

Upstream vs. Downstream CO2 Trading: A Comparison for the Electricity Context

EPRG Working Paper 1010

Cambridge Working Paper in Economics 1018

Benjamin F. Hobbs, James Bushnell and Frank A. Wolak

Abstract

In electricity, “downstream” CO2 regulation requires retail suppliers to buy energy from a mix of sources so that their weighted emissions satisfy a standard. It has been argued that such “load-based” regulation would solve emissions leakage, cost consumers less, and provide more incentive for energy efficiency than traditional source-based cap-and-trade programs. Because pure load-based trading complicates spot power markets, variants (GEAC and CO2RC) that separate emissions attributes from energy have been proposed. When all energy producers and consumers come under such a system, these load-based programs are equivalent to source-based trading in which emissions allowances are allocated by various rules, and have no necessary cost advantage. The GEAC and CO2RC systems are equivalent to giving allowances free to generators, and requiring consumers either to subsidize generation or buy back excess allowances, respectively. As avoided energy costs under source-based and pure load-based trading are equal, the latter provides no additional incentive for energy efficiency. The speculative benefits of load-based systems are unjustified in light of their additional administrative complexity and cost, the threat that they pose to the competitiveness and efficiency of electricity spot markets, and the complications that would arise when transition to a federal cap-and-trade system occurs.

Keywords Emissions trading, greenhouse gas regulation, electricity market models

JEL Classification Q52, Q54, Q58

Contact
Publication
Financial Support

bhobbs@jhu.edu.
March 2010
California Independent System Operator, NSF Grant ECE-0621920, and the UK Engineering and Physical Sciences Research Council and EPRG industrial partners via the Supergen Flexnet Consortium, Grant EP/E04011X/1



Upstream vs. Downstream CO₂ Trading: A Comparison for the Electricity Context

Benjamin F. Hobbs¹

Department of Geography & Environmental Engineering, The Johns Hopkins University

Baltimore, MD 21218 USA

Electricity Policy Research Group, University of Cambridge, Cambridge UK CB3 9DE

James Bushnell

Department of Economics, Iowa State University, Ames, IA 50011 USA

Frank A. Wolak

Department of Economics, Stanford University, Stanford, CA 94305 USA

1. Introduction

As climate policy continues to evolve around the world, there are continuing debates over where in the supply chain to impose Greenhouse Gas (GHG) limits. Proposals range from far upstream at the sale of fossil fuels to far downstream at the purchase of manufactured products and energy by ultimate consumers. In the power industry, the upstream vs. downstream discussion has focused on whether to place the burden of compliance on plants that produce electricity, on the companies that distribute power, or even individual retail consumers. This has, for example, been the focus of debate over how to implement California's AB32 and the subsequent Western Climate Initiative.

There are five broad alternatives for implementing GHG regulations in the electricity sector. The first is to regulate emissions at least partially "downstream" by placing a reporting and compliance obligation on retail providers of energy (here called "Load Serving Entities", or LSEs). Under this basic "load-based" approach, LSEs would have to demonstrate that the power they have purchased represents a mix of sources that achieves a specified target in terms of carbon intensity. Because electricity in a looped transmission network flows according to the laws of physics, it is impossible to determine the GHG emissions caused by each MWh of electricity consumed by each LSE. For this reason, an administrative procedure must be used to assign GHG emissions to each MWh of electricity; in the basic load-based system, this is accomplished

¹ Corresponding author: bhobbs@jhu.edu. Contact address: Electricity Policy Research Group, Dept. of Economics, Cambridge University, Cambridge, UK CB3 9DE, +44 1223 335248, +44 1223 335299 (fax).

by assigning emissions to bilateral power supply purchases based on the emissions rate of the generator who sells the power.

The load-based approach is similar in philosophy to other downstream mechanisms, such as the idea of tradable personal carbon allowances (PCAs) (Fleming, 1997) which have been extensively discussed in the UK. For example, the UK government recently proposed personal carbon “credit cards”, in which carbon emissions associated with a consumer’s purchases would be tracked and then limited to the number of credits that consumer was allocated or bought (Lane et al., 2008). Thus, consumers would be responsible for limiting emissions, analogous to the responsibility of LSEs under load-based proposals. Similar proposals have been made for Sweden (Varnäs & Nykvist, 2009) and California (Niemeyer et al., 2008).

The focus of this paper is on a comparison of load-based trading with the second, more upstream alternative for GHG regulation. The latter is “pure” source-based cap-and-trade system for power generators similar to systems such as the Title IV SO₂ trading system, the Regional Greenhouse Gas Initiative, and the EU Emissions Trading System. A source-based approach places compliance responsibility on the facility that is emitting the pollution (the source). Each facility would need to acquire emissions permits to offset their total emissions. However, this system has the disadvantage of not covering product or electricity imports, which means that emissions can “leak” out if imports from uncapped regions increase.

A third alternative would be to implement some hybrid cap-and-trade system that would effectively act like a source-based program for plants within a jurisdiction, while still trying to capture the emissions impact of power imports in some fashion. This approach seems most advanced in the western U.S., where several climate policy initiatives are underway.² There, the “first seller” approach currently favored by California and the Western Climate Initiative is the most widely discussed version of this hybrid concept.³ A fourth alternative is to move further upstream in the supply chain, regulating the fossil fuel inputs to power plants. The fifth and last alternative would be to focus GHG reduction efforts on mechanisms other than cap-and-trade, such as stringent renewable portfolio standards.

A choice among these approaches should consider various economic and environmental goals. These include, among others, efficiency of system dispatch

² California’s “Global Warming Solutions Act of 2006” (AB 32) established a goal of reducing the state’s greenhouse gas (GHG) emissions to 1990 levels by the year 2020. The bill covers more than 80% of the state’s CO₂ emissions. The discussions have since expanded to include the members of Western Climate Initiative, which involves six other western states as well as some Canadian provinces.

³ Under the California first seller proposal, a first seller is an entity that first brings power into the state’s market (CMAC, 2007). All generation units located in the California ISO control area are first sellers of electricity. So in this sense, the first-seller approach is a source-based approach because it is straightforward to determine the GHG emissions per MWh of energy produced from the technical operating characteristics of the in-state generation unit. However, for imports of electricity, the first seller is the entity importing the power into the state. An administrative procedure assigns a GHG emissions rate per MWh of energy imported into California for each importing entity.

and the performance of wholesale and retail electricity markets, the efficiency of investment in new generation facilities and energy efficiency technologies, consumer costs, administrative simplicity, effectiveness in achieving GHG reduction goals, and future compatibility with multi-state or federal GHG regulation. Bluemel (2009), Burtraw (2008), Bushnell (2008), and Van Horn (2008) discuss many of these considerations.

Several advantages have been claimed for the basic load-based trading proposal. One is that it, along with hybrid approaches, are claimed to regulate the GHG content of imported electricity. This advantage is overstated. Although firms would not be able to avoid compliance by physically moving their sources of production out of the state (“leakage”), they would be able achieve much the same ends by “reshuffling” their purchases of imported energy to originate from clean sources (Bushnell, 2008).⁴ The issues of leakage and shuffling in California have been analyzed elsewhere using modeling approaches. One study finds that certain versions of load-based, source-based, and first-seller based trading result in the same amount of leakage and contract shuffling, and estimates that contract shuffling will eliminate nearly all the purported emissions reductions that would be accomplished by any California-only system that attempts to attribute emissions to imports (Chen et al., 2008a). Other studies have focused on the effect of alternative allowance allocation schemes in the context of a first seller system (Palmer et al. 2009; Bushnell & Chen, 2009).

A second claimed advantage of load-based trading is that it would lower costs to consumers by avoiding bequeathing windfall profits to power producers and allowing LSEs to pay a premium only to cleaner producers, unlike source-based systems which raise prices paid to all producers (Synapse Energy, 2007; Bluemel, 2009). Experience with the EU Emissions Trading System has shown that high prices for CO₂ translate into higher prices of electricity, and that profits increase (Chen et al., 2008b). That increase has been very controversial, and this experience motivated stakeholder groups in the western US to search for other trading-based systems for reducing the power sector’s carbon emissions. The increase in profits had two sources. One was the economic rent associated with emissions allowances that were largely given away to producers under Phase I of the EU system. The second source is what we call the “rents of clean generation” in which clean plants benefited from higher energy prices because those price increases exceeded their expense of allowances. Some advocates of a load-based system claim that it would lower generation profits, and consumers would thereby benefit.

A third advantage claimed for load-based trading is that, compared to source-based systems, it would provide more motivation to LSEs to sponsor energy efficiency programs (Bluemel, 2009). By putting the compliance burden on LSEs, who are in a better position to implement such programs than generators, it is argued that such programs would be pursued more aggressively.

⁴ Several options for mitigating reshuffling have been suggested (Bluemel, 2009), but they remain among the most controversial and legally vulnerable aspects of load-based and first-seller based programs.

These claimed advantages have also been made for the related proposal of personal carbon allowances. It has been argued that PCAs could be surrendered when consumers buy imported goods, addressing carbon leakage; if given away for free, PCAs could lessen consumer costs and windfall producer profits; and by making consumers more conscious of the carbon associated with purchases, they would motivate carbon reductions more readily than would price increases due to carbon taxes. It is also argued that: PCAs can cover more sectors than source-based allowances; they are more acceptable than taxes; PCAs can be used to avoid regressive impacts of carbon regulation on the poor; and they promote the building of community commitment to sustainability (Harwatt, 2008; Hyams, 2009).

Our purpose here is to undertake a model-based investigation of the second and third claims for load-based trading (lower consumer costs and greater motivation to pursue energy efficiency). In order to focus on those claims and to simplify the derivations, we disregard power imports and the associated issues of leakage and contract shuffling, which have been investigated using more sophisticated models elsewhere (Chen et al., 2008a). Thus, our analysis is most relevant to a situation where imports are a small portion of total demand—for instance, if California successfully entices all the other western states, as well as relevant Canadian provinces, to join the Western Climate Initiative.

We investigate the two claims by constructing simple models of a load-based GHG trading system and then comparing it to source-based trading. We find that source-based trading and the basic load-based system provide the same financial incentive for investments in energy efficiency. Furthermore, load-based programs are shown to cost consumers no less than source-based systems in which all allowances are auctioned and the proceeds used to benefit consumers.⁵ However, in terms of administrative complexity, compatibility with existing spot-market based power markets, and consistency with likely federal GHG legislation, load-based systems have serious disadvantages compared to any of the other options. Therefore, contrary to some claims, the resulting cost of energy to consumers would likely be *higher* under a load-based trading system.

Because basic load-based trading requires LSEs to keep track of whom they buy power from and the associated emissions, power from different sources would fetch different prices, as we show later. As a consequence, retail entities will either be unable to, or be discouraged from buying energy in spot markets run by entities such as the California Independent System Operator (CAISO) (Gillenwater and Breidenreich, 2009). This is because CAISO-type spot markets (of which there are six in the US) do not track the emissions associated with different sources, and cannot sell different “flavors” of power at different prices depending on the emissions associated with their production. Similarly, low emitting producers would not want to sell power in such markets because they would not obtain the premium they could get from LSEs who desire their cleaner power (Bluemel, 2009). This disincentive to participate in the CAISO-type

⁵ Chen et al. (2008a) have also established the equivalency of source-based and the pure load-based program, but their derivation is much more complex than ours, and they do not consider the GEAC and CO₂RC load-based systems.

markets would lower their liquidity, and could even endanger reliability by giving operators of those markets fewer resources to draw upon during system emergencies.

Due to these concerns, variants of load-based trading have been proposed that unbundle emissions from energy, so that power producers can sell energy to CAISO-type markets while selling, in a separate market, the emissions attributed to consumers. These are the Generation Emissions Attribute Certificate (GEAC) and CO₂ Reduction Credit (CO₂RC) systems, which are proposed by Gillenwater and Breidenreich (2009) and Michel and Nielsen (2008), respectively. We also develop simple models of those systems, and conclude that, like the basic load-based approach, their costs to consumers are no less than, and likely greater than, source-based trading. Indeed, as we show, these systems can be viewed as being equivalent to source-based trading systems in which unusual (and complex) rules are used to allocate emissions allowances to producers to the detriment of consumers.

The paper is structured as follows. In Section 2, we present a simple model of a power and emissions allowance price equilibrium for the basic load-based trading system. Then in Section 3, we describe a model for source-based trading, and then demonstrate in Section 4 the equivalence of the two systems in terms of total cost of energy to final consumers—under assumptions that ignore the potentially higher consumer costs of a load-based approach due to possible damage to CAISO-type spot markets. A numerical example is given that illustrates the equivalence. Section 5 addresses the question of whether incentives for sponsoring energy efficiency programs are greater under the basic load-based systems. In Sections 6 and 7, we analyze the GEAC and CO₂RC proposals to unbundle emissions attributes from power in a load-based system, and establish their equivalence to source-based trading systems that involve significant subsidies of producers. Conclusions are presented in Section 8.

2. Market Equilibrium Model for Basic Load-Based Trading

The model for a load-based system consists of submodels of LSE and producer decision making, which, when combined with a market clearing condition, define the market equilibrium. For simplicity, we consider energy and emissions trading only for a single hour, and all entities behave competitively (*i.e.*, do not exercise market power). Transmission is disregarded, as are imports.⁶

We start with the LSE model. A single LSE serving all consumers is assumed; this model is readily generalized to multiple LSEs who can trade emissions allowances (as described in Gillenwater and Breidenich, 2009), and the fundamental results do not change. LSEs are assumed to obtain power on behalf of consumers by contracting bilaterally with producers; a spot-market could also be included, but would complicate the analysis without providing additional

⁶In actual trading systems, emissions are usually accounted for on an annual basis, often with banking allowed between years, while energy markets have to balance in every hour. Modeling analyses can account for how emissions may thereby shift among hours, and for how the price of emissions can evolve stochastically over the year in response to, *e.g.*, unanticipated energy supply and demand changes. Including multiple hours in the examples would complicate the analysis, but not alter the conclusions

insight. Here, LSEs are assumed to be regulated so that they minimize costs of meeting demand (as is the case with the utilities in California); a model based upon the alternative assumption of competition among profit maximizing LSEs could instead be formulated, but would not change our fundamental results. Consistent with the definition of load-based trading, the LSE model includes an upper bound upon the quantity-weighted emissions of the LSE's energy portfolio. Consumer demand for energy is assumed to be perfectly inelastic. The notation of the LSE model is given below; throughout this paper, lower case letters represent variables, while upper case letters are fixed parameters.

x_{Li} = MW purchased by the LSE from producer i in the basic load-based system

p_{Li} = \$/MWh price paid for power from producer i in the load-based system. Consistent with the competitive assumption, prices are viewed by the LSE as being exogenous, but in actuality are endogenous to the market as a whole. In general, these prices might differ among i because consumers will be willing to pay more for power from cleaner producers.

E_i = ton/MWh emissions rate for producer i

L = MW load for the LSE

K = tons/MWh emission cap for load; for instance, 0.5 might be chosen since it approximates the emissions rate of reasonably efficient gas-fired generators.

The LSE chooses which producers to buy power from in order to minimize the cost of meeting two constraints: the consumers' demand for power and the emissions constraint:

$$\text{MIN}_{\{x_{Li}\}} \text{Expenditures}_L = \sum_i p_{Li} x_{Li} \quad (1a)$$

$$\text{subject to: } -\sum_i E_i x_{Li} \geq -K L \quad (\text{shadow price } \alpha_L) \quad (1b)$$

$$\sum_i x_{Li} = L \quad (\text{shadow price } \beta_L) \quad (1c)$$

$$x_{Li} \geq 0 \quad \forall i \quad (1d)$$

The emissions constraint is expressed as a \geq inequality so that the shadow price will be positive, since the shadow price is defined as the marginal change in the objective with respect to an increase in the constraint right-hand side.

Turning to producers, we assume one plant per producer, with a constant marginal cost and a fixed capacity. Each producer is a price taker. The needed notation is:

y_{Li} = MW sales from producer i to LSE in the basic load-based system

$C_i = \$/\text{MWh}$ marginal cost of production for producer i

$CAP_i = \text{MW}$ generation capacity for producer i

The producer's problem is to maximize net revenues subject to the capacity constraint:

$$\begin{aligned} \text{MAX } \text{Profit}_{Li} &= (p_{Li} - C_i)y_{Li} \\ \{y_{Li}\} \end{aligned} \quad (2a)$$

$$\text{subject to: } 0 \leq y_{Li} \leq CAP_i \quad (\text{shadow price } \mu_{Li}), \forall i \quad (2b)$$

Of course, this simplistic representation disregards time varying prices and loads, unit commitment constraints, and other complications, but their absence does not affect our fundamental results.

An equilibrium is achieved when each market party (LSE and producers) is optimizing their objective subject to the market prices, and markets clear. Mathematically, this is accomplished by forming an equilibrium model from the first-order (Kuhn-Tucker) conditions for each party's optimization problem together with the clearing condition that demand equals supply for each producer:

$$x_{Li} = y_{Li} \quad (\text{price } p_{Li}), \forall i \quad (3)$$

This general approach to constructing equilibrium models is commonly used to simulate power and other commodity markets (*e.g.*, Hobbs & Helman, 2004; Gabriel & Smeers, 2006). We define separate market clearing constraints for each producer, rather than one for the entire market, because consumers need to account for emissions from their power contracts. If properly formulated, the resulting model is a "square" system (as many conditions as unknowns) that can be solved for the unknowns $\{x_{Li}, y_{Li}, p_{Li}, \alpha_L, \beta_L, \mu_{Li}\}$. The full model is presented in Appendix A.1.

In Appendix A.1 we show that, in equilibrium, cleaner producers get a premium for their power, representing its value to the LSE for meeting its emissions constraint. In particular:

$$p_{Li} = p_{L0} - \alpha_L E_i, \forall i \quad (4)$$

where p_{L0} is the price that a producer with zero emissions would receive.

3. Market Equilibrium Model for Source-Based Equilibrium with Auctioned Allowances

Here we develop, for comparison purposes, a model of a source-based market in which allowances are auctioned, and the proceeds returned to consumers. We call this Source-Based Model I, as source-based systems that distribute allowances in other ways will be compared with the CO₂RC system in Section 7. Notation for this model is the same as for the load-based equilibrium, except that the subscript "SI" is substituted for "L" on all variables.

The model for LSEs acting on behalf of consumers omits the emissions constraint of the load-based model, but has an extra objective function term:

$$\text{MIN } \text{Expenditures}_{SI} = \sum_i p_{Sli} x_{Sli} - \alpha_{SI} K L \quad (5a)$$

$$\{x_{Sli}\}$$

$$\text{subject to: } \sum_i x_{Sli} = L \quad (\text{shadow price } \beta_{SI}) \quad (5b)$$

$$x_{Sli} \geq 0, \quad \forall i \quad (5c)$$

The second expenditure term consists of the proceeds of the allowance auction. Since the decision variable x_{Sli} does not enter that term, the LSE views it as a constant. Meanwhile, the producer model differs from the load-based version because producers now bear the expense of buying allowances from an auctioneer at price α_{SI} :

$$\text{MAX } \text{Profit}_{Sli} = (p_{Sli} - C_i - \alpha_{SI} E_i) y_{Sli} \quad (6a)$$

$$\{y_{Sli}\}$$

$$\text{subject to: } 0 \leq y_{Sli} \leq CAP_i \quad (\text{shadow price } \mu_{Sli}), \quad \forall i \quad (6b)$$

Market clearing conditions complete the equilibrium model. In addition to the energy market, there is now a clearing condition for allowance trading that ensures that total emissions do not exceed a cap.

$$x_{Sli} = y_{Sli} \quad (\text{price } p_{Sli}), \quad \forall i \quad (7a)$$

$$\sum_i E_i y_{Sli} \leq K L \quad (\text{nonnegative price } \alpha_{SI}) \quad (7b)$$

Again, prices are allowed to differ among energy sources. Meanwhile, the emissions price can be positive only if the emissions constraint binds. For comparison's sake, the total number of allowances is assumed to be the same as the maximum emissions KL under the load-based model of Section 2.

The source-based equilibrium model consists of the first-order conditions for each of the market participants' optimization problems together with the market clearing conditions, yielding a square system (see Appendix A.1). The unknowns are $\{x_{Sli}, y_{Sli}, p_{Sli}, \alpha_{SI}, \beta_{SI}, \mu_{Sli}\}$. Unlike the load-based case, it turns out that the energy prices p_{Sli} paid to all producers i are equal (Appendix A.1).

4. Equivalence of the Basic Load-Based and Source-Based Models

The following results for the relationship of the two models are demonstrated in Appendix A.1. The first set of results concerns the relationship between the equilibrium values of the price and quantity variables of the load- and source-based models:

$$p_{Li} = p_{Sli} - \alpha_{SI} E_i, \quad \forall i$$

$$\{x_{Li}, y_{Li}, \alpha_L, \beta_L, \mu_{Li}\} = \{x_{Sli}, y_{Sli}, \alpha_{Si}, \beta_{Si}, \mu_{Sli}\} \quad (9)$$

That is, the load-based energy price for a particular producer i equals the source-based price *minus* a penalty for i 's emissions. The penalty is the \$/ton shadow price of emissions (which is implicit in the LSE's maximization problem) times the ton/MWh emissions rate. All other variables for the load- and source-based equilibria are equal.

The second set of results establishes the equivalence of the two systems in terms of consumer payments and producer profits, if allowances are auctioned to producers and the proceeds are returned to consumers. Thus, the "Rents to Clean Generation" that producers earn in the source-based system are also retained by producers in the load-based system. The conclusion of Synapse Energy (2007) that consumers would gain those rents under the load-based system is incorrect.

We illustrate this equivalence with a numerical example. Consider a power system in which there is one LSE and three producers each with different types of generation (A, B, and C).

- The load serving entity has constant load $L = 2000$ MW. Under the load-based system, it is obliged to buy power contracts that, on average, have an emissions rate of $K = 0.55$ tons/MWh, so total emissions will be 1100 tons (0.55×2000).
- Generation type A (wind or hydro) has emissions E_A of 0 tons/MWh, marginal cost $C_A = 0$ \$/MWh, and capacity $CAP_A = 500$ MW.
- Generation type B (natural gas) emits $E_B = 0.6$ tons/MWh, incurs cost $C_B = 80$ \$/MWh, and has ample capacity CAP_B (no limit).
- Generation type C (coal) has emissions E_C of 1 ton/MWh, cost $C_C = 40$ \$/MWh, and ample capacity CAP_C (no limit).⁷

The solution to Section 2's load-based model yields the following generation, cost, and prices:

- MW generation y_{Li} from companies $i=A,B,C$: $y_{LA} = 500$ MW, $y_{LB} = 1000$ MW, $y_{LC} = 500$ MW. These also equal the MW purchases by the LSE (x_{LA} , x_{LB} , and x_{LC} , respectively).
- Prices p_{Li} paid by the LSE for each type of generation $i=A,B,C$: $p_{LA} = \$140$ /MWh; $p_{LB} = \$80$ /MWh; $p_{LC} = \$40$ /MWh.
- The total paid for power by the LSE is \$170,000, or \$85/MWh.
- Only producer A makes a profit ($\$140$ /MWh \times 500 MW, or \$70,000).

⁷ More elaborate assumptions about capacity limits on all units and dispatch over multiple hours of the year would not alter the fundamental conclusions of this analysis, but could of course change the specific numerical results. A binding capacity constraint for natural gas generation in a given hour would mean, in this more general case, that an emissions constraint would either force more natural gas generation in other hours (those with lower demand) when that constraint is not binding, or additional clean generation from other even more costly sources, if available. But in the simple single hour example of this section, if the capacity of the gas plant (B) was less than 1000 MW, then there would be no feasible solution – there is no dispatch that would result in the emissions limit being satisfied, as the solution involving both clean units (A and B) producing at capacity, displacing as much coal generation as possible, would still have higher emissions than the cap.

Thus, cleaner generation earns a premium in this market which results from the value it provides by making it easier for the LSE to achieve its emissions target. That is, an LSE is willing to pay more for cleaner power. As we show above, it turns out that the “shadow price” of the LSE’s emissions constraint—\$100/ton—equals the price of emissions allowances in the source-based example, below.

Now consider the source-based system of Section 3 with the same cap of 1100 tons, with allowances being auctioned and the proceeds going to consumers. The following is the equilibrium:

- MW generation y_{Si} from companies $i=A,B,C$: $y_{SIA} = 500$ MW, $y_{SIB} = 1000$ MW, $y_{SIC} = 500$ MW. These also equal MW purchases by the LSE (x_{SIA} , x_{SIB} , and x_{SIC} , respectively).
- The price for power is \$140/MWh, and is the same for all producers.
- The allowance price is \$100/ton, so the allowances rent is \$110,000. This price means that the net marginal cost for B’s output is \$140/MWh ($=\$80/\text{MWh}$ for fuel + $0.6 \text{ ton/MWh} * \$100/\text{ton}$ for allowances), which is the same as for C ($=\$40/\text{MWh}$ for fuel + $1.0 \text{ ton/MWh} * \$100/\text{ton}$). Neither B nor C earns any operating profit, as price equals their marginal cost.
- On the other hand, A’s marginal cost is \$0, as it has neither fuel costs nor emissions; therefore, it will produce at its 500 MW capacity, and earn \$70,000 in profits ($\$140/\text{MWh} * 500 \text{ MW}$).
- The LSE pays \$280,000 for its power ($\$140/\text{MWh} * 2000 \text{ MW}$). But since consumers get the proceeds of the allowances auction, they accrue the allowances rent (\$110,000), so the net cost to the consumers is \$170,000 or \$85/MWh.

Thus, the two systems (load-based and source-based/consumer-owned allowances) result in the same cost to load. The “Rent to Clean Generation” in both cases accrues to Producer A (the cleanest generator). Producer A earns this rent in the source-based case because it earns the full power price without having to pay for any allowances. It earns the same rent in the load-based case because LSEs are willing to pay a premium for its power relative to higher-emissions sources.

5. Impact on LSE Incentives for Energy Efficiency

It has been argued that a load-based system will result in a greater incentive for LSE investments in energy efficiency technology than a source-based system (Bluemel, 2009). The argument is that LSEs have more options than generators for reducing the need for allowances and that the load-based system “paints a target on the back” of the LSE, making it more accountable for its carbon footprint. However, there are two reasons why the incentives for demand-side programs under the basic load-based system would not differ from those under source-based systems, at least in California.

The first reason is that California’s LSEs are already required to account for and report the GHG emissions associated with their contracts no matter what sort of GHG regulatory system is implemented under AB 32. There will be public

visibility and pressure to pursue energy efficiency to lower emissions under either load-based or source-based systems.

The second reason is that California investor-owned utilities are subject to an extensive regulatory system that arguably provides more incentives than any other state for investment in energy efficiency. These incentives include procurement priorities that place efficiency at the top of the list among all resources; a charge paid by all California electricity consumers to fund cost-effective energy efficiency programs; the decoupling of utility revenues from sales; and rate-of-return incentives adopted by the CPUC in September 2007. With implementation of AB 32, carbon costs will be included as part of the “avoided energy costs” in the “Total Resource Cost Test” used to identify beneficial efficiency programs under California’s rules; as a result, more energy efficiency programs will become cost-effective. This will be true under either load- or source-based programs. California’s strong regulatory incentives will then motivate utilities to pursue many, if not most, of those opportunities.

In particular, the avoided cost of energy will be the same in the simple load- and source-based programs of Sections 2 and 3. The above numerical example illustrates this. Under the California “Standard Practice” for benefit-cost analysis of demand-side programs (CPUC, 2001), “utility avoided costs” quantify the utility’s energy cost savings resulting from changes in load. Assuming that implementation of energy efficiency programs would not change the total emissions cap of 1100 tons in our example, the only impact of energy efficiency upon the LSE’s optimization problem is that a unit decrease in load L lowers the right-hand side of the LSE’s load constraint by 1 MWh. The shadow price for that constraint, $\beta_L = \$140/\text{MWh}$, indicates the amount that the LSE’s objective would thereby decrease. This is the avoided cost, which is the change in LSE expenditures, given that the total emission tonnage constraint is unchanged. This value is the same as the price of emissions-free power ($p_{LA} = \$140/\text{MWh}$). Meanwhile, in the source-based model of Section 3, a unit decrease in L again decreases the right-hand side of the LSE’s load constraint by 1 unit. Since that constraint’s shadow price is $\beta_{SI} = \$140/\text{MWh}$ (the same as the market price of power), the cost-savings to the LSE is the same as in the load-based model.

Thus, “utility avoided cost” is the same under the load-based and source-based models ($\beta_L = \beta_{SI}$). As it is this cost that is compared to the expense of energy efficiency, an LSE has no more economic incentive to pursue efficiency under the load-based system than under the source-based system.

6. Analysis of the Generation Emissions Attribute Certificate Load-Based Proposal

6.1 Model

The GEAC load-based system proposed by Gillenwater and Breidenich (2009) unbundles emissions and energy so that power markets, such as the CAISO, would not have to track emissions associated with generators. The proposal has

the producer unbundle the GHG emissions rate from power production; then the producer can sell the GHG rights to load, and power to whomever it wants. The rights are called GEACs, have units of energy (MWh), and have the additional attribute of the actual emissions rate (tons/MWh) of the generator. Thus, GEACs are a differentiated commodity. Each load-serving entity (LSE) is responsible for buying enough MWh of GEACs to meet its load, and the total emissions associated with the GEACs it buys (the sum of the weighted product of the GEACs and their associated emissions) must be no more than the LSE's emissions limit.

The idea of the GEAC proposal is captured in the following market equilibrium model, consisting of a LSE model, a producer model, and clearing conditions. The subscript G on the variables indicates that they are GEAC market equilibrium values. Two sets of prices that clear the market: p_{Gi} (the \$/MWh price of power from producer i) and π_{Gi} (the \$/MWh price of GEACs from i).

We start with the LSE's optimization problem. Choose (1) the amount of electricity x_{Gi} to buy from each producer i and (2) the amount of GEACs u_{Gi} to purchase from each producer i in order to minimize the cost of meeting demand, subject to regulatory constraints concerning the amount and mix of GEACs that each LSE has to buy.

$$\begin{aligned} \text{MIN } \text{Expenditures}_G = \sum_i p_{Gi} x_{Gi} + \sum_i \pi_{Gi} u_{Gi} \\ \{x_{Gi}, u_{Gi}\} \end{aligned} \quad (10a)$$

$$\text{subject to: } \sum_i x_{Gi} = L \quad (\text{shadow price } \beta_G) \quad (10b)$$

$$\sum_i u_{Gi} - \sum_i x_{Gi} = 0 \quad (\text{shadow price } \gamma_G) \quad (10c)$$

$$\sum_i (T - E_i) u_{Gi} \geq (T - K) L \quad (\text{shadow price } \alpha_G) \quad (10d)$$

$$x_{iG}, u_{Gi} \geq 0, \quad \forall i \quad (10e)$$

The notation is the same as in the previous sections, with three exceptions: the addition of a new constant T , a new decision variable u_{Gi} , and its price π_{Gi} . T is a default emissions rate per MWh set by the regulator. This can be the target rate K or a higher rate; for instance, Gillenwater and Breidenich (2009) propose a T equal to the highest rate among all plants in the market. The new variable u_{Gi} is the MWh of GEACs that the LSE buys from producer i . Its price π_{Gi} will, in general, vary among producers i , because different emissions rates are associated with GEACs from different sources.

Meanwhile, the second and third constraints are new. The second one says that the number of GEACs has to equal the amount of energy consumed. The third constraint is equivalent to the basic load-based constraint (1b) that says that the emissions-weighted energy purchases cannot exceed the target emissions. However, because of the way that GEACs are defined, we express it differently (but equivalently) to help derive the equilibrium GEAC prices. In particular, the sum of the GEACs, weighted by their emissions rate reduction relative to the default rate $(T - E_i)$, must be at least equal to the load times $(T - K)$, the emissions

reduction implied by the target emissions rate K relative to the default rate T . Some algebra shows that (10d) is equivalent to (1b). This is done by rearranging the terms in (10d), and then substituting in (10b) and (10c) as follows:

$$\begin{aligned} T \sum_i u_{Gi} - \sum_i E_i u_{Gi} &\geq T L - K L \\ T \sum_i x_{Gi} - \sum_i E_i u_{Gi} &\geq T \sum_i x_{Gi} - K L \\ -\sum_i E_i u_{Gi} &\geq -K L \end{aligned} \quad (11)$$

The last expression is the simple load-based constraint (1b) on LSE emissions.

Considering now the producer problem, each i has to choose the amount of generation y_{Gi} [MWh] and GEACs v_{Gi} to sell in order to maximize profit.

$$\begin{aligned} \text{MAX}_{\{y_{Gi}, v_{Gi}\}} \text{ Profit} &= (p_{Gi} - C_j)y_{Gi} + \pi_{Gi} v_{Gi} \end{aligned} \quad (12a)$$

$$\text{subject to: } y_{Gi} - v_{Gi} = 0 \text{ (shadow price } \theta_{Gi}), \forall i \quad (12b)$$

$$0 \leq y_{Gi} \leq CAP_i \text{ (shadow price } \mu_{Gi}), \forall i \quad (12c)$$

There are two market clearing conditions. First, for energy from each producer:

$$x_{Gi} = y_{Gi} \text{ (price } p_{Gi}), \forall i \quad (13a)$$

Second, the amount of GEACs bought from each producer has to equal the amount it produces.

$$u_{Gi} = v_{Gi} \text{ (price } \pi_{Gi}), \forall i \quad (13b)$$

As with the other models, the market equilibrium can now be defined by combining these clearing conditions with the first-order conditions of the consumer and producer models (as in Appendix A.2).

Gillenwater and Breidenich (2009) (*e.g.*, Figure 2) suggest that GEACs from producer i would fetch a market price π_{Gi} proportional to $(T - E_i)$. Appendix A.2 shows that this is indeed a market equilibrium and that the constant of proportionality is then α_G , the market price/ton of emissions; *i.e.*,

$$\pi_{Gi} = \alpha_G (T - E_i), \quad \forall i \quad (14)$$

The relative size of the default and plant emissions rates determines the plant's GEAC price, which can be negative. A plant that is cleaner than the default ($T > E_i$) gets paid for credits ($\pi_{Gi} > 0$), while if it is dirtier than the default ($T < E_i$), it has to pay consumers to take the credits off its hands ($\pi_{Gi} < 0$). The logic is that LSEs should be willing to pay a premium for a certificate that makes it easier to comply with its emissions constraint (*e.g.*, a GEAC whose $E_i < K$), while a LSE would have to be bribed to accept a certificate that makes it more difficult to comply with that constraint (*i.e.*, a GEAC with a very high E_i). Thus, low emission

producers would be paid handsomely for their GEACs, while a coal plant might have to pay LSEs to take the GEACs off its hands, depending where T is pegged. (This presupposes a regulatory system that requires producers to get rid of all their GEACs, and an effective enforcement system.) If, as Gillenwater and Breidenich (2009) propose, T is set at a very high level, then coal plants may get instead get a small positive or zero price, depending on their emissions rate.

The choice of target T can affect the price of GEACs; it also affects the price of power. However, in a closed power market in which load L is fixed, in equilibrium, it turns out that total profit for each producer is unaffected (see Appendix A.2). Although increasing T would increase GEAC prices (and thus producer revenues), power prices decrease by an identical amount. The *same* generation and consumption solution and consumer costs result for all values of T .

The value of T also affects the net payments from consumers to producers through the GEAC mechanism. Having a higher default emissions rate ($T > K$) would result in payments, on net, from LSEs to producers, although power prices would be lower in compensation. Setting $T = K$ instead results in zero net payments for GEACs by LSEs, and even smaller values of T would mean that producers instead pay LSEs, on average. Since consumer costs, including power costs, are the same in each case, setting $T = K$ (yielding pricing rule $\pi_{Gi} = \alpha_G(K - E_i)$) is arguably the easiest to administer. This is because LSEs would pay nothing on net to producers—in fact, they would not need to be involved in the system at all, as the GEAC system reduces to source-based trading, as shown below.

As a numerical example of the GEAC system with $T = K$, consider an LSE with a load of $L = 1$ MWh. Two producers can serve that load: A, which has high emissions ($E_A = 1$ ton CO₂/MWh) and B, which has low emissions ($E_B = 0.5$ ton/MWh). The default and target emissions rates are equal, $T = K = 0.75$ tons/MWh. A's marginal generation cost is \$40/MWh, and B's is \$70/MWh. The equilibrium energy price is $p_{GA} = p_{GB} = \$55/\text{MWh}$, so there is only one electricity price and the ISO does not have to track different "flavors" of electricity. Meanwhile, the price of emissions is $\alpha_G = \$60/\text{ton}$. Consequently, dirty producer A has to bribe the LSE \$15/MWh to take its credits, while clean producer B gets paid the same amount for its GEACs. Neither producer earns any profit.

Interestingly, the LSE pays *nothing* on net for its GEACs. In particular, it pays $\$60 \cdot (0.75 - 0.5) = \$15/\text{MWh}$ for 0.5 GEACs from producer B, but is paid $\$60 \cdot (1 - 0.75) = \$15/\text{MWh}$ for the 0.5 GEACs it accepts from producer A. As noted above, this is no coincidence; each LSE pays \$0 for its GEACs if the target T is set equal to K and if dirty producers ($E_i > K$) are forced to pay LSEs to take their GEACs. So there is no point in having LSEs participate in the GEAC market if $T = K$; it turns out that an equivalent source-based system can be devised that only involves producers.

6.2 Equivalence of GEAC to a Source-Based System with Free Allocation of Allowances to Producers

Assume that $T = K$, and dirty producers must pay LSEs to take their GEACs. The resulting GEAC model simplifies if it is recognized that the assumed pricing rule will result in the consumer's emissions constraint being binding in an optimal solution. We can then combine the emissions constraint (10d) and the LSE's demand constraint (10b), yielding:

$$\sum_i E_i u_{Gi} = K L = K \sum_i x_{Gi} = K \sum_i u_{Gi} \quad (15)$$

which implies that the objective function term $(\sum_i \pi_{Gi} u_{Gi} = \sum_i \alpha_G (K - E_i) u_{Gi})$ is identically zero. This means that each LSE pays nothing, on net, for its GEACs. Thus, there is no need to have load participate in this market. The complications of having not only to monitor plant emissions but also track sales of GEACs to LSEs serve no purpose and can be avoided. As shown in Appendix A.2, this nominally load-based trading system is actually a source-based system with the following properties:

1. An elastic emissions cap that is proportional to the target emissions rate K times total production (here, L). So if demand, and thus production, grows, so do emissions.
2. Free allocation of allowances to producers in proportion to their sales, rather than an auction.

The free allocation of allowances in proportion to sales implicitly subsidizes marginal production compared to a system in which allowances are auctioned or even given away free according to some grandfathering rule that is independent of present output decisions. However, because distributing allowances in proportion to generator sales lowers generator marginal costs, energy prices decrease (Fischer, 2003); in this simple model, the allowances rent in the GEAC system is entirely returned to consumers in the form of lower energy prices.

What if a more general default emissions rate of T is used, so that the pricing rule is $\pi_{Gi} = \alpha_G(T - E_i)$? If the equilibrium emissions price α_G and pattern of GEAC purchases were unchanged (which would be the case here, see the Appendix), the increase in LSE payments due to increasing the default rate to T from K would be the change in the last term of the LSE's objective:

$$\alpha_G[\sum_i (T - E_i) u_{Gi}] - \alpha_G[\sum_i (K - E_i) u_{Gi}] = \alpha_G(T - K)L$$

That is, this would be equivalent to taxing the consumer by $\alpha_G(T - K)$ per MWh; producers would receive a payment of this amount per MWh they generate (assuming no resistance losses, so generation equals load). Thus, energy production by all producers would be subsidized. So there is no theoretical reason to set up an elaborate load-based accounting system to implement a system with a default emission rate $T \neq K$ if all producers must participate.⁸

⁸ As Gillenwater and Breidenich (2009) point out, however, if participation by producers is voluntary (as might be in the case of importers of power from unregulated jurisdictions), then a higher default rate might

Instead, an energy tax can be imposed on consumption, and its proceeds passed to generators, or used for other purposes.

Further, assuming L is fixed (perfectly inelastic), then in a competitive equilibrium, any tax payments by consumers that are given to producers would be returned to consumers in the form of lower power prices. Nothing would then be accomplished—the net costs to consumers would be exactly the same (see Appendix A.2). So there would be a reason to do this only if the taxes were used for some purpose other than a subsidy to producers.

Continuing with the above example, if $T = K = 0.75$ tons/MWh, then, as pointed out earlier, the equilibrium energy price is \$55/MWh (whether in the GEAC system or its equivalent source-based system). The LSE bears only the price of energy, and the payments it receives for accepting dirty GEACs exactly offsets its payments for clean GEACs. But if instead T is set to the emissions rate of the dirtiest unit (here, 1 ton/MWh), the LSE has to pay for all their GEACs, but the equilibrium price of power falls in compensation. In particular, the LSE buys 0.5 GEACs from dirty producer A for $\alpha_G(T-E_A)u_{GA} = \$60(1-1)0.5 = \$0$, and 0.5 GEACs from clean producer B for $\alpha_G(T-E_B)u_{GB} = \$60(1-0.5)0.5 = \$15$ total. The equilibrium power price however is \$40/MWh, so the LSE will spend a total of \$55 for its 1 MWh of load—the same as in the $T = K$ case.

To sum up, the GEAC proposal has been shown to be equivalent to a version of source-based trading in which allowances are distributed free to generators in proportion to their sales. If the default emissions rate used to define GEACs is higher than the targeted rate, then, in effect, consumers are taxed to subsidize production (by paying more for emissions reductions by producers), although in equilibrium this tax is returned to consumers in the form of lower power prices.

7. Analysis of the CO₂RC Load-Based Proposal

7.1 Model

Like the GEAC proposal, the CO₂RC variant of load-based trading unbundles emissions and energy. Thus, LSEs do not track emissions associated with individual power sales, which is more compatible with CAISO-type spot markets than the basic load-based proposals. To explore the properties of the CO₂RC proposal, we first develop a model of the price and emissions market equilibrium under an alternative source-based system, and then show it is equivalent to CO₂RC.

Consider the following somewhat peculiar source-based system, which we label Source-Based System II. It is the same as Section 3's source-based system with two exceptions:

1. Each producer i is granted $T y_{SIIi}$ allowances per year for free, where, T is a high “default” emissions rate (e.g., 1 ton/MWh) that is larger than K , the

be preferred in order to incent participation. However, the payments from consumers to producers would then be even greater.

target per-MWh emissions rate. Thus, if a generator sells more power, it gets more allowances, unlike Source-Based System I. Since energy supply equals demand (disregarding imports and resistance losses), this means that a total of TL allowances are distributed to generators, well in excess of the desired cap.

2. Because there would otherwise be too many allowances relative to the cap, the LSE is required to buy back and retire $(T-K)L$ tons/yr of emissions allowances from the market.

The second feature is the peculiar aspect of this CO₂ trading system, in that in normal source-based systems (*e.g.*, the EU ETS), LSEs do not have to buy allowances.

We model this system by developing models of market party behavior, and imposing market clearing to calculate an equilibrium. The LSE minimizes the cost of buying power and allowances:

$$\text{MIN } \text{Expenditures}_{SII} = \sum_i p_{SII} x_{SII} + \alpha_{SII} (T-K)L \quad (16a)$$

$$\{x_{SII}\}$$

$$\text{subject to: } \sum_i x_{SII} = L \quad (\text{shadow price } \beta_{SII}) \quad (16b)$$

$$x_{SII} \geq 0, \quad \forall i \quad (16c)$$

The subscript SII indicates that these are the equilibrium values for Source-Based System II. Now, the producer chooses generation y_{SII} to maximize profit (equaling energy revenue minus production and emissions costs, plus the value of the free allowances it is allocated), subject to a capacity constraint:

$$\text{MAX } \text{Profit} = (p_{SII} - C_i - \alpha_{SII} E_i) y_{SII} + \alpha_{SII} T y_{SII} \quad (17a)$$

$$\{y_{SII}\}$$

$$\text{subject to: } 0 \leq y_{SII} \leq CAP_i \quad (\text{shadow price } \mu_{SII}), \quad \forall i \quad (17b)$$

There are two market clearing conditions in Source-Based System II. One is that sales equals generation for each i , as before:

$$x_{SII} = y_{SII} \quad (\text{price } p_{SII}), \quad \forall i \quad (18a)$$

The other is the market clearing condition for emissions allowances, which is that consumer allowance purchases plus generator emissions do not exceed the allowances allocated to generators:

$$(T-K)L + \sum_i E_i y_{SII} \leq TL \quad (\text{nonnegative price } \alpha_{SII}) \quad (18b)$$

When rearranged, this is the same as total emissions not exceeding the target KL , as it must:

$$\sum_i E_i y_{SII} \leq KL \quad (\text{nonnegative price } \alpha_{SII}) \quad (18b')$$

Once again, gathering the first-order conditions for optimality for the producers and the LSE together with the market clearing conditions allows us to solve for the variables $\{x_{SII}, y_{SII}, p_{SII}, \alpha_{SII}\}$ as well as for the shadow prices for the producers' and LSE's constraints. As in the case of Section 3's source-based system, it can be shown that the energy price received by all producers that generate a positive amount of energy is the same ($p_{SII} = p_{SIIj}$ for all i and j that sell power) (Appendix A.3).

Now, this Source-Based System II trading can be shown to be economically equivalent to the proposed CO₂RC system as follows. Under the CO₂RC proposal:

- Each producer i sells CO₂RC's equal to $(T-E_i)y_{IIi}$ tons, receiving price α_{SII} for each ton. This results in *exactly* the same profit function (17a) as in Source-Based System II.
- The LSE buys CO₂RC's equal to $(T-K)L$, paying price α_{SII} for each ton. This results in *exactly* the same LSE expenditure (16a) as in Source-Based System II.

Consequently, it follows that the *same* exact market equilibrium $\{x_{SII}, y_{SII}, p_{SII}, \alpha_{SII}\}$, profit, and consumer costs will result in this CO₂RC system as in Source-Based System II. There are a couple of notable characteristics of the equilibrium for this unusual source-based system:

- The producers obtain allowance rents because they are given allowances free; but because allowances are allocated in proportion to sales, this decreases the opportunity cost of production. Consequently, electricity prices decrease, a general characteristic of source-based systems in which allowance allocations are tied to output (Fischer, 2003). Here, the price decrease results in returning every last penny of the allowance rents to consumers. (This is proven in Appendix A.3 by mathematically comparing the market equilibrium for this source-based system with the equilibrium for Source-Based System I in which allowances are auctioned to producers, Section 3).
- There is extra bookkeeping compared to a more typical source-based system, because the LSEs must also participate in the allowances market.

The following additional results can also be proven mathematically (see Appendix A.3). We now compare the CO₂RC system to a third source-based system where the LSE does not have to buy allowances, and allowances are allocated freely to generators at rate Ky_i (rather than the higher Ty_i , the rate that is implicit in the CO₂RC system). LSEs do not have to buy allowances back from producers in this system, which we call Source-Based System III.

- CO₂RC and the Source-Based Systems I, II, and III all have the same price of allowances α as well as the same pattern of generation x , sales y , and avoided cost of serving load β
- Producer profits are the same in all four of these systems, as are the total costs to LSEs/consumers (accounting for both energy and payments allowances).

- The price of power in the CO₂RC system (and System II) is less by $(T-K)\alpha$ per MWh compared to Source-Based System III. The lower revenue that producers earn under CO₂RC/Source-Based System II is *exactly* made up by the extra allowance revenue resulting from producers being given more allowances (T tons per MWh of production under CO₂RC/Source-Based System II rather than the lower K tons per MWh under System III). This distortion in the price of power under CO₂RC/System II could have significant implications for power trade with neighboring regions not subject to the allowances cap.
- Both the CO₂RC and Source-Based Systems II and III have lower power prices than Source-Based System I (Section 3) in which allowances are auctioned to producers. However, if consumers are given the revenues from the auction, then the value that consumers obtain from the auction exactly makes up for the electricity price differences.

Thus, the CO₂RC system has no theoretical advantage over a pure source-based system. But it has the disadvantage of more administrative complexity by unnecessarily involving LSEs in allowance markets.

7.2 Numerical Example

We return to the two producer example of Section 6.2 in which load is 1 MWh. The default emissions rate $T = 1$ ton/MWh, and the target emissions rate is 0.75 tons. We compare the CO₂RC and three source-based systems:

- *Source-Based System I.* Allowances are auctioned to producers, and the consumers receive the revenues from the auction ($=\alpha_{SI}KL = \alpha_{SI}0.75$).
- *Source-Based System II* (identical to CO₂RC). Allowances are freely allocated to producers at rate Ty_{SIIi} ($=1y_{SIIi}$), and the LSE must buy $(T-K)L$ ($=(1-0.75)*1 = 0.25$) allowances back from the producers.
- *Source-Based System III.* Allowances are freely allocated to producers at rate Ky_{SIIIi} ($=0.75y_{SIIIi}$), resulting in a total of $KL = 0.75$ allowances being allocated.

In all three source-based systems, each producer i consumes $E_i y_i$ allowances.

In equilibrium, all four systems have the same output, allowances price, profits, and LSE cost:

- Each of the two producers generates 0.5 MWh.
- The allowance price $\alpha = \$60/\text{ton}$.
- Each generator earns no profit. (In general, capacity constraints would result in nonzero profits for some generators, as in Section 4, but their profits would be the same under all systems.)
- Consumer cost is \$55/year (energy plus any costs or proceeds from allowances).

However, the energy prices differ:

- For a given system, the price of power is the same for all producers ($p_A = p_B$); however this uniform price differs among the four systems.
- The CO₂RC system and its equivalent source-based system (System II) have the same $p = \$40/\text{MWh}$. Producer A's profit is $(p - C_i - \alpha E_i)y_i + \alpha T y_i = (40 - 40 - 60 \cdot 1)0.5 + 60 \cdot 1 \cdot 0.5 = 0$. For B, $(p - C_i - \alpha E_i)y_i + \alpha T y_i = (40 - 70 - 60 \cdot 0.5)0.5 + 60 \cdot 1 \cdot 0.5 = 0$. Note that the power price (\$40) is less than the clean plant B's marginal fuel cost (\$70), but B still breaks even because it is given more allowances than it consumes. The LSE pays only $\$40 \cdot 1 = \40 for its energy, but it also must buy back 0.25 allowances @ \$60/ton, making its total cost \$55/yr.
- Source-Based System III has a higher power price ($p = \$55/\text{MWh}$). However, the generators still earn zero profit, because they are given fewer allowances (0.75 tons per MWh sold rather than 1 ton). The LSE's total cost is just the energy cost, $\$55 \cdot 1 = \$55/\text{yr}$, as it neither buys allowances nor receives allowance auction revenues in this system.
- Source-Based System I has a still higher power price, $p = \$100/\text{MWh}$ (also the price under the basic load-based system in Section 2). This is because the price of power reflects the full opportunity cost of allowances, and is not distorted by an allowance allocation that gives free allowances in proportion to energy sales. Profits are still zero, even though the plants' fuel cost is less than p ; this is because producers now have to buy all their allowances. Although the LSE pays $\$100 \cdot 1 = \$100/\text{yr}$ for energy, it receives the proceeds of the allowance auction, which equal $\$60/\text{ton} \cdot 0.75 \text{ tons/yr} = \$45/\text{yr}$. As a result, the net cost to load is, like all the above systems, \$55/yr.

In summary, under these simple assumptions, the CO₂RC system has the same consumer costs and generator profits as source-based systems. The most relevant of these assumptions include no market power, perfectly inelastic demand,⁹ and an emissions trading system that involves all generators. The price of power is the same under the CO₂RC system and a source-based system in which generators receive $T y_i$ free allowances, where T is the “dirty” or other high benchmark emissions rate, and LSEs are required to buy back and retire allowances so that total emissions meets the target. But the CO₂RC system is administratively more complex while lacking any obvious advantages compared to simpler source-based systems that do not require consumers to buy allowances (Systems I and III).

⁹ In general, for any of these proposals, an analysis of the case of elastic demand would require that additional assumptions be made about how side payments from consumers to producers (e.g., to buy back excess allowances in the CO₂RC case) or to consumers from producers (e.g., revenues from allowance auctions in the source-based case) are translated into consumer rates. Development of models based on such assumptions, and the analysis of their implications for the level and timing of consumer demand and system costs, would be of interest in future research, but are out of the scope of this paper. The fact that consumer costs under all systems are the same under inelastic demand (given allowance auctions in source-based systems) suggests that it may be possible to define retail rate structures for all of the proposals that would yield the same retail prices for consumers and thus the same quantities demanded. Indeed, this is the conclusion of Chen et al. (2008a)'s comparison of source-based and the pure load-based proposal under elastic demand. On the other hand, if proceeds from allowance auctions were refunded to consumers via adjustments in, say, income taxes, then source-based systems could have higher electricity prices than the other systems, with consequent implications for power consumption and allocative efficiency.

8. Conclusion

If it is decided that regulation of the GHG emissions of the California power sector should proceed immediately under AB 32 and the Western Climate Initiative, we recommend that a first-seller system based on source-based trading be implemented, rather than a load-based system. We conclude that a load-based system, rather than lowering energy costs to Californian consumers relative to a source-based system, would likely result in higher costs. As our analyses have shown, at best, the load-based system is no less expensive to consumers than the source-based approach, if both result in efficient dispatch and if emission allowance rents (in the form of proceeds from emissions allowance auctions) are allocated to LSEs. Contrary to previous assertions, the economic rents that clean power plants earn because electricity prices rise remain in the hands of those producers under load-based trading, just like source-based systems. However, the basic load-based approach poses significant risk to dispatch efficiency by discouraging cleaner sources from submitting bids to the California ISO's day-ahead and real-time markets, thereby decreasing the flexibility and competitiveness of those markets. In contrast, a source-based system utilizes those markets to help achieve the GHG policy objectives more effectively and efficiently.

The speculative benefits of a load-based system, in terms of possibly greater incentives for energy efficiency programs, cannot be justified in light of the additional administrative complexity and cost of such a system, the threat that it would pose to the competitiveness and efficiency of the electricity spot markets, and the additional difficulties that would arise when transition to a federal cap-and-trade system would occur. Indeed, we show that a basic load-based program would not provide greater incentives for efficiency programs, because the total avoided cost of power (as used in benefit-cost tests for energy efficiency) is the same for the load- and source-based system.

These conclusions are also applicable to personal carbon allowance systems. With cost-minimizing consumers and profit-maximizing producers, our models imply that such systems are likely to be economically equivalent to a carbon tax or source-based trading. However, an argument in favor of PCAs is that when consumers consume more than the cost-minimizing amount of energy due to ignorance or other reasons (i.e., X-inefficiency), PCAs would raise the saliency of energy expenditures and thus encourage conservation. However, the huge administrative costs associated with PCAs (House of Commons, 2008) could only be justified if they motivate consumers to undertake large amounts of carbon reductions whose cost is below the market price of allowances, but would otherwise not be undertaken even with the economic incentive of price rises due to source-based allowances. The equity advantages of PCAs can also be attained by source-based systems by adjusting the tax system to return the proceeds of allowance auctions to consumers.

The GEAC and CO₂RC systems have been proposed as modified load-based approaches that have the advantage of allowing energy spot markets to operate as presently. Those proposals do this by unbundling emissions and energy at the

source, and requiring load-serving entities to buy both separately. However, we have demonstrated that under some simple assumptions, they can both be viewed as source-based trading systems with some unusual (and undesirable) features and additional administrative costs. In the case where the “default” emissions rate in GEAC is higher than the target emissions rate for LSEs and price elasticity is zero, GEAC is equivalent to a source-based system where not only are emissions allowances granted freely to producers, but also consumers pay a per MWh tax to subsidize energy production. Additional transaction costs are incurred because consumers must track and purchase a differentiated commodity, GEACs. Meanwhile, CO₂RC essentially distributes an excess number of allowances freely to generators in proportion to their sales, and then requires LSEs to buy back some of those allowances. Both systems are no cheaper to consumers than source-based trading with allowance auction proceeds returned to consumers. Further, the involvement of LSEs in the CO₂RC and GEAC systems introduces administrative complexities not present in most source-based cap-and-trade programs.

Thus, we believe that the California Public Utilities Commission has correctly chosen to recommend a first-seller approach to regulate power sector GHG emissions, combining a source-based approach for in-state resources and emissions accounting for imports in order to limit emissions leakage (CPUC, 2008). This proposal is compatible with federal proposals and, if expanded to the entire west, will result in an emissions trading system that is as or more efficient than load-based alternatives.

Acknowledgements

Support was provided by the California Independent System Operator, NSF Grant ECE-0621920, and the UK Engineering and Physical Sciences Research Council and EPRG industrial partners via the Supergen Flexnet Consortium, Grant EP/E04011X/1. We thank H. van der Weijde and two reviewers for their suggestions. All views expressed are our responsibility.

References

- Bluemel, E.B., 2009. Regional Regulatory Initiatives Addressing GHG Leakage in the USA, Ch. 9. In Faure, M., and Peeters, M. (Eds.), *Climate Change and European Emissions Trading: Lessons for Theory and Practice*, Edward Elgar Publishing.
- Burtraw, D., 2008. Regulating CO₂ in electricity markets: Sources or consumers? *Climate Policy* 8(6) 588-606.
- Bushnell, J., 2008. The Implementation of California AB 32 and its Impact on Wholesale Electricity Markets, Center for the Study of Energy Markets. *Climate Policy*. 8, 277-292.
- Bushnell, J., Chen Y. 2009. Regulation, Allocation, and Leakage in Cap-and-Trade Markets for CO₂. Center for the Study of Energy Markets Working Paper CSEMWP-183, University of California, Berkeley.
- California Market Advisory Committee (CMAC), 2007. Recommendations for Designing a Greenhouse Gas Cap-and-Trade System for California: Recommendations of the Market Advisory Committee to the California Air

Resources Board, June 30.

California Public Utilities Commission (CPUC), 2001. California Standard Practice Manual: Economic Analysis of Demand-Side Programs and Projects, San Francisco, October.

California Public Utilities Commission (CPUC), 2008. Decision, Interim Opinion on Greenhouse Gas Regulatory Strategies, Rulemaking 06-04-009, San Francisco, CA, March 13.

Chen Y., Liu, A., Hobbs, B.F., 2008a. Economic and Emissions Implications of Load-based, Source-based and First-seller Emissions Trading Programs under California AB 32. UCEI Power Meeting, March.

Chen, Y., Sijm, J., Hobbs, B.F., Lise, W., 2008b. Implications of CO₂ Emissions Trading for Short-run Electricity Market Outcomes in Northwest Europe. *Journal of Regulatory Economics* 34(3), 251-281.

Fischer, C., 2003. Combining rate-based and cap-and-trade emissions policies. *Climate Policy* 3(S2), S89-S109.

Fleming, D., 1997. Tradable Quotas: Using Information Technology to Cap National Carbon Emissions. *European Environment* 7, 139-148.

Gabriel, S.A., Smeers, Y. 2006. Complementarity Problems in Restructured Natural Gas Markets. In Seeger, A., *Recent Advances in Optimization. Lecture Notes in Economics and Mathematical Systems*, Vol. 563, Springer-Verlag, Berlin, 343-373.

Gillenwater, M., Breidenich, C., 2009. Internalising carbon costs in electricity markets: Using certificates in a load-based emissions trading scheme. *Energy Policy* 37(1), 290-299.

Harwatt, H., 2008. Reducing carbon Emissions from Personal Road Transport Through the Application of a Tradable Carbon Permit Scheme: Empirical Findings and Policy Implications from the UK. Institute for Transport Studies, University of Leeds, 2008.

Hobbs, B.F., Helman, U., 2004. Complementarity-Based Equilibrium Modeling for Electric Power Markets, Ch. 5. In Bunn, D.W. (ed.), *Modeling Prices in Competitive Electricity Markets*, J. Wiley Series in Financial Economics, London, 2004.

House of Commons, 2008. Personal Carbon Trading, HC 565. Environmental Audit Committee. Fifth Report of Session 2007-08, London.

Hyams, K., 2009. A Just Response to Climate Change: Personal Carbon Allowances and the Normal-Functioning Approach. *The Journal of Social Philosophy* 40(2), 237-256.

Lane, C., Harris, B., Roberts, S. 2008. An Analysis of the Technical Feasibility and Potential Cost of a Personal Carbon Trading Scheme: A Report to the Department for Environment, Food and Rural Affairs. Accenture, with the Centre for Sustainable Energy (CSE). Defra, London.

Michel, S., Nielsen, J., 2008. Popping the CO₂RC: An Alternative Load-Based CO₂ Cap-and-trade Instrument for the Electricity Sector. *The Electricity Journal* 21(4), 31-42.

Niemeier D., Gould G., Karner A., Hixson M., Bachmann B., Okma C., Lang Z., Heres Del Valle D., 2008. Rethinking Downstream Regulation: California's Opportunity to Engage Households in Reducing Greenhouse Gases. *Energy Policy* 36(9), 3436-3447.

Palmer, K.L., Burtraw, D., Paul, A. 2009. Allowance Allocation in a CO₂

Emissions Cap-and-Trade Program for the Electricity Sector in California, RFF DP 09-41, Resources for the Future.

Synapse Energy, 2007. Exploration of Costs for Load Side and Supply Side Carbon Caps for California, Joint *En Banc* Hearing of PUC and CEC on Point of Regulation in the Electricity Sector (R.06-04-009), August 21.

Van Horn, A., Remedios, E., 2008. A Comparison of Three Cap-and-Trade Market Designs and Incentives for New Technologies to Reduce Greenhouse Gases. *The Electricity Journal* 21(2), 51-62.

Varnäs, A., Nykvist, B., 2009. Effects of Personal Carbon Trading. In A. Klein and V.W. Thresen (Eds.), *Making a Difference: Putting Consumer Citizenship into Action*, Proceedings of the Sixth International Conference of The Consumer Citizenship Network, Berlin, Germany 2009.

APPENDICES

A.1. Relationships of Load-Based System and Source-Based System I

First order conditions for inequality constrained optimization problems often involve conditions of the form $\{x \geq 0, f(\underline{X}) \geq 0, x \perp f(\underline{X}) = 0\}$, where x is a scalar variable and $f(\underline{X})$ is a function of a vector of variables \underline{X} . Here, we write such conditions in the equivalent, more compact form $\{0 \leq x \perp f(\underline{X}) \geq 0\}$, where “ \perp ” is the “perp” symbol.

The equilibrium problem for the load-based market in Section 2 is to find $\{x_{Li}, y_{Li}, p_{Li}, \alpha_L, \beta_L, \mu_{Li}\}$ that solve the following set of conditions:

$$0 \leq x_{Li} \perp p_{Li} + E_i \alpha_L - \beta_L \geq 0, \quad \forall i \quad (A1a)$$

$$0 \leq \alpha_L \perp -\sum_i E_i x_{Li} + K L \geq 0 \quad (A1b)$$

$$\sum_i x_{Li} = L \quad (\beta_L \text{ unrestricted}) \quad (A1c)$$

$$0 \leq y_{Li} \perp p_{Li} - C_i - \mu_{Li} \leq 0, \quad \forall i \quad (A1d)$$

$$0 \leq \mu_{Li} \perp y_{Li} - CAP_i \leq 0, \quad \forall i \quad (A1e)$$

$$x_{Li} = y_{Li} \quad (p_{Li} \text{ unrestricted}) \quad \forall i \quad (A1f)$$

(A1a-c) and (A1d-e) are the Kuhn-Tucker optimality conditions for optimization problems (1) and (2), respectively, and (A1f) is the market clearing condition (3). If there is a plant with zero emissions and strictly positive output ($x_{Li} = y_{Li} > 0$), then (A1a) implies that its energy price (p_{L0}) equals β_L . Further, (A1a) also implies that the price p_{Li} for any generator i with positive output must equal $p_{L0} - E_i \alpha_L$.

Meanwhile, the equilibrium problem for Source-Based System I (Section 3) consists of solving for $\{x_{Sli}, y_{Sli}, p_{Sli}, \alpha_{Sl}, \beta_{Sl}, \mu_{Sli}\}$ that satisfy the below equilibrium conditions.

$$0 \leq x_{Sli} \perp p_{Sli} - \beta_{Sl} \geq 0, \quad \forall i \quad (A2a)$$

$$\sum_i x_{Sli} = L \quad (\beta_{Sl} \text{ unrestricted}) \quad (\text{A2b})$$

$$0 \leq y_{Sli} \perp p_{Sli} - C_i - \alpha_{Sl} E_i - \mu_{Sli} \leq 0, \quad \forall i \quad (\text{A2c})$$

$$0 \leq \mu_{Sli} \perp y_{Sli} - CAP_i \leq 0, \quad \forall i \quad (\text{A2d})$$

$$x_{Sli} = y_{Sli} \quad (p_{Sli} \text{ unrestricted}), \quad \forall i \quad (\text{A2e})$$

$$0 \leq \alpha_{Sl} \perp -\sum_i E_i x_{Sli} + K L \geq 0 \quad (\text{A2f})$$

(A2a-b) and (A2c-d) are the LSE and producer first-order conditions, respectively, and (A2e-f) are the market clearing conditions. By (A2a) and (A2e), all power plants whose sales y_{Sli} are strictly positive have the same price ($p_{Sli} = \beta_{Sl}$ for all $y_{Sli} > 0$).

To establish the equivalence of the equilibria defined by (A1a)-(A1f) and (A2a)-(A2f), as asserted in Section 4, it is sufficient to note that a solution to one set of conditions also satisfies the other set, and vice versa. In particular, if $\{x_{Sli}, y_{Sli}, p_{Sli} - E_i \alpha_{Sl}, \alpha_{Sl}, \beta_{Sl}, \mu_{Sli}\}$ is substituted for $\{x_{Li}, y_{Li}, p_{Li}, \alpha_L, \beta_L, \mu_{Li}\}$ in the load-based conditions (A1a)-(A1f), then the source-based equilibrium conditions (A2a)-(A2f) result. Going the other way, substituting $\{x_{Li}, y_{Li}, p_{Li}, \alpha_L, \beta_L, \mu_{Li}\}$ for $\{x_{Sli}, y_{Sli}, p_{Sli} - E_i \alpha_{Sl}, \alpha_{Sl}, \beta_{Sl}, \mu_{Sli}\}$ in the source-based conditions (A2a)-(A2f) yields the load-based equilibrium conditions (A1a)-(A1f). Thus, an equilibrium for one market is an equilibrium for the other if we note that the load-based energy price p_{Li} is equivalent to the source-based price adjusted downwards by the cost of associated emissions allowances $p_{Sli} - E_i \alpha_{Sl}$. Further, the avoided cost of energy for LSEs in the load-based market (the shadow price of the load constraint β_L) is also an equilibrium avoided cost for the source-based market (β_{Sl}), as claimed in Section 5.

That the producer profits and consumer costs are the same in the load- and source-based systems of Sections 2 and 3, respectively, can be established by substituting $p_{Sli} - E_i \alpha_{Sl}$ and y_{Sli} for their equivalents p_{Li} and y_{Li} , respectively, in the load-based profit expression (2a):

$$Profit_{Li} = (p_{Li} - C_i)y_{Li} = (p_{Sli} - \alpha_{Sl}E_i - C_i)y_{Sli} \quad (\text{A3})$$

which equals $Profit_{Sli}$ (3a). Similarly, substituting $p_{Sli} - E_i \alpha_{Sl}$ and x_{Sli} in place of p_{Li} and x_{Li} , respectively, in the load-based LSE cost expression (1a) yields:

$$\sum_i p_{Li} x_{Li} = \sum_i (p_{Sli} - \alpha_{Sl}E_i)x_{Sli} \quad (\text{A4})$$

Rearranging, and assuming that (1b) holds as an equality $\sum_i E_i x_{Sli} = K L$ (otherwise, regulation would not lower GHG emissions):

$$\sum_i (p_{Sli} - \alpha_{Sl}E_i)x_{Sli} = \sum_i p_{Sli} x_{Sli} - \alpha_{Sl} \sum_i E_i x_{Sli} = \sum_i p_{Sli} x_{Sli} - \alpha_{Sl} K L \quad (\text{A5})$$

which is $Expenditures_{Sl}$ (4a).

A.2 Relationships of GEAC and Source-Based Systems

The equilibrium problem for the GEAC market in Section 6 is to find $\{x_{Gi}, u_{Gi}, y_{Gi}, v_{Gi}, p_{Gi}, \pi_{Gi}, \alpha_G, \beta_G, \gamma_G, \mu_{Gi}, \theta_{Gi}\}$ that solve the below market equilibrium conditions:

$$0 \leq x_{Gi} \perp p_{Gi} - \beta_G + \gamma_G \geq 0, \quad \forall i \quad (\text{A6a})$$

$$0 \leq u_{Gi} \perp \pi_{Gi} - \gamma_G - (T-E_i)\alpha_G \geq 0, \quad \forall i \quad (\text{A6b})$$

$$\sum_i x_{Gi} = L \quad (\beta_G \text{ unrestricted}) \quad (\text{A6c})$$

$$\sum_i u_{Gi} - \sum_i x_{Gi} = 0 \quad (\gamma_G \text{ unrestricted}) \quad (\text{A6d})$$

$$0 \leq \alpha_G \perp \sum_i (T-E_i)u_{Gi} - (T-K)L \geq 0 \quad (\text{A6e})$$

$$0 \leq y_{Gi} \perp p_{Gi} - C_i - \theta_{Gi} - \mu_{Gi} \leq 0, \quad \forall i \quad (\text{A6f})$$

$$0 \leq v_{Gi} \perp \pi_{Gi} + \theta_{Gi} \leq 0, \quad \forall i \quad (\text{A6g})$$

$$y_{Gi} - v_{Gi} = 0 \quad (\theta_{Gi} \text{ unrestricted}), \quad \forall i \quad (\text{A6h})$$

$$0 \leq \mu_{Gi} \perp y_{Gi} - CAP_i \leq 0, \quad \forall i \quad (\text{A6i})$$

$$x_{Gi} = y_{Gi} \quad (p_{Gi} \text{ unrestricted}), \quad \forall i \quad (\text{A6j})$$

$$u_{Gi} = v_{Gi} \quad (\pi_{Gi} \text{ unrestricted}), \quad \forall i \quad (\text{A6k})$$

(A6a-e) and (A6f-i) are the first-order conditions for problems (10) and (12), respectively, while (A6j-k) are the market clearing conditions (13) for energy and GEACs.

The set of conditions (A6) is linearly dependent, because (A6j-k) imply (A6d). This implies that there are multiple equilibria. In particular, it turns out that γ_G is arbitrary. As a result, although the sum of the energy and GEAC price for any generator $p_{Gi} + \pi_{Gi}$ is not arbitrary, the split between them is: given that a producer i 's output is positive, then by (A6a,b):

$$p_{Gi} = \beta_G - \gamma_G; \pi_{Gi} = \gamma_G + (T-E_i)\alpha_G; p_{Gi} + \pi_{Gi} = \beta_G + (T-E_i)\alpha_G, \quad \forall i \quad (\text{A7})$$

Any solution paying generators a total of $\beta_G + (T-E_i)\alpha_G$ for their output is an equilibrium, with the split between GEAC and energy revenues (determined by the arbitrary choice of γ_G) not mattering. If we set $\gamma_G = 0$, then by (A6b), the GEAC price $\pi_{Gi} = (T-E_i)\alpha_G$, a la Gillenwater and Breidenich (2009).

Now we show the equivalence of GEAC to a modified source-based system in which the original producer objective (2a) is altered so that each i receives K free

allowances for each MWh they sell and also a subsidy S \$/MWh from LSEs, as claimed in Section 6. (In this section, all variables and constants will have subscript S in this source-based system.) The new version of (2a) would then be:

$$\text{MAX}_{\{y_{Si}\}} \text{Profit} = (p_{Si} - C_i - \alpha_S E_i) y_{Si} + \alpha_S K y_{Si} + S y_{Si} \quad (\text{A8})$$

Meanwhile, the LSE objective (1a) is modified in parallel—they no longer receive the allowance auction revenues (as all KL allowances are now given away to producers) and furthermore they pay the producer subsidy for their entire load:

$$\text{MIN}_{\{x_{Si}\}} \text{Expenditures}_S = \sum_i p_{Si} x_{Si} + SL \quad (\text{A9})$$

The constraints are the same as in (1) and (2). The resulting equilibrium conditions for this modified source-based system are the same as (A2) with the exception of the allowance allocation and subsidy terms in (A2a) and (A2c):

$$0 \leq x_{Si} \perp p_{Si} - \beta_S \geq 0, \quad \forall i \quad (\text{A2a}')$$

$$0 \leq y_{Si} \perp p_{Si} - C_i + \alpha_S (K - E_i) + S - \mu_{Si} \leq 0, \quad \forall i \quad (\text{A2c}')$$

This source-based equilibrium can be shown to be an equilibrium for the GEAC system, as claimed, if the subsidy S is defined as $(T-K)\alpha_G$. The demonstration proceeds as follows. First we simplify the GEAC model by eliminating several variables. By (A6h), (A6j), and (A6k), we can eliminate u_{Gi} and v_{Gi} . Now (A6j) and (A6k) are redundant, so we can eliminate one of those two conditions. We can then add (A6a) and (A6b) together (since $0 \leq x \perp f(X) \geq 0$ and $0 \leq x \perp g(X) \geq 0$ implies $0 \leq x \perp f(X) + g(X) \geq 0$), yielding $0 \leq x_{Gi} \perp p_{Gi} + \pi_{Gi} - \beta_G - (T - E_i)\alpha_G \geq 0$. Similarly combining (A6f) and (A6g) yields $0 \leq y_{Gi} \perp p_{Gi} + \pi_{Gi} - C_i - \mu_{Gi} \leq 0$. In the process, we've eliminated dual variables γ_G and θ_{Gi} . Finally, we note that the T terms on the right side of (A6e) cancel (as in (11), above.) The result of the simplifications is that the GEAC equilibrium problem has been reduced to finding $\{x_{Gi}, y_{Gi}, p_{Gi} + \pi_{Gi}, \alpha_G, \beta_G, \mu_{Gi}\}$ such that:

$$0 \leq x_{Gi} \perp p_{Gi} + \pi_{Gi} - \beta_G - (T - E_i)\alpha_G \geq 0, \quad \forall i \quad (\text{A10a})$$

$$\sum_i x_{Gi} = L \quad (\beta_G \text{ unrestricted}) \quad (\text{A10b})$$

$$0 \leq \alpha_G \perp -\sum_i E_i y_{Gi} + K L \geq 0 \quad (\text{A10c})$$

$$0 \leq y_{Gi} \perp p_{Gi} + \pi_{Gi} - C_i - \mu_{Gi} \leq 0, \quad \forall i \quad (\text{A10d})$$

$$0 \leq \mu_{Gi} \perp y_{Gi} - CAP_i \leq 0, \quad \forall i \quad (\text{A10e})$$

$$x_{Gi} = y_{Gi} \quad (p_{Gi} + \pi_{Gi} \text{ unrestricted}), \quad \forall i \quad (\text{A10f})$$

Note that this system defines $p_{Gi} + \pi_{Gi}$ (the sum of the energy and GEAC price), and not p_{Gi} and π_{Gi} separately, consistent with the arbitrary nature of η , as explained above.

The reduced GEAC conditions (A10) are equivalent to the modified source-based conditions (A2a'), (A2c'), (A2b), (A2d-f) because (a) a solution to one also solves the other and (b) the two systems' profits and consumer costs are the same. In particular, assume a solution $\{x_{Gi}, y_{Gi}, p_{Gi} + \pi_{Gi}, \alpha_G, \beta_G, \mu_{Gi}\}$ has been found to the GEAC model. Now consider the modified source-based system assuming that the subsidy is set at $S = (T-K)\alpha_G$. If instead of $\{x_{Si}, y_{Si}, p_{Si}, \alpha_S, \beta_S, \mu_{Si}\}$ we substitute $\{x_{Gi}, y_{Gi}, p_{Gi} + \pi_{Gi} - (T-E_i)\alpha_G, \alpha_G, \beta_G, \mu_{Gi}\}$ in the modified source-based conditions, the GEAC equilibrium conditions (A10) result. Going the other way, assume that we have obtained a solution to the modified source-based model $\{x_{Si}, y_{Si}, p_{Si}, \alpha_S, \beta_S, \mu_{Si}\}$ based upon $S = (T-K)\alpha_G$. If we then substitute the resulting $\{x_{Si}, y_{Si}, p_{Si} + (T-E_i)\alpha_S, \alpha_S, \beta_S, \mu_{Si}\}$ for $\{x_{Gi}, y_{Gi}, p_{Gi} + \pi_{Gi}, \alpha_G, \beta_G, \mu_{Gi}\}$ in the GEAC model (A10), we then get back the modified source-based conditions with that assumed subsidy.

Finally, we need to show that profits and LSE expenditures are the same in the GEAC and modified source-based systems. The GEAC profits (12a) and LSE expenditures (10a) can be shown to be the same as the modified source-based profit (A8) and expenditures (A9) by (i) substituting $\{p_{Si} + (T-E_i)\alpha_S, S\}$ for their equivalents $\{p_{Gi} + \pi_{Gi}, (T-K)\alpha_G\}$ in (12a) and (10a), (ii) noting that $u_{Gi} = v_{Gi} = x_{Gi} = y_{Gi}$, (iii) assuming that the emissions market constraint (7b) is binding, and then (iv) rearranging. Thus, the GEAC market equilibrium is equivalent to a source-based model in which LSEs pay energy subsidy $(T-K)\alpha_G$ \$/MWh to producers and allowances are granted freely to producers at rate K tons/MWh.

Finally, we show that producer profits and consumer costs are independent of choice of default emissions rate T , as asserted in Section 6. Consider solution $\{x_{Gi}, y_{Gi}, p_{Gi} + \pi_{Gi}, \alpha_G, \beta_G, \mu_{Gi}\}$ for a given T . If we change T to T' , consider a candidate solution for T' , $\{x_{Gi}', y_{Gi}', p_{Gi}' + \pi_{Gi}', \beta_G', \alpha_G', \mu_{Gi}'\} \equiv \{x_{Gi}, y_{Gi}, p_{Gi} + \pi_{Gi}, \alpha_G, \beta_G - (T' - T)\alpha_G, \mu_{Gi}\}$. First, the primal variables $\{x_{Gi}, y_{Gi}\}$ still satisfy (A10) for the new T' , as those variables appear only in equalities (A10b,f), the left sides of (A10a,d) and the right sides of (A10c,e), and those conditions do not depend on T . Meanwhile, the price variables $\{p_{Gi} + \pi_{Gi}, \alpha_G, \beta_G - (T' - T)\alpha_G, \mu_{Gi}\}$ satisfy (A10b-f), since T does not appear in any of those conditions and there is no restriction on β_G' . Finally, the prices also satisfy (A10a), as there is no change in the value of its right side of (A10a): its value under T ($= p_{Gi} + \pi_{Gi} - \beta_G - (T-E_i)\alpha_G$) is the same as under T' ($= p_{Gi} + \pi_{Gi} - (\beta_G - (T' - T)\alpha_G) - (T' - E_i)\alpha_G$). Therefore, if $\{x_{Gi}, y_{Gi}, p_{Gi} + \pi_{Gi}, \alpha_G, \mu_{Gi}\}$ is an equilibrium under one value of T , it is an equilibrium under any value. This implies that profits and expenditures are unaffected by T since they depend only on $\{x_{Gi}, y_{Gi}, p_{Gi} + \pi_{Gi}, \alpha_G\}$.

A.3 Relationships of CO₂RC and Source-Based Systems

We start with Source-Based System II's equilibrium conditions. As mentioned in Section 7, these are the same as the equilibrium conditions for CO₂RC. They are developed from the producer and LSE models in the same way that (A1a)-(A1f) were derived in Appendix A.1 from the Source-Based System I models in Section

2. Indeed, the equilibrium conditions are the same as for Source-Based System I with two exceptions: subscript SII replaces SI in all variables, and (A2c') replaces (A2c):

$$0 \leq y_{SIIi} \perp p_{SIIi} - C_i + \alpha_{SII} (T - E_i) - \mu_{SIIi} \leq 0, \quad \forall i \quad (\text{A2c}')$$

Further, the equilibrium conditions for Source-Based System III are the same as for System II, except that all variables have subscripts SIII and condition (A2c') is replaced by:

$$0 \leq y_{SIIIi} \perp p_{SIIIi} - C_i + \alpha_{SIII} (K - E_i) - \mu_{SIIIi} \leq 0, \quad \forall i \quad (\text{A2c}'')$$

The claim in Section 7 is that the equilibria for the three source-based systems are related as follows:

$$\{x_{SIi}, y_{SIi}, \alpha_{SI}, \beta_{SI}, \mu_{SIi}\} = \{x_{SIIi}, y_{SIIi}, \alpha_{SII}, \beta_{SII}, \mu_{SIIi}\} = \{x_{SIIIi}, y_{SIIIi}, \alpha_{SIII}, \beta_{SIII}, \mu_{SIIIi}\} \quad (\text{A11a})$$

$$p_{SII} = p_{SIIi} + \alpha_{SII} T = p_{SIIIi} + \alpha_{SIII} K \quad (\text{A11b})$$

$$\text{Profit}_{SI} = \text{Profit}_{SII} = \text{Profit}_{SIII} \quad (\text{A11c})$$

$$\text{Expenditures}_{SI} = \text{Expenditures}_{SII} = \text{Expenditures}_{SIII} \quad (\text{A11d})$$

(A11a) and (A11b) are established as follows. By substituting the SII terms from (A11a) and (A11b) into the Source-Based System I equilibrium conditions (A2a)-(A2f), the result is the Source-Based System II equilibrium conditions. The reverse can also be shown by substituting the SI terms into the Source-Based System II equilibrium conditions. Likewise, this can be done with Systems I and III as well as II and III. This establishes that the solution for one system is also an equilibrium for the others, if the energy price adjustment (A11b) is made. Since by assumption $T > K > 0$, (A8b) then implies that System I (producers pay for all allowances) has higher energy prices than System III (producers receive free allowances at rate K per MWh of production), whose energy prices in turn exceed those of System II/CO₂RC (equivalent to producers getting T free allowances per MWh output).

Finally (A11c) and (A11d) are demonstrated by inserting one source-based system's energy and allowance prices in another system's profit and expenditure functions, and then noting (for expenditures) that $\sum_i x_i = L$ (as at the end of Appendix A.1). As a result, the second system's functions reduce to those of the first system. This can be done for any pair of the systems (I, II, or III). Thus, the profits from the three source-based systems and CO₂RC are equal, and so are LSE expenditures.