vary by the levels of the power consumptions. However, because of our price-taking assumption concerning producers, we would expect that the market outcomes would not be too sensitive to our assumption of elasticity.

Table 1 Summary of Results for the Cases 1 and 2 (RPS=20% & Cap=500 tons)

	Case 1			Case 2		
Consumer surplus [k$]	18.1			18.1		
Producers surplus [k$]	60.8			60.8		
ISO revenue [k$]	1.2			1.2		
Social surplus [k$]	80.0			80.0		
REC price [$/MWh]	54.3			36.3		
GHG permit price [$/ton]	53.8			53.8		
Variables / LSE	A	B	C	A	B	C
Power price [$/MWh]	71.1	69.7	82.4	71.1	69.7	82.4
Green premium [$/MWh]	43.9	18.0	54.3	43.9	18.0	54.3
Ordinary power [MWh]	307.0	310.2	174.2	307.0	310.2	174.2
Green power [MWh]	76.8	77.5	45.7	76.8	77.5	45.7
RPS requirement [MWh]	76.8	77.5	44.0	76.8	77.5	44.0
Ord. procurement [MWh]	305.3	308.4	176.0	307.0	310.2	174.2
Green procurement [MWh]	78.5	77.5	44.0	76.8	77.5	45.7
RECs sales [MWh]	1.7	0.0	−1.7	0.0	0.0	0.0

4.2 Results

Tables 1 and 2 summarize, respectively, the solutions from Cases 1–2 and 3–4 when RPS=20% and cap=500 tons. The results from the RPS equal to 10% and cap=300 tons are in Tables 3–4 and 5–6. Each case is solved by GAMS using solver PATH within a few seconds. Each table contains three sections. The top section reports the results of social welfare analysis, including the consumers and produces surplus, ISO revenue and total social surplus. The middle section gives the equilibrium prices of RECs and GHG emissions permit. The bottom section presents the detailed results for each LSE, including the power prices and green premium in each location, power procurement by types, the amount of RECs sold (+) or purchased (−) and

Table 2 Summary of Results for the Cases 3 and 4 (RPS=20% & Cap=500 tons)

	Case 3			Case 4		
Consumer surplus [k$]	12.3			12.3		
Producers surplus [k$]	55.2			55.2		
ISO revenue [k$]	0.5			0.5		
Social surplus [k$]	68.0			68.0		
REC price [$/MWh]	91.7			91.7		
GHG permit price [$/ton]	36.0			36.0		
Variables / LSE	A	B	C	A	B	C
Power price [$/MWh]	73.7	70.7	79.7	73.7	70.7	79.7
Green premium [$/MWh]	90.0	80.0	91.7	90.0	80.0	91.7
Ordinary power [MWh]	347.4	371.3	231.8	347.4	371.3	231.8
Green power [MWh]	0.0	0.0	8.3	0.0	0.0	8.3
RPS requirement [MWh]	69.5	74.3	48.0	69.5	74.3	48.0
Ord. procurement [MWh]	279.9	291.6	187.3	277.6	293.6	187.5
Green procurement [MWh]	67.5	79.7	52.8	69.7	77.7	52.5
RECs sales [MWh]	−2.0	5.5	−3.5	0.3	3.5	−3.8

Table 3 Summary of Results for the Cases 1 and 2 (RPS=10% & Cap=500 tons)

	Case 1			Case 2		
Consumer surplus [k$]	18.4			18.4		
Producers surplus [k$]	61.4			61.4		
ISO revenue [k$]	0.8			0.8		
Social surplus [k$]	80.6			80.6		
REC price [$/MWh]	38.3			38.3		
GHG permit price [$/ton]	59.7			59.7		
Variables / LSE	A	B	C	A	B	C
Power price [$/MWh]	72.6	67.9	82.0	72.6	67.9	82.0
Green premium [$/MWh]	38.3	38.3	38.3	38.3	38.3	38.3
Ordinary power [MWh]	276.4	364.2	161.4	276.4	364.2	161.4
Green power [MWh]	86.2	52.1	61.7	86.2	52.1	61.7
RPS requirement [MWh]	36.3	41.6	22.3	69.5	74.3	48.0
Ord. procurement [MWh]	326.3	374.7	101.0	276.4	364.2	161.4
Green procurement [MWh]	36.3	41.6	122.1	86.2	52.1	61.7
RECs sales [MWh]	−49.9	−10.5	60.4	0.0	0.0	0.0

how LSE acquires RECs and bundles with ordinary power to sell to customers as green power. We first discuss the detailed results for each case, which will be followed by the cross-comparison between them.

4.2.1 RPS=20% & Cap=500 tons

In Case 1, the sales of ordinary (green) power in three locations are 307.0 (76.8) MWh, 310.2 (77.5) MWh and 174.2 (45.7) MWh, respectively. Given RPS is set at 20%, it implies that the respective RPS requirements are 76.8 (=0.2×(307.0+76.8)) MWh, 77.5 (=0.2×(310.2+77.5)) MWh and 44.0 (=0.2×(174.2+45.7)) MWh. The solution indicates that three LSEs acquire 305.3 (78.5) MWh, 310.2 (77.5) MWh, 176.0 (40.0) MWh of ordinary (green)

Table 4 Summary of Results for the Cases 3 and 4 (RPS=10% & Cap=500 tons)

	Case 3			Case 4		
Consumer surplus [k$]	14.5			14.5		
Producers surplus [k$]	60.1			60.1		
ISO revenue [k$]	0.8			0.8		
Social surplus [k$]	63.9			63.9		
REC price [$/MWh]	63.9			63.9		
GHG permit price [$/ton]	49.1			49.1		
Variables / LSE	A	B	C	A	B	C
Power price [$/MWh]	72.6	67.9	82.0	72.6	67.9	82.0
Green premium [$/MWh]	63.9	63.9	63.9	63.9	63.9	63.9
Ordinary power [MWh]	319.1	396.1	187.0	319.1	396.1	187.0
Green power [MWh]	43.5	20.1	36.1	43.5	20.1	36.1
RPS requirement [MWh]	36.3	41.6	22.3	36.3	41.6	22.3
Ord. procurement [MWh]	293.9	330.1	178.1	289.9	334.6	177.6
Green procurement [MWh]	68.7	86.2	45.1	72.7	81.7	45.6
RECs sales [MWh]	−11.0	24.4	−13.4	−7.1	20.0	−12.9

Table 5 Summary of Results for the Cases 1 and 2 (RPS=20% & Cap=300 tons)

	Case 1			Case 2		
Consumer surplus [k$]	11.3			11.3		
Producers surplus [k$]	52.8			52.8		
ISO revenue [k$]	1.6			1.6		
Social surplus [k$]	65.6			65.6		
REC price [$/MWh]	42.6			29.2		
GHG permit price [$/ton]	85.0			85.0		
Variables / LSE	A	B	C	A	B	C
Power price [$/MWh]	79.9	73.9	97.1	79.9	73.9	97.1
Green premium [$/MWh]	42.6	29.2	42.6	42.6	29.2	42.6
Ordinary power [MWh]	179.8	254.0	51.5	179.8	254.0	51.5
Green power [MWh]	79.1	63.5	57.4	79.1	63.5	57.4
RPS requirement [MWh]	51.8	63.5	21.8	51.8	63.5	21.8
Ord. procurement [MWh]	207.1	254.0	24.2	179.8	254.0	51.5
Green procurement [MWh]	51.8	63.5	84.7	79.1	63.5	57.4
RECs sales [MWh]	−27.3	27.3	0.0	0.0	0.0	0.0

power through bilateral contracts with producers. LSE A takes full advantage of both double-counting and bundling (or "*un-bundling*"). First, it buys 1.7 MWh (=78.5−76.8 MWh) more green power from suppliers than it needs. The 76.8 MWh is used to meet RPS and sell to customer as green energy ("*double-counting*"), and the remaining 1.7 MWh is then "*un-bundled*" into ordinary power and RECs. As a result, it sells 1.7 MWh more ordinary electricity than it initially acquired, with 1.7 MWh RECs into the market. Whereas LSE B does not participate in REC market, LSE C acquires less green power than what it needs and purchases 1.7 MWh RECs from the market to bundle as green power. So, LSE A (C) is a net seller (buyer) in the REC market. Thus, consistent with Proposition 1, the REC price equals the green premium for LSE C, and is higher than the REC prices for LSEs A and B.

Table 6 Summary of Results for the Cases 3 and 4 (RPS=20% & Cap=300 tons)

	Case 3			Case 4		
Consumer surplus [k$]	6.8			6.8		
Producers surplus [k$]	49.9			49.9		
ISO revenue [k$]	1.4			1.4		
Social surplus [k$]	58.1			58.1		
REC price [$/MWh]	73.3			73.3		
GHG permit price [$/ton]	68.4			68.4		
Variables / LSE	A	B	C	A	B	C
Power price [$/MWh]	81.0	73.3	96.4	81.0	73.3	96.4
Green premium [$/MWh]	73.3	73.3	73.3	73.3	73.3	73.3
Ordinary power [MWh]	215.1	319.7	87.6	215.1	319.7	87.6
Green power [MWh]	27.8	8.4	26.7	27.8	8.4	26.7
RPS requirement [MWh]	48.6	65.6	22.9	48.6	65.6	22.9
Ord. procurement [MWh]	175.6	232.3	77.3	174.3	233.7	77.3
Green procurement [MWh]	67.3	95.8	37.0	68.7	94.3	37.0
RECs sales [MWh]	−9.2	21.8	−12.6	−7.7	20.3	−12.6

In Case 2, LSE B's decisions are the same as those in Case 1, but the LSEs A and C adjusted their ordinary and green power procurement to avoid REC trades, since bundling is no longer allowed in Case 2. The resulting social surplus and the GHG prices are the same as those in Case 1, but the REC price reduces to \$36.3/MWh, which verifies Proposition 5.

The results from Case 3 are very different from those in Case 1, mainly due to the fact that double-counting is disallowed in Case 3. As a result, most of the green power procured by LSEs are used to fulfill the RPS requirements, ordinary power sales have increased and only LSE C sells 8.3 MWh to the green pricing program. It acquires 52.8 MWh of green power and purchases 3.5 MWh of REC, which is used together to meet the 48 MWh RPS requirement and which also leads to 8.3 MWh of green power sales. LSE A procures less green power than the RPS requirement and makes up the difference by purchasing the deficiency from the REC market. LSE B acquires 79.7 MWh of green power, of which 74.3 MWh offsets the RPS requirement and the remaining 5.4 MWh is sold into the REC market. Therefore, both of its green and ordinary power procurements are sold as ordinary power. As concluded in Proposition 1, the REC price is equal to the green premium for LSE C and is higher than that for the other two LSEs.

Finally, when neither the bundling nor the double-counting is allowed, the results in Case 4 are only slightly different from those in Case 3, resulting in the same nodal sales, green premium, REC, GHG allowances and power prices. As alluded to by the Proposition 2, the REC price is equal to the green premium at zone C and greater than those in zones A and B. We point out that although the LSE C purchases RECs, it does not violate the no-bundling requirement since the 8.3 MWh of the green power sales comes from its own procurement, and the 3.5 MWh of RECs are used to help fulfill the RPS requirement.

Comparisons between Cases 1 and 2 and 3 and 4 indicate that the flexibility associated with the double-counting rendered by the first two cases reduces the overall compliance costs for RPS and lowers the REC price and the green premium accordingly. The level of green power sales is considerably higher in the first two cases. They also result in higher social surpluses. In the following section, we will show that when RPS is reduced from 20–10%, LSEs' strategies will be different because more RECs are allowed to be traded in the market when the RPS policy is less restrictive.

4.2.2 RPS=10% & Cap=500 tons

In this subsection, we report the results when the RPS is equal to 10% and the cap is 500 tons. The motivation is to see (i) how LSE's strategy might change in response to a different RPS requirement, and (ii) whether the surplus comparison among the four cases remains consistent. Tables 3 and 4 summarize the results of Cases 1&2 and 3&4, respectively.

Not surprisingly, the REC price and the green premium all fall as the RPS is relaxed from 20–10%. A lower RPS yields a lower electricity price, which in turn encourages more electricity consumption that then elevates the demand of and thus the price of the GHG permits. The GHG permit price is increased by \$5.9/ton (10%) and \$13.1/ton (36%) for Cases 1&2 and 3&4, respectively, compared to their counterparts in Tables 1 and 2.

When the RPS is reduced to 10%, more green procurement is released from meeting the RPS requirement, thus the green power sales have increased considerably, especially in Cases 3 and 4. Hence, the RPS and green pricing programs become two competing markets when the double-counting is not allowed (i.e., Cases 3 and 4). On the contrary, the synergy provided by the permission of double-counting in the first two cases allows LSE to utilize their green resources more flexibly and efficiently. This also can be seen from the volumes of the transaction in the RECs markets when the REC price is above zero. The average transaction in the REC markets is 40 MWh (both RPS=10 and 20%) in Cases 1 and 2 compared to less than 5 MWh in Case 3 and 4. Recall that the efficiency gain associated with any emission or RECs trading programs is by selling and purchasing permits to equate the compliance cost across all sources or participants. A low volume of transactions thus could be a proxy of the under-performance of the REC trading programs. Finally, lowering the RPS requirement induces some significant alternations to the LSEs' strategy. For instance, when the RPS is reduced from 20–10%, LSE B starts to participate in the REC market by buying 10.5 MWh of RECs, whereas the LSE C changes from a REC buyer to a seller. Cases 1 and 2 remain to be better choices in terms of the social surplus. The flexibility associated with the double-counting and bundling benefits consumers more than the producers, partially because it lowers the RPS compliance cost, and such benefits eventually pass on to the consumers through the reduction in the electricity prices.

4.2.3 RPS=20% & Cap=300 tons

Results for the RPS=20% and cap=300 tons scenario are summarized in Tables 5 and 6 for Cases 1&2 and 3&4, respectively. Reducing the cap in the C&T program from 500 to 300 tons has a direct impact on the GHG allowance price, which increases by 71.8% and 79.2% for Cases 1&2 and 3&4, respectively, compared to those in Tables 1 and 2. The allowance costs are then passed on to the electricity prices, suppressing the electricity demand. The lower electricity demand implies a loose RPS requirement, and consequently, the REC price drops by 32.8% and 19.7% for Cases 1&2 and 3&4, respectively. The decline in the REC price results in overall higher green power sales since *un-bundling* green procurements into REC and ordinary power is less profitable.

4.2.4 Sensitivity analysis

We performed two sets of sensitivity analyses to study the effect of the RPS requirement and emissions cap on the market equilibrium results. In one situation, the RPS was increased from 5–25% by an increment of 5% as the CO_2 cap was kept at 500 tons, and in the other, we changed the CO_2 cap from 400–600 tons with an incremental of 50 tons as the RPS was held at 20%.

Figure 2 reports the results of the consumers surplus, producers surplus, ISO revenue and social surplus from top to bottom for the sensitivity analysis on the RPS (left) and the CO_2 cap (right). Two observations emerge from the figure. First, consistent with Propositions 3 and 4, Cases 1 and 2 as well as Cases 3 and 4, respectively result in the same market equilibrium when even the details in

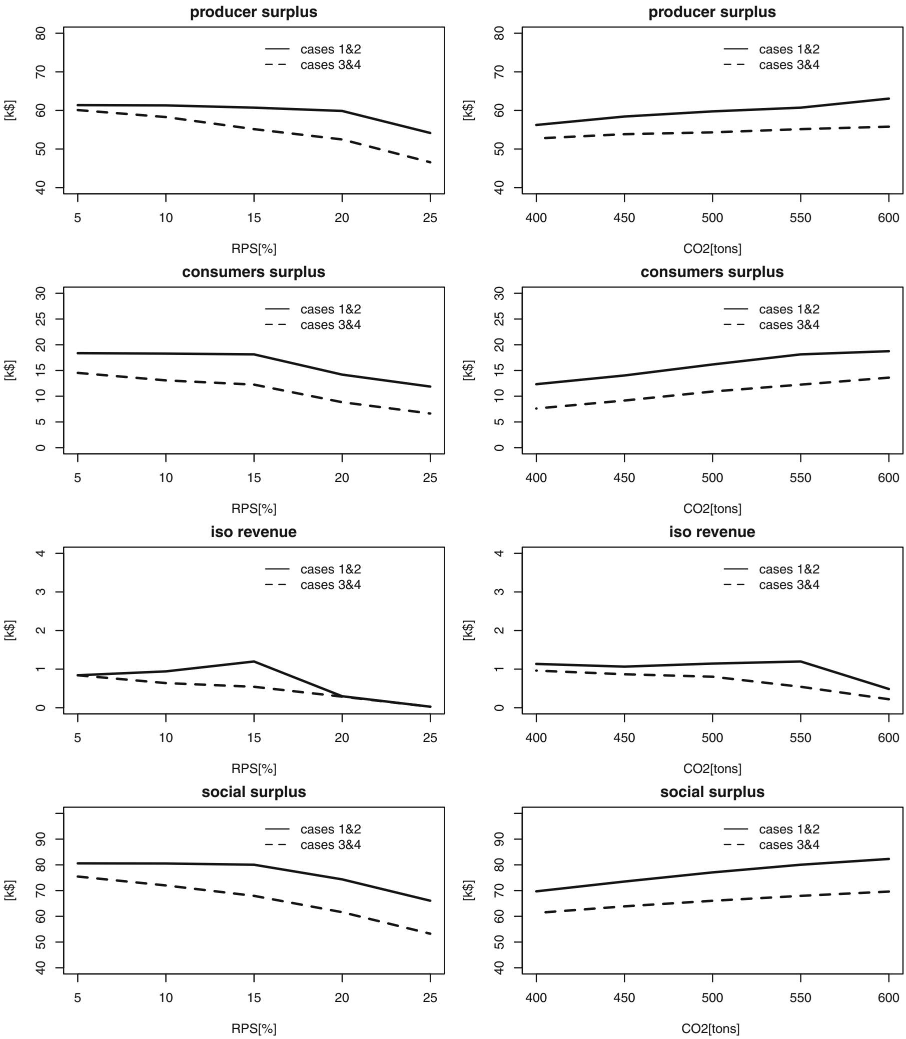

Fig. 2 Results of the sensitivity analyses on the RPS and CO_2 cap

strategies are different. Second, except for the ISO revenue, the consumers surplus, producers surplus and social surplus rise when the CO_2 cap is lifted or the requirement of RPS is less restrictive. As the ISO revenue represents the level of the congestion in the network, Fig. 2 implies that the change in the ISO revenue or congestion is not monotonic with either the CO_2 cap or RPS. In principle, there is no theory about the effect of proposed policies, e.g., RPS and CO_2, on the network congestion. We illustrate this in the following hypothetical example. A simple network is composed with two zones linked by a congested line, in which a generator is located in each end. If the imposition of a CO_2 cap or RPS levels the marginal cost of two generators, it will alleviate the congestion, thereby reducing ISO revenue. This could occur in a situation in which the high marginal cost unit is also more polluting. The reverse is true when a policy amplifies the difference in the marginal costs.

5 Conclusion

Greenhouse gas emissions trading, green pricing programs and renewable portfolio standard are three policies that are currently coexisting in several states in the Northeast and the Mid-Atlantic regions in the United States. Although their designs and goals are different, they are all market-based instruments integrated with competitive electric markets. This paper presents a quantitative framework together with an analytical analysis and numeric illustration to study the interactions among the three policies, examining their impacts on the power markets. We focus on two aspects of designs in the RPS markets: double-counting and bundling. When the double-counting is allowed, the same MWh of the procured renewable power can be used to meet RPS and sell to consumers as green power. On the other hand, if the bundling is permitted, load serving entities can purchase the renewable energy credits from secondary markets and sell to consumers as green power by bundling them with ordinary power. Each policy combination is formulated as a market model. This paper focuses on examining how LSEs might respond to these policies and studies the relationship between the REC price and green premium. We explicitly derive the conditions under which these two quantities will be equivalent or serving as an upper bound of the other. We show that the bundling in the presence of the “no double-counting” requirement could be redundant when LSEs opt to sell surplus RECs to REC markets. One important question for future research is how might future renewable capacity unfold under each policy scenario since the goal under RPS is to promote new renewable capacity. We predict that it will be different under each scenario, depending on how renewable producers benefit from different policy designs.

As seen in the “The American Clean Energy and Security Act of 2009,” the cap-and-trade program and the renewable electricity standard (or known as renewable portfolio standard), together with offset and strategic reserve provisions, are expected to play a central role in the United States energy and climate policy (Committe on Energy and Commerce 2008). The conclusions reached in this paper could help policymakers and the energy industry understand how different market-based instruments might interact with each other in competitive product (power) markets. The framework developed herein is ready to be expanded further to multi-period and to incorporate offset and strategic reserve provisions and consider long-run investment decisions.

Acknowledgement The second author is partially supported by the National Science Foundation under the Award 0835989.

Appendix A: Equilibrium market models

Table 7 summarizes the corresponding sets of equilibrium conditions under each case. Notice that these are the concatenated conditions for all market participants, including consumers, LSEs, producers and the ISO. In the remainder of this section, we present the KKT conditions for each market participants: LSE, producers, and ISO.

KKT for LSEs

Case 1 both double-counting and bundling are allowed.

$$\forall f, i, h \in H_{\mathrm{if}}^{\mathrm{O}}, j \qquad 0 \le z_{fihj} \perp p_{\mathrm{fihj}} - \omega_j^{\mathrm{O}} \ge 0 \tag{25}$$

$$\forall f, i, h \in H_{\mathrm{if}}^{\mathrm{G}}, j \qquad 0 \le z_{fihj} \perp p_{\mathrm{fihj}} - \omega_j^{\mathrm{G}} \ge 0 \tag{26}$$

$$\forall j \qquad 0 \le z_j^{\mathrm{O}} \perp \theta_j + R\phi_j + R\tau_j \ge 0 \tag{27}$$

$$\forall j \qquad 0 \le z_j^{\mathrm{G}} \perp \theta_j + (R-1)\phi_j + (R-2)\tau_j - \delta_j \ge 0 \tag{28}$$

$$\forall j \qquad 0 \le s_j^{\mathrm{O}} \perp -P_j^0 + \frac{P_j^0}{Q_j^0}\left(s_j^{\mathrm{O}} + s_j^{\mathrm{G}}\right) - \theta_j \ge 0 \tag{29}$$

$$\begin{aligned} \forall j \qquad 0 \le s_j^{\mathrm{G}} \perp -P_j^0 + \frac{P_j^0}{Q_j^0}\left(s_j^{\mathrm{O}} + s_j^{\mathrm{G}}\right) - P_j^{\mathrm{G}} + \frac{P_j^{\mathrm{G}}}{Q_j^{\mathrm{G}}} s_j^{\mathrm{G}} \\ -\theta_j + \tau_j + \delta_j \ge 0 \end{aligned} \tag{30}$$

$$\forall j \qquad \omega_j^{\mathrm{O}} \text{ free} \perp z_j^{\mathrm{O}} = \sum\nolimits_{f,i,h \in H_{\mathrm{if}}^{\mathrm{O}}} z_{fihj} \tag{31}$$

$$\forall j \qquad \omega_j^{\mathrm{G}} \text{ free} \perp z_j^{\mathrm{G}} = \sum\nolimits_{f,i,h \in H_{\mathrm{if}}^{\mathrm{G}}} z_{fihj} \tag{32}$$

$$\forall j \qquad s_j^{\mathrm{REC}} \text{ free} \perp -p^{\mathrm{REC}} + \phi_j + \tau_j + \delta_j = 0 \tag{33}$$

$$\forall j \qquad \theta_j \text{ free} \perp z_j^{\mathrm{O}} + z_j^{\mathrm{G}} = s_j^{\mathrm{O}} + s_j^{\mathrm{G}} \tag{34}$$

Table 7 Summary of equilibrium market models

Cases	Policies	Equations
Case 1	Both	Eqs. (20)–(23), (25)–(37), (51)–(55)
Case 2	Double-counting	Eqs. (20)–(23), (38)–(41), (51)–(55)
Case 3	Bundling	Eqs. (20)–(23), (42)–(47), (51)–(55)
Case 4	Neither	Eqs. (20)–(23), (48)–(55)

$$\forall j \qquad 0 \le \phi_j \perp z_j^{\mathrm{G}} - R\left(z_j^{\mathrm{O}} + z_j^{\mathrm{G}}\right) - s_j^{\mathrm{REC}} \ge 0 \tag{35}$$

$$\forall j \qquad 0 \le \tau_j \perp 2z_j^{\mathrm{G}} - s_j^{\mathrm{REC}} - R\left(z_j^{\mathrm{O}} + z_j^{\mathrm{G}}\right) - s_j^{\mathrm{G}} \ge 0 \tag{36}$$

$$\forall j \qquad 0 \le \delta_j \perp z_j^{\mathrm{G}} - s_j^{\mathrm{REC}} - s_j^{\mathrm{G}} \ge 0. \tag{37}$$

Case 2 double-counting is allowed but bundling is not.

$$\text{Constraints (25)–(27), (29), (31)–(37)} \tag{38}$$

$$\forall j \qquad 0 \le z_j^{\mathrm{G}} \perp \theta_j + (R-1)\phi_j + (R-2)\tau_j - \delta_j - \kappa_j \ge 0 \tag{39}$$

$$\forall j \qquad 0 \le s_j^{\mathrm{G}} \perp -P_j^0 + \frac{P_j^0}{Q_j^0}\left(s_j^{\mathrm{O}} + s_j^{\mathrm{G}}\right) - P_j^{\mathrm{G}} + \frac{P_j^{\mathrm{G}}}{Q_j^{\mathrm{G}}} s_j^{\mathrm{G}} - \theta_j + \tau_j + \delta_j + \kappa_j \ge 0 \tag{40}$$

$$\forall j \qquad 0 \le \kappa_j \perp z_j^{\mathrm{G}} - s_j^{\mathrm{G}} \ge 0. \tag{41}$$

Case 3 bundling is allowed but double-counting is not.

$$\text{Constraints (25), (26), (29), (31), (32), (34), and (35)} \tag{42}$$

$$\forall j \qquad 0 \le z_j^{\mathrm{O}} \perp \theta_j + R\phi_j + R\gamma_j \ge 0 \tag{43}$$

$$\forall j \qquad 0 \le z_j^{\mathrm{G}} \perp \theta_j + (R-1)\phi_j + (R-2)\gamma_j \ge 0 \tag{44}$$

$$\forall j \qquad 0 \le s_j^{\mathrm{G}} \perp -P_j^0 + \frac{P_j^0}{Q_j^0}\left(s_j^{\mathrm{O}} + s_j^{\mathrm{G}}\right) - P_j^{\mathrm{G}} + \frac{P_j^{\mathrm{G}}}{Q_j^{\mathrm{G}}} s_j^{\mathrm{G}} - \theta_j + \gamma_j \ge 0 \tag{45}$$

$$\forall j \qquad s_j^{\mathrm{REC}} \text{ free} \perp -p^{\mathrm{REC}} + \phi_j + \gamma_j = 0 \tag{46}$$

$$\forall j \qquad 0 \le \gamma_j \perp z_j^{\mathrm{G}} - s_j^{\mathrm{REC}} - R\left(z_j^{\mathrm{O}} + z_j^{\mathrm{G}}\right) - s_j^{\mathrm{G}} \ge 0. \tag{47}$$

Case 4 neither double-counting nor bundling is allowed.

$$\text{Constraints (25), (26), (29), (31), (32), (34), (35), (41), (43), (46), and (47)} \tag{48}$$

$$\forall j \qquad 0 \le z_j^{\mathrm{G}} \perp \theta_j + (R-1)\phi_j + (R-1)\gamma_j - \kappa_j \ge 0 \tag{49}$$

$$\forall j \qquad 0 \le s_j^{\mathrm{G}} \perp -P_j^0 + \frac{P_j^0}{Q_j^0}\left(s_j^{\mathrm{O}} + s_j^{\mathrm{G}}\right) - P_j^{\mathrm{G}} + \frac{P_j^{\mathrm{G}}}{Q_j^{\mathrm{G}}} s_j^{\mathrm{G}} - \theta_j + \gamma_j + \kappa_j \ge 0. \tag{50}$$

KKT for Producers

$$\forall f, i, h \in H_{\mathrm{if}}, j \qquad 0 \le x_{\mathrm{fihj}} \perp -p_{\mathrm{fihj}} + C_{\mathrm{fih}} + (w_j - w_i) + p^{\mathrm{GHG}} E_{\mathrm{fih}} + \rho_{\mathrm{fih}} \ge 0 \tag{51}$$

$$\forall f, i, h \in H_{\mathrm{if}}, j \qquad 0 \le \rho_{\mathrm{fih}} \perp X_{\mathrm{fih}} - \sum_j x_{\mathrm{fihj}} \ge 0. \tag{52}$$

Condition (51) suggests that the price offered by a firm to LSE j is equal to the sum of the costs associated with fuel (C_{fih}), transmissions ($w_j - w_i$), emissions ($p^{\mathrm{GHG}} E_{\mathrm{fih}}$) and the capacity scarcity rent (ρ_{fih}.)

KKT for ISO

$$\forall i \qquad y_i \text{ free} \perp \textstyle\sum_k PTDF_{\text{ki}}(\lambda_k^+ - \lambda_k^-) - w_i = 0 \tag{53}$$

$$\forall k \qquad 0 \le \lambda_k^+ \perp T_k - \textstyle\sum_i PTDF_{\text{ki}} y_i \ge 0. \tag{54}$$

$$\forall k \qquad 0 \le \lambda_k^- \perp T_k + \textstyle\sum_i PTDF_{\text{ki}} y_i \ge 0. \tag{55}$$

Appendix B: Equivalent quadratic programming formulations

We construct four quadratic programs that are equivalent to the four cases in the sense that the KKT conditions of these quadratic programs are the same as the market equilibrium conditions outlined in Table 7. Since all four objectives are maximization of concave quadratic functions, a Nash equilibrium is a solution of the KKT conditions if and only if it is an optimal solution of the corresponding quadratic program. Notice that the objective function of the quadratic programs for all four cases is to maximize the social welfare. These formulations are useful for proving some of the propositions presented in Section 3.3.

Case 1 both double-counting and bundling are allowed.

$$\begin{aligned} \max \qquad \Pi_1 = & \textstyle\sum_j \left[P_j^0 \left(s_j^{\text{G}} + s_j^{\text{O}} \right) - \frac{P_j^0}{2Q_j^0} \left(s_j^{\text{G}} + s_j^{\text{O}} \right)^2 \right] \\ & + \textstyle\sum_j \left[P_j^{\text{G}} s_j^{\text{G}} - \frac{P_j^{\text{G}}}{2Q_j^{\text{G}}} \left(s_j^{\text{G}} \right)^2 \right] \\ & - \textstyle\sum_{f,i,h \in H_{\text{if}},j} C_{\text{fih}} x_{\text{fihj}} \end{aligned} \tag{56}$$

$$\begin{array}{llll}
\text{s.t.} \quad \forall j, & z_j^{\text{G}} - R\left(z_j^{\text{O}} + z_j^{\text{G}} \right) - s_j^{\text{REC}} \ge 0 & (\phi_j \ge 0) & (57) \\
\forall j, & 2z_j^{\text{G}} - R\left(z_j^{\text{O}} + z_j^{\text{G}} \right) - s_j^{\text{REC}} - s_j^{\text{G}} \ge 0 & (\tau_j \ge 0) & (58) \\
\forall j, & z_j^{\text{G}} - s_j^{\text{REC}} - s_j^{\text{G}} \ge 0 & (\delta_j \ge 0) & (59) \\
\forall f, i, h \in H_{\text{if}}, & X_{\text{fih}} - \sum_j x_{\text{fihj}} \ge 0 & (\rho_{\text{fih}} \ge 0) & (60) \\
\forall k, & T_k - \sum_i PTDF_{\text{ki}} y_i \ge 0 & (\lambda_k^+ \ge 0) & (61) \\
\forall k, & T_k + \sum_i PTDF_{\text{ki}} y_i \ge 0 & (\lambda_k^- \ge 0) & (62) \\
 & \sum_j s_j^{\text{REC}} \ge 0 & (p^{\text{REC}} \ge 0) & (63) \\
 & \overline{E} - \sum_{f,i,h \in H_{\text{if}},j} E_{\text{fih}} x_{\text{fihj}} \ge 0 & (p^{\text{GHG}} \ge 0) & (64) \\
\forall f, i, h \in H_{\text{if}}, j, & x_{\text{fihj}} = z_{fihj} & (p_{\text{fihj}} \text{ free}) & (65) \\
\forall i, & \sum_{f,h \in H_{\text{if}},j} x_{\text{fihj}} - s_i^{\text{O}} - s_i^{\text{G}} + y_i = 0 & (w_i \text{ free}) & (66) \\
\forall j, & s_j^{\text{O}} + s_j^{\text{G}} = z_j^{\text{O}} + z_j^{\text{G}} & (\theta_j \text{ free}) & (67)
\end{array}$$

$$\forall j, \qquad z_j^{\mathrm{O}} = \sum\nolimits_{f,i,h\in H_{\mathrm{if}}^{\mathrm{O}}} z_{fihj} \qquad (\omega_j^{\mathrm{O}}) \tag{68}$$

$$\forall j, \qquad z_j^{\mathrm{G}} = \sum\nolimits_{f,i,h\in H_{\mathrm{if}}^{\mathrm{G}}} z_{fihj} \qquad (\omega_j^{\mathrm{G}}) \tag{69}$$

$$\forall f, i, h, j, x_{\mathrm{fihj}}, z_j^{\mathrm{O}}, z_j^{\mathrm{G}}, s_j^{\mathrm{O}}, s_j^{\mathrm{G}} \geq 0; s_j^{\mathrm{REC}}, y_i \text{ free.} \tag{70}$$

Case 2 double-counting is allowed but bundling is not.

$$\begin{aligned} \max \qquad \Pi_2 = \sum\nolimits_j \left[P_j^0 \left(s_j^{\mathrm{G}} + s_j^{\mathrm{O}} \right) - \tfrac{P_j^0}{2Q_j^0} \left(s_j^{\mathrm{G}} + s_j^{\mathrm{O}} \right)^2 \right] \\ + \sum\nolimits_j \left[P_j^{\mathrm{G}} s_j^{\mathrm{G}} - \tfrac{P_j^{\mathrm{G}}}{2Q_j^{\mathrm{G}}} \left(s_j^{\mathrm{G}} \right)^2 \right] - \sum\nolimits_{f,i,h\in H_{\mathrm{if}},j} C_{fih} x_{fihj} \end{aligned} \tag{71}$$

$$\text{s. t.} \qquad \text{Constraints (57)–(70)} \tag{72}$$

$$\forall j \quad z_j^{\mathrm{G}} - s_j^{\mathrm{G}} \geq 0 \quad (\kappa_j \geq 0). \tag{73}$$

Case 3 bundling is allowed but double-counting is not.

$$\begin{aligned} \max \Pi_3 = \sum\nolimits_j \left[P_j^0 \left(s_j^{\mathrm{G}} + s_j^{\mathrm{O}} \right) - \tfrac{P_j^0}{2Q_j^0} \left(s_j^{\mathrm{G}} + s_j^{\mathrm{O}} \right)^2 \right] + \sum\nolimits_j \left[P_j^{\mathrm{G}} s_j^{\mathrm{G}} - \tfrac{P_j^{\mathrm{G}}}{2Q_j^{\mathrm{G}}} \left(s_j^{\mathrm{G}} \right)^2 \right] \\ - \sum\nolimits_{f,i,h\in H_{\mathrm{if}},j} C_{\mathrm{fih}} x_{\mathrm{fihj}} \end{aligned}$$

$$\text{s. t.} \qquad \text{Constraints (57), (60)–(70)}$$

$$\forall j \quad z_j^{\mathrm{G}} - R\left(z_j^{\mathrm{O}} + z_j^{\mathrm{G}} \right) - s_j^{\mathrm{REC}} - s_j^{\mathrm{G}} \geq 0 \quad (\gamma_j \geq 0). \tag{74}$$

Case 4 neither double-counting nor bundling is allowed.

$$\begin{aligned} \max \qquad \Pi_4 = \sum\nolimits_j \left[P_j^0 \left(s_j^{\mathrm{G}} + s_j^{\mathrm{O}} \right) - \tfrac{P_j^0}{2Q_j^0} \left(s_j^{\mathrm{G}} + s_j^{\mathrm{O}} \right)^2 \right] \\ + \sum\nolimits_j \left[P_j^{\mathrm{G}} s_j^{\mathrm{G}} - \tfrac{P_j^{\mathrm{G}}}{2Q_j^{\mathrm{G}}} \left(s_j^{\mathrm{G}} \right)^2 \right] - \sum\nolimits_{f,i,h\in H_{\mathrm{if}},j} C_{\mathrm{fih}} x_{\mathrm{fihj}} \end{aligned} \tag{75}$$

$$\text{s. t.} \qquad \text{Constraints (57), (60)–(70), (73), (74).} \tag{76}$$

Appendix C: Proofs

Proposition 1

Proof For Case 1. From $s_j^{\mathrm{O}} > 0$, Eqs. (29)–(33) and (35), we have $p^{\mathrm{REC}} - p_j^{\mathrm{G}} \geq \phi_j \geq 0$. Suppose bundling occurs at firm j, which means $s_j^{\mathrm{G}} > z_j^{\mathrm{G}} \geq 0$. From $s_j^{\mathrm{O}} > 0$, Eqs. (30), and (33) we have $p^{\mathrm{REC}} - \phi_j = p_j^{\mathrm{G}}$. From Eqs. (35) and (36) we have $z_j^{\mathrm{G}} - R(z_j^{\mathrm{O}} + z_j^{\mathrm{G}}) - s_j^{\mathrm{REC}} = [2z_j^{\mathrm{G}} - s_j^{\mathrm{REC}} - R(z_j^{\mathrm{O}} + z_j^{\mathrm{G}}) - s_j^{\mathrm{G}}] + (s_j^{\mathrm{G}} - z_j^{\mathrm{G}}) > 0$. Therefore, $\phi_j = 0$ and $p^{\mathrm{REC}} = p_j^{\mathrm{G}}$. The proof for Case 3 is similar with $\tau_j + \delta_j$ replaced by γ_j in the demonstration. □

Proposition 2

Proof For Case 2. From $s_j^{\mathrm{REC}} > 0$, Eqs. (34), (37) and (41), we have $s_j^{\mathrm{O}} = z_j^{\mathrm{O}} + z_j^{\mathrm{G}} - s_j^{\mathrm{G}} \geq z_j^{\mathrm{G}} - s_j^{\mathrm{G}} \geq s_j^{\mathrm{REC}} > 0$ and $\kappa_j = 0$. From Eqs. (29), (40), (33) and (35), we have $p^{\mathrm{REC}} - p_j^{\mathrm{G}} \geq \phi_j \geq 0$. Moreover, if $s_j^{\mathrm{G}} > R(z_j^{\mathrm{O}} + z_j^{\mathrm{G}})$, then $p^{\mathrm{REC}} - p_j^{\mathrm{G}} = \phi_j = 0$. The last equation is because in Eq. (35) $z_j^{\mathrm{G}} - R(z_j^{\mathrm{O}} + z_j^{\mathrm{G}}) - s_j^{\mathrm{REC}} = z_j^{\mathrm{G}} - s_j^{\mathrm{REC}} - s_j^{\mathrm{G}} + [s_j^{\mathrm{G}} - R(z_j^{\mathrm{O}} + z_j^{\mathrm{G}})] > 0$, using Eq. (37). The proof for Case 4 is similar with $\tau_j + \delta_j$ replaced by γ_j in the demonstration. □

Proposition 3

Proof We show that for any Case 1 solution $(s_j^{\mathrm{G}}, s_j^{\mathrm{O}}, x_{\mathrm{fihj}}, z_{fihj}, y_i, s_j^{\mathrm{REC}})$, there exists a Case 2 solution $(\hat{s}_j^{\mathrm{G}}, \hat{s}_j^{\mathrm{O}}, \hat{x}_{\mathrm{fihj}}, \hat{z}_{fihj}, \hat{y}_i, \hat{s}_j^{\mathrm{REC}})$ that satisfies the following constraints:

$$\forall j, \qquad \hat{s}_j^{\mathrm{G}} = s_j^{\mathrm{G}} \tag{77}$$

$$\forall j, \qquad \hat{s}_j^{\mathrm{O}} = s_j^{\mathrm{O}} \tag{78}$$

$$\forall i, \qquad \hat{y}_i = y_i \tag{79}$$

$$\forall f, i, h \in H_{\mathrm{if}}, \qquad \textstyle\sum_j \hat{x}_{\mathrm{fihj}} = \sum_j x_{\mathrm{fihj}} \tag{80}$$

$$\forall f, i, h \in H_{\mathrm{if}}, \qquad \hat{x}_{\mathrm{fihj}} = \hat{z}_{fihj} \tag{81}$$

$$\forall j, \qquad \hat{z}_j^{\mathrm{G}} := \textstyle\sum_{f,i,h \in H_{\mathrm{if}}^{\mathrm{G}}} \hat{z}_{fihj} \tag{82}$$

$$\forall j, \qquad \hat{z}_j^{\mathrm{O}} := \textstyle\sum_{f,i,h \in H_{\mathrm{if}}^{\mathrm{O}}} \hat{z}_{fihj} \tag{83}$$

$$\forall j, \qquad \hat{z}_j^{\mathrm{G}} - R\left(z_j^{\mathrm{O}} + z_j^{\mathrm{G}}\right) - \hat{s}_j^{\mathrm{REC}} \geq 0 \qquad (\phi_j \geq 0) \tag{84}$$

$$\forall j, \qquad 2\hat{z}_j^{\mathrm{G}} - R\left(z_j^{\mathrm{O}} + z_j^{\mathrm{G}}\right) - \hat{s}_j^{\mathrm{REC}} - s_j^{\mathrm{G}} \geq 0 \qquad (\tau_j \geq 0) \tag{85}$$

$$\forall j, \qquad \hat{z}_j^{\mathrm{G}} - \hat{s}_j^{\mathrm{REC}} - s_j^{\mathrm{G}} \geq 0 \qquad (\delta_j \geq 0) \tag{86}$$

$$\textstyle\sum_j \hat{s}_j^{\mathrm{REC}} \geq 0 \qquad (p^{\mathrm{REC}} \geq 0) \tag{87}$$

$$\forall j, \qquad \hat{z}_j^{\mathrm{G}} + \hat{z}_j^{\mathrm{O}} = s_j^{\mathrm{G}} + s_j^{\mathrm{O}} \qquad (\theta_j \text{ free}) \tag{88}$$

$$\forall j, \qquad \hat{z}_j^{\mathrm{O}} \geq 0, \hat{z}_j^{\mathrm{G}} \geq 0, \hat{s}_j^{\mathrm{REC}} \text{ free} \tag{89}$$

$$\forall j, \qquad \hat{z}_j^{\mathrm{G}} \geq s_j^{\mathrm{G}} \qquad (\kappa_j \geq 0). \tag{90}$$

It is easy to see that, given $(x_{\mathrm{fihj}}, \hat{z}_j^{\mathrm{G}}, \hat{z}_j^{\mathrm{O}})$, there exists a solution (possibly among infinitely many others) $(\hat{x}_{\mathrm{fihj}}, \hat{z}_{fihj})$ that satisfies Eqs. (80)–(83). For any given Case 1 solution $(s_j^{\mathrm{G}}, z_j^{\mathrm{G}}, z_j^{\mathrm{O}})$, we prove the existence of $(\hat{z}_j^{\mathrm{O}}, \hat{z}_j^{\mathrm{G}}, \hat{s}_j^{\mathrm{REC}})$

that satisfies Eqs. (84)–(90) by showing the non-existence of a solution to the following constraints:

$$\sum_j \Big[R\left(z_j^{\mathrm{O}} + z_j^{\mathrm{G}}\right)(\phi_j + \tau_j)$$

$$+ s_j^{\mathrm{G}}\left(\tau_j + \delta_j + \theta_j + \kappa_j\right) + s_j^{\mathrm{O}}\theta_j \Big] > 0 \tag{91}$$

$$\forall j, \qquad \phi_j + 2\tau_j + \delta_j + \theta_j + \kappa_j \leq 0 \qquad (z_j^{\mathrm{G}} \geq 0) \tag{92}$$

$$\forall j, \qquad \theta_j \leq 0 \qquad (z_j^{\mathrm{O}} \geq 0) \tag{93}$$

$$\forall j, \qquad -\phi_j - \tau_j - \delta_j + p^{\mathrm{REC}} \leq 0 \qquad (s_j^{\mathrm{REC}} \text{ free}) \tag{94}$$

$$\forall j, \qquad \phi_j, \tau_j, \delta_j, \kappa_j, p^{\mathrm{REC}} \geq 0; \theta_j \text{ free.} \tag{95}$$

According to Farkas' lemma (Bertsimas and Tsitsiklis 1997), for any $A \in \mathbb{R}^{m\times n}$ and $b \in \mathbb{R}^{m\times 1}$, exactly one of these two sets is empty: $\{x \in \mathbb{R}^{n\times 1} : Ax \geq b, x \geq 0\}$ and $\{y \in \mathbb{R}^{m\times 1} : b^\top y > 0, A^\top y \leq 0, y \geq 0\}$. In this context, Farkas' lemma means that Eqs. (84)–(90) possesses a solution if and only if the set of Eqs. (91)–(95) does not. We prove the infeasibility of Eqs. (91)–(95) by contradiction. Suppose $(\phi_j^0, \tau_j^0, \delta_j^0, \kappa_j^0, p^{\mathrm{REC0}}, \theta_j^0)$ satisfies Eqs. (91)–(95), then it is easy to see that $(\phi_j = \phi_j^0, \tau_j = \tau_j^0, \delta_j = \delta_j^0 + \kappa_j^0, \kappa_j = 0, p^{\mathrm{REC}} = p^{\mathrm{REC0}}, \theta_j = \theta_j^0)$ also satisfies Eqs. (91)–(95). However, the latter further implies, also by Farkas' lemma, that Eqs. (84)–(89) is infeasible, which contradicts the fact that $(\hat{z}_j^{\mathrm{O}} = z_j^{\mathrm{O}}, \hat{z}_j^{\mathrm{G}} = z_j^{\mathrm{G}}, \hat{s}_j^{\mathrm{REC}} = s_j^{\mathrm{REC}})$ satisfies Eqs. (84)–(89). As a result, the $\hat{p}_j^{\mathrm{G}}$ and $\hat{\Pi}$ for Case 2 will be the same with those in Case 1.

We prove that $\hat{p}^{\mathrm{REC}} \leq p^{\mathrm{REC}}$ as follows:

$$\hat{p}^{\mathrm{REC}} - p^{\mathrm{REC}} \tag{96}$$

$$= \hat{\phi}_j + \hat{\tau}_j + \hat{\delta}_j - (\phi_j + \tau_j + \delta_j), \qquad \forall j \tag{97}$$

$$= \hat{\tau}_j + \hat{\delta}_j - (\tau_j + \delta_j), \qquad \forall j : s_j^{\mathrm{G}} > z_j^{\mathrm{G}} \tag{98}$$

$$= -\hat{\kappa}_j \leq 0, \qquad \forall j : s_j^{\mathrm{G}} > z_j^{\mathrm{G}}, s_j^{\mathrm{O}} > 0. \tag{99}$$

Here, Eq. (97) is from Eq. (33). Equation (98) is because in Eqs. (35) and (36) we have

$$z_j^{\mathrm{G}} - R\left(z_j^{\mathrm{O}} + z_j^{\mathrm{G}}\right) - s_j^{\mathrm{REC}}$$

$$= \left[2z_j^{\mathrm{G}} - s_j^{\mathrm{REC}} - R\left(z_j^{\mathrm{O}} + z_j^{\mathrm{G}}\right) - s_j^{\mathrm{G}}\right] + (s_j^{\mathrm{G}} - z_j^{\mathrm{G}}) > 0.$$

Therefore, $\phi_j = 0$, and similarly $\hat{\phi}_j = 0$. Equation (99) is due to Eqs. (29), (30), and (40), which yield that $\tau_j + \delta_j = \hat{\tau}_j + \hat{\delta}_j + \hat{\kappa}_j$. □

Proposition 4

Proof The first part of the proof is similar to that of Proposition 3, except that Eqs. (85) and (86) are substituted with

$$\forall j, \qquad \hat{z}_j^{\mathrm{G}} - R\left(z_j^{\mathrm{O}} + z_j^{\mathrm{G}}\right) - \hat{s}_j^{\mathrm{REC}} - s_j^{\mathrm{G}} \geq 0 \qquad (\gamma_j \geq 0). \tag{100}$$

Using a similar argument, we can prove that Eqs. (87)–(90) and (100) possesses a solution if and only if the following set of Eqs. (101)–(105) does not.

$$\sum_j \left[R\left(z_j^{\mathrm{O}} + z_j^{\mathrm{G}}\right) \gamma_j + s_j^{\mathrm{G}}(\gamma_j + \delta_j + \theta_j + \kappa_j) + s_j^{\mathrm{O}}\theta_j \right] > 0 \tag{101}$$

$$\forall j, \qquad \gamma_j + \delta_j + \theta_j + \kappa_j \leq 0 \qquad (z_j^{\mathrm{G}} \geq 0) \tag{102}$$

$$\forall j, \qquad \theta_j \leq 0 \qquad (z_j^{\mathrm{O}} \geq 0) \tag{103}$$

$$\forall j, \qquad -\gamma_j - \delta_j + p^{\mathrm{REC}} \leq 0 \qquad (s_j^{\mathrm{REC}} \text{ free}) \tag{104}$$

$$\forall j, \qquad \delta_j, \kappa_j, p^{\mathrm{REC}} \geq 0; \gamma_j, \theta_j \text{ free}. \tag{105}$$

It is easy to see that the $\hat{p}_j^{\mathrm{G}}$ and $\hat{\Pi}$ for Case 4 will be the same with those in Case 3. We prove that $\hat{p}^{\mathrm{REC}} \leq p^{\mathrm{REC}}$ as follows:

$$\begin{aligned} &\hat{p}^{\mathrm{REC}} - p^{\mathrm{REC}} && (106)\\ &= \hat{\phi}_j + \hat{\gamma}_j - (\phi_j + \gamma_j), \qquad \forall j && (107)\\ &= \hat{\gamma}_j - \gamma_j, \qquad \forall j : s_j^{\mathrm{G}} > 0 && (108)\\ &= -\hat{\kappa}_j \leq 0, \qquad \forall j : s_j^{\mathrm{G}} > 0, s_j^{\mathrm{O}} > 0. && (109) \end{aligned}$$

Here, Eq. (107) is from Eq. (46). Equation (108) is because in Eqs. (35) and (47) we have

$$\begin{aligned} &z_j^{\mathrm{G}} - R\left(z_j^{\mathrm{O}} + z_j^{\mathrm{G}}\right) - s_j^{\mathrm{REC}} \\ &= \left[z_j^{\mathrm{G}} - s_j^{\mathrm{REC}} - R\left(z_j^{\mathrm{O}} + z_j^{\mathrm{G}}\right) - s_j^{\mathrm{G}} \right] + s_j^{\mathrm{G}} > 0. \end{aligned}$$

Therefore, $\phi_j = 0$, and similarly $\hat{\phi}_j = 0$. Equation (109) is due to Eqs. (29), (45), and (50), which yield that $\gamma_j = \hat{\gamma}_j + \hat{\kappa}_j$. □

Proposition 5

Proof From Propositions 3 and 4, we have that $\Pi_1 = \Pi_2$ and $\Pi_3 = \Pi_4$, respectively. Moreover, any feasible solution to Case 3 is also feasible to Case 1, since Constraint (74) is tighter than Eq. (58), which is the only difference between the two cases. Therefore, $\Pi_1 \geq \Pi_3$. □

Appendix D: Data

Table 8 Assumptions of generation characteristics

Gen. ID	Zone	Producer ID	Marginal cost [$/MWh]	GHG rate [kg/MWh]	Gen. cap. [MW]
1	B	3	38.0	580	250
2	A	1	35.7	545	200
3	A	2	36.8	600	450
4	B	1	15.5	500	150
5	B	2	16.2	500	200
6	B	3	0.0	0	200
7	C	1	17.6	1216	400
8	C	1	16.6	1249	400
9	C	1	19.4	1171	450
10	C	3	18.6	924	200

Table 9 Derived power transfer distribution factor and transmission thermal limit

Link\zone	A	B	C	Thermal limit [MW]
A–B	0.3333	−0.3333	0	255
B–C	0.3333	0.6667	0	120
C–A	−0.6667	−0.3333	0	30

Table 10 Assumptions of the inverse demand curves

Zone\variables	P_j^0	Q_j^0	P_j^G	Q_j^G
A	98.20	1400	90	150
B	93.12	1540	80	100
C	111.60	840	100	100

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