The Economics of Renewable Resource Credits[1]

Christiaan Hogendorn and Paul Kleindorfer[2]

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1. Introduction

Liberalization of electricity markets has provided consumers with a choice of power suppliers. In turn, this means that power suppliers can differentiate their products to appeal to consumer tastes. While electricity is in some ways a commodity product, one major source of potential differentiation is the method of generating the power. "Green" or renewable sources of power, e.g. wind, solar, biomass, and hydro, cause less pollution and produce less toxic waste than non-green alternatives. Some renewables also clearly generate less carbon dioxide emissions per kWh of energy delivered, and they have the potential therefore to assist in meeting national or regional targets to reduce CO_2 emissions. As analyzed in the pioneering work of Awerbuch and Berger (2002), renewables also contribute to the diversity and local sourcing of energy and therefore improve the security of domestic and regional energy supply. Renewable energy sources have been given great impetus by Renewable Portfolio Standards in many US states and in regional agreements such as the EU Directive (2001/77/EC), which set a renewable energy target to increase the portion of electricity generated from renewable sources in the EU to 22 percent by 2010.

As a result of both consumer preferences and national targets for renewable energy production, there has been a growth of interest in renewable energy credits or "tradable green certificates" (TGCs) and other approaches to promote the development and deployment of renewable generation technologies. These have taken several forms, including the nature of the technologies covered by these credits (e.g., specifically for biofuels, solar or wind or covering a broader class of renewable energy sources) and in

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[2] Respectively, Assistant Professor of Economics, Wesleyan University, Middletown, CT 06459, chogendorn@wesleyan.edu and Anheuser-Busch Professor of Management Science (Emeritus), The Wharton School, University of Pennsylvania, Philadelphia, PA 19104.

terms of the reporting or payment obligations attached to these credits.[3] There are many differences in national programs to promote renewable energy, either by discouraging non-renewables or encouraging renewables. However, specific programs can take many forms, including the following:

The generic Renewable Portfolio Standard (RPS) approach applied to generators: Constraints are imposed on generators to include in their generation mix a certain percentage of specific types of renewables (measured in terms of total MWh sold into the grid), where satisfying this constraint can be accomplished by either owning/leasing the generation source, by contracting for it through bilateral or tolling contracts, or by TGCs.

The generic RPS approach applied to suppliers/distributors: Constraints are imposed on suppliers/distributors to include in their supply portfolios a certain percentage of specific types of renewables (measured in terms of total MWh sold to consumers in their territory), where satisfying this constraint can be accomplished by bilateral agreements with generators (who are then required to provide proof of the particular RPS characteristics they advertise), or by TGCs.

The generic RPS approach applied to consumers: Constraints are imposed on customers to include in their consumptions portfolios a certain percentage of specific types of renewables (measured in terms of total MWh bought by these consumers), where satisfying this constraint can be accomplished by showing that they have purchased energy from suppliers who satisfy the appropriate RPS characteristic (who are then required to provide proof of the particular RPS characteristics they advertise), or by TGCs.

The generic carbon tax approach: For each ton of CO_2 emitted, a payment is made to a carbon fund or a carbon emissions permit is obtained from a tradable emissions permit market, where such markets may be subject to banking, grandfathering and airshed totals, as well as other administrative rules. The logic here derives from the SO_2 and NOx markets, used to control acid rain and precursors of atmospheric ozone.

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[3] See Lauber, 2004; Holt and Bird, 2005; Ford et al., 2007 for details on some of the different approaches to Renewable Energy Credits implemented in the US and Europe.

The generic REFIT approach: Payments are made to renewable generators according to a certain agreed schedule, set in advance in consultation with stakeholders and enforced by regulation (with audits and sanctions). This schedule can either be a single payment per MWh actually delivered to the grid, or it could be a multi-part payment consisting of a fixed payment per MW/year as well as a payment per MWh delivered to the grid.[4] Both the capacity charge (if any) and the energy charge for REFIT programs are often implemented administratively (i.e., by setting a fixed subsidy per MW or MWh for a specific period of time). The guaranteed charges can be paid for either through government subsidies or they can be mandated by regulatory fiat or statute, and paid ultimately by consumers.[5]

Mixed or hybrid approaches: The above approaches can be combined in various ways. For example, taxes on fossil fuel plants can be used to provide funds for REFIT programs. RPS-type programs can also be coupled with carbon taxes or with REFIT programs. Programs can also be mandatory (regulatory fiat) or voluntary (consumer driven). The RPS/TGC approach was a voluntary scheme in its original incarnation in California, but 18 states in the US and some EU countries have imposed mandatory targets and associated TGC arrangements, notably Belgium, Italy, Sweden and the United Kingdom.

The point that we develop in this paper is that implementing any of these programs that involves either assuring RPS standards or providing subsidies to renewable energy sources per MWh produced can be accomplished efficiently by TGCs. We also argue that if the government wishes to provide subsidies (as opposed to mandating renewables use through one of the RPS approaches), it can do so through participation in the TGC market. The use of TGCs to implement payments per MWh of energy generated by renewables does not preclude the government providing additional per MW-Year subsidies to encourage entry of specific types of renewables (where the MW subsidy could itself be set by a separate market-based mechanism such as auctions per Lesser and Su (2007)).

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[4] On the functioning of two-part tariffs for TGC markets, see Lesser and Su (2007).

[5] A well-known example of the regulatory fiat approach has been the German law, which sets floors for wholesale renewable energy prices as a percentage of the final retail tariff.

A further approach, which continues in use in several jurisdictions, is the use of direct subsidies for renewables implemented through grants or projects. While this might have been a reasonable approach in the very early days of renewable generation, it is out of step with current maturing markets for renewable generation and supporting equipment. The use of grants and projects to implement renewable subsidies encourages rent-seeking and bureaucratic intervention rather than integration of renewables within the overall energy market. TGCs and most REFIT programs, on the other hand, allow the government to provide subsidies to renewable energy sources in a manner that can be integrated with normal market operations. Under TGCs, for example, the government can purchase a quantity of TGCs on the open market, perhaps guaranteeing a minimum price for these for a particular period of time to provide needed price stability for potential investors (Agnolucci, 2007).

The idea of TGCs was apparently first proposed by the Enron Corporation, under the title of "green tags" (Enron, 1997; Holt and Bird, 2005). Green certificate programs (i.e. TGCs) simply separate the market for the environmental characteristics of electricity from the electricity itself and allow trading in both the environmental good and the electricity good. It is based on the idea that the consumer's desire can be separated into two components: a desire for general-purpose electricity and a desire that more electricity be generated from green sources. Since an electron generated by a green generator is identical to an electron from any other type of generator, the consumer presumably does not care who actually receives the green electron. They do care, however, that the green electron was generated and displaced a non-green electron.

Each megawatt hour (MWh) of energy generated by a green generator earns one TGC. The tag is not attached to the electricity in any way; it simply guarantees that one MWh of green electricity was generated and injected into the transmission grid (and hence used by someone whose identity may be unknown). The TGC can then be sold by the green generator to a power marketing company. The power marketer, in turn, advertises (or verifies to its regulator) that its power is X% green, based on how many TGCs it has purchased. It may not be that the electrons its customers receive are actually from the generators that sold the tags, but those customers are assured that their electricity payments were used for the generation of green electricity.

The first TGC exchange that we were aware of was launched in the United States in the Automated Power Exchange (APX), one of California's competitive power exchanges. Buyers and sellers who use the APX market to trade generic electric power may also purchase "green tickets" that represent one MWh of green power. More recently, several other TGC marketers have entered in various U.S. states; the Department of Energy maintains a list of these marketers, with some 25 states now either allowing or mandating the use of TGCs for purposes of verifying compliance with portfolio standards or to advertise to customers the green content of power marketing offers.[6] The situation in the European Union was noted above, and remains an exemplary standard in the global arena for attempts to implement the Kyoto Protocol and beyond. The situation in Asia and Oceana has also developed quickly and market-based approaches to renewable energy supply, including TGCs, have been implemented in Australia, Japan and Korea, with other countries moving to join this trend.[7]

This paper examines the economics of the TGC market including the integration of TGC markets with the generic approaches described above to renewable resource credits. In particular, we analyze the use of the TGC mechanism to implement government subsidies for green power producers. Amundsen and Mortensen (2001) have modeled the Danish TGC scheme and show how the price of TGCs is affected by various parameters and by a simultaneous market for carbon dioxide emission permits (see also Morthorst (2003) for a similar market-level approach). Our basic model is similar to theirs at the aggregate market level. However, our approach does not begin at the market level, but rather is grounded in traditional demand theory and in the preferences of citizens/customers who will be affected in the long run by climate change and other impacts that provide the rationale for the shift to renewable energy in the first place.

The plan of the paper is as follows. We analyze an ideal scheme in which there are only two types of generation, renewable (or "green") and non-renewable (or "non-green"), and in which each kWh of green power generated at a particular plant is verifiable without error. In the next Section, we present a simple model of TGCs and

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[6] The list is available online at the DOE Green Power Network website, www.eren.doe.gov/greenpower/.

[7] See, e.g., http://www.ec-asean-greenippnetwork.net/dsp_page.cfm?view=page&select=231 for a survey of TGC implementation worldwide.

analyze the effects of TGCs at the market equilibrium when the government plays no role other than authenticating green power production. In Section 3, we analyze and compare the impacts of various government policies to promote renewable energy, including Pigouvian taxes on non-green power, subsidies of green power, and government purchase of TGCs. In Section 4, we discuss some of the details of practical policies for implementing TGCs and some open research questions.

2. TGCs in the Electricity Market

This section examines the effects of a stylized TGC system in a simple market setting. Those consumers who value green power sufficiently choose to purchase TGCs, and their revealed preference for TGCs is conveyed through these purchases. The TGC market is assumed to operate separately from the power market. Green generators receive the market-clearing price of a TGC for every kWh of energy they produce. The interaction of the two markets is described in detail below.

The Consumer's Problem

Consumers may purchase one of two goods, non-green power and green power, where non-green power consumption is denoted by x and green power consumption by y. Non-green power produces pollution — if the total amount of non-green power produced is X, then the amount of pollution is $G(X)$. Green power is assumed not to produce pollution.

A typical consumer's utility function is developed according to two principles:

1. Energy produced from green sources is identical to that produced from non-green sources. Thus, x and y are perfect substitutes in terms of their ability to provide energy to perform household and industrial tasks.
2. Consumers fall into different types indexed by θ, where high-θ consumers are more concerned about the pollution caused by non-green power.

A rational consumer must value both types of electricity the same in terms of their ability to do work, and any value placed on green power must ultimately derive from

concerns about the pollution caused by non-green power. We represent consumer θ's utility function as[8]

$$U(x+y,\theta) + V(y,G(X),\theta) + M \tag{1}$$

The functions U and V represent willingness-to-pay for electricity consumption and for environmental attributes of electric power, respectively. The final term M is just the Hicksian aggregate utility for all other goods in the economy with M taken as the numeraire good. The first argument of U, $x+y$, is the total amount of energy consumed. As noted above, the two types of electricity are perfect substitutes, so they enter the utility function additively. The function V, reflecting the consumer's valuation of the environmental attributes of green power, depends on total green power consumed and on the total amount of pollution $G(X)$, where X is the aggregate non-green power consumed, and G is a non-negative and monotonically increasing function.[9]

Why does green power consumption, y, enter the utility function as a separate argument? One possibility is that the level of green power consumption is apparent to others, in which case *prestige benefits* might accrue to the buyer (Harbaugh, 1998). Alternatively, consumers may receive utility in the form of a *warm glow* for having done their part to help reduce $G(X)$.[10] Finally, it may be that some type of *social norm* develops to encourage purchases of green power (Kreps, 1997; Bernheim, 1994). It is possible, of course, that none of these "social" effects are present and that, because of free-rider problems, the only rationale for green energy purchase is government mandated purchases by consumers (as in Sweden, for example). Even in the absence of such social effects, it seems reasonable to assume that there are real perceived costs associated with increased use of non-renewable energy, providing the basic public choice rationale for the move to renewables. We consider the various possibilities below.

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[8] We assume separability here between the willingness to pay for electric power per se and for the environmental attributes of electric power. In particular, we use the same symbol y to represent both the consumption good "green energy" and the environmental attributes derived from y units of this good. We analyzed several other more general utility functions, including further interaction terms across electric and environmental attributes. Not much is gained, and considerable complexity is added, from this more general treatment. We therefore stick to the separable case (1) throughout.

[9] We return in Section 4 to the issue of the scope of damage of emissions. The easiest assumption is that the physical effects of pollution are the result of aggregate pollution, although consumers might be affected non-uniformly by aggregate pollution.

[10] Palfrey and Prisbrey (1997) give results suggesting warm glow is positive for most people.

We assume that $U(x+y,\theta)$ and $V(y,G(X),\theta)$ conform to the following conventional assumptions about willingness-to-pay:

$$U_1 > 0,\ U_{11} < 0,\ V_1 \geq 0,\ V_{11} \leq 0,\ V_2 > 0$$

The assumption that V_1 is non-negative implies that green power has a non-negative social effect over and above providing energy to do work. A consumer's type θ influences the strength of his or her preference for green power. The utility function (1) can be represented by many common functional forms. For example, the utility functions

$$U(x+y,\theta) = A(x+y)^{\alpha};\quad V(y,G(X),\theta) = B\theta((y-\tau)^{+})^{\beta}G(X)^{\gamma},\ y>0,\ V(0,\cdot,\cdot)=0 \tag{2}$$

where, for any real number z, $z^{+} = \max(z, 0)$, $0 < \alpha, \beta < 1$; $\gamma > 0$; and $A > 0$, $B > 0$ would satisfy the assumed properties for U and V. (This example also includes a threshold level of consumption of green power τ. The absence or presence of a threshold level does not affect any of the theoretical results presented.)

Now let the price of x be p, and let the price of y be $p+g$ where g is the price of the TGC associated with each unit of y. Given the assumed utility function (1), the consumer's problem is

$$\text{Max } U(x+y,\theta) + V(y,G(X),\theta) - px - (p+g)y \tag{3}$$

In the electricity market, total non-green energy X is large relative to each consumer's consumption x, and the pollution level $G(X)$ is therefore relatively insensitive to changes in x brought about by price changes. We therefore assume that consumers do not take account of the effect of x on G in their consumption decisions, and we assume that a change in total pollution G brought about by changes in x does not significantly change the marginal utility of consuming green power (i.e. we assume that $V_{12} \approx 0$). Taking first-order conditions, we see that:

$$\partial U/\partial x = U_1 \leq p, \text{ with equality if } x > 0 \tag{4}$$

$$\partial U/\partial y + \partial V/\partial y = U_1+V_1 \leq p+g, \text{ with equality if } y > 0 \tag{5}$$

Taking p and g as given, as well as $G(X)$, it is straightforward to solve the conditions above. The solution is obtained by first solving (5) for y and then using this in (4), assumed to hold as an equality, for x. We obtain

$$y(g,G(X),\theta) = [V_1^{-1}(g,G(X),\theta)]^{+} \tag{6}$$

$$x(p,g,G(X),\theta) = [U_1^{-1}(p,\theta) - y(g,G(X),\theta)]^{+} \tag{7}$$

where $z^+ = \text{Max}[z,0]$ and where the inverse functions in (6) and (7) are defined by the inequalities

$$U_1[U_1^{-1}(p,\theta),\theta] \leq p; \qquad V_1[V_1^{-1}(g,G(X),\theta),G(X),\theta] \leq g \tag{8}$$

In case some mandated percentage of renewables were required to be purchased by each consumer (as in the current case of Sweden), then a similar problem to (3) above would obtain, subject to the additional constraint that $\xi x \leq (1-\xi)y$, where ξ is the required lower bound on the fraction of renewable energy consumed. The key, as in any economic analysis of efficiency, is to trace the consequences of policies such as these mandated minimum proportional purchases back to the underlying preferences and choices of the affected economic agents. We will rely on the direct formulation (1)-(8) in what follows. However, more interventionist or "paternalistic" policies could be appropriate to guide consumer choice, if lack of information, myopia or other behavioral biases undermine efficient energy choice by consumers (see Kunreuther et al. (1998) and Thaler and Sunstein (2003)).

For some utility functions, $V_1(0,G(X),\theta) = \infty$ for every θ. In this case, some green power will be purchased by every consumer. In general, however, one would expect a possibly significant proportion of consumers to have $y(g,G(X),\theta) = 0$, especially if there were a non-zero connection charge or information cost to obtain green power. The reader can check directly from (6)-(7), and our assumptions about U and V, that the necessary and sufficient FOCs (5) hold. In particular, it follows from (7) and $U_1^{-1}(p,\theta) > 0$ that if $y(g,G(X),\theta) = 0$, then $x(p,g,G(X),\theta) > 0$, so that some power is consumed by every consumer. Also, the comparative statics yield the expected results[11] for x and y, viz.

i) Total power, $x(p,g,G(X),\theta) + y(g,G(X),\theta)$, is monotonic decreasing in p, and unaffected by g.

ii) Non-green power $x(p,g,G(X),\theta)$ is monotonic non-increasing (non-decreasing) in p (in g).

iii) Green power $y(g,G(X),\theta)$ is monotonic non-increasing in g, unaffected by p.

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[11] See the appendix for all proofs of propositions and some technical details, including those related to comparative statics.

The weak monotonicity results reflect the fact that some consumers may not purchase a particular form of power unless p or g is sufficiently low. Note that implementing TGCs effectively reduces g from positive infinity to some finite amount, so property (ii) indicates that a TGC system will increase the amount of green power consumed.

Market Demand

The market demand functions $X(p,g)$ and $Y(p,g)$ depend on the distribution of the consumer types, where we denote the number of consumers of type θ as $dF(\theta)$, so that:

$$X(p,g) = \int x(p,g,G(X(p,g)),\theta)dF(\theta) \tag{9}$$

$$Y(p,g) = \int y(g,G(X(p,g)),\theta)dF(\theta) \tag{10}$$

We now present a lemma that indicates that the market demand functions X and Y preserve the properties of the individual demand functions x and y. The proof of this lemma is simplified by our assumption that V_{12}=0. This assumption is more than we need to aggregate demand, but it allows a better comparison of government policies in Section 3.

Lemma 1: If V_{12}=0, all the comparative static properties of the individual demand functions x and y are preserved in the market demand functions X and Y. In particular, we can write $Y(g)$ instead of $Y(p, g)$.

Supply and Market Equilibrium

Generation of power takes place in a perfectly competitive market in which there are two types of firms (or equivalently two separable types of generation). Those that produce non-green power have aggregate cost function $C_N(Q)$ while those that produce green power have $C_G(Q)$. Let the industry-level marginal costs be denoted by $c_N(Q)$ and $c_G(Q)$. It is assumed that $c_N < c_G$ at the equilibrium quantity — if it were not, then no one would ever buy non-green power. Clearly, profit-maximizing firms will adjust output until marginal cost and price are equated, so that at the industry level (see also Amundsen and Mortensen (2001)):

$$c_N(Q_N) = p; \quad c_G(Q_G) = p + g \tag{9}$$

The market equilibrium quantities $X^* = X(p, g)$ and $Y^* = Y(g)$ are given by the simultaneous solution of the consumer and firm problems as:

$$c_N(X(p, g)) = p; \; c_G(Y(g)) = p + g \tag{10}$$

Assuming that marginal costs are increasing, in accord with merit-order dispatch, the usual comparative statics obtain. Market equilibrium quantities will increase as technological progress decreases cost or as exogenous conditions increase demand.

Effects of TGCs

The market equilibrium conditions make clear some important effects of implementing the TGC proposal. First, the price of a TGC is always the difference in cost between green and non-green power. This means the TGC market is efficient in the sense that consumers equate their social effects of buying green power with the extra cost of that power.

Second, if there are enough high-θ consumers, a large amount of green power could be produced. If there were any learning curve or scale effects in green power, this might decrease its cost. It is shown below in the discussion of producer subsidies (which operate the same as a cost decrease) that the price of TGCs would fall, which would encourage more consumption of green power. Since G enters as a pure externality in consumption, it would seem that there is a case to be made for government intervention, a topic to which we now turn.

3. Government Intervention in the Green Power Market

From a social point of view, the TGC market could increase welfare in two ways. First, it would allow people to achieve their social objectives of decreasing pollution by contributing to the production of green power. Second, and presumably more important, it could result in a substitution away from non-green power, thus reducing the pollution externality $G(X)$. The following sections consider interventions by a government agency whose primary goal is reducing the externality.

The Goal of Environmental Policy

The full social planner's problem takes account of the pollution externality and allocates green power in such a way as to maximize the "social effect" for each consumer. If the planner allocates $x(\theta)$ and $y(\theta)$ to consumers of type θ, then the welfare function is:

$$\begin{aligned} W &= \int \left[U\left(x(\theta)+y(\theta),\theta\right)+V\left(y(\theta),G(X),\theta\right)\right]dF(\theta)-C_N(X)-C_G(Y) \\ X &= \int x(\theta)dF(\theta) \qquad Y = \int y(\theta)dF(\theta) \end{aligned} \tag{11}$$

The conditions for social optimum are[12]

$$\begin{aligned} &\frac{\partial U}{\partial x}+\frac{\partial V}{\partial G}\frac{dG}{dX}=c_N \quad \forall\theta \\ &\frac{\partial U}{\partial y}+\frac{\partial V}{\partial y}=c_G \quad \forall\theta \end{aligned} \tag{12}$$

Since the market equilibrium sets $\partial U/\partial y + \partial V/\partial y = p+g = c_G$, the conditions for the social optimum (12) make it clear that the TGC market equilibrium given by (10) is efficient — the planner does not want to increase or decrease the amount of green power produced. The problem comes in the non-green market, where the free-market price p does not reflect the pollution externality $(\partial V/\partial G)(dG/dX) < 0$. An environmental policy-maker thus has an incentive to intervene in the market in such a way as to reduce the production and consumption of non-green power.

Clearly the first-best solution is a Pigouvian tax on non-green power equal to the amount of the pollution externality. Despite its seeming simplicity, such a scheme has several well recognized problems. First, the information requirements required to set the tax are enormous. Second, the externality is not really caused by non-green electricity alone, but actually by all sources of pollution (e.g., CO_2 by carbon-based fuels used in all sectors of the economy). Thus a comprehensive (e.g., carbon) tax would be required to achieve the true social optimum. Third, and most important, the scale of this intervention is enormous, causing major changes in the economy. Thus, unsurprisingly, we have only seen piecemeal sectoral approaches to global pollution regulations.

Government Intervention with a Fixed Budget

If Pigouvian taxation of non-green power is not an option, an alternative environmental policy might involve extra spending in the green power sector. The budget, B, available for such spending might come from general taxation, or it might come from a less-than-Pigouvian tax on the non-green power industry. If the budget comes from general government revenues, there would be some cost associated with the deadweight loss from taxation.

In the following sections, several policy options are considered for using the budget B to reduce the externality $G(X)$. The first options are the traditional tools of a producer or a consumer subsidy. These could be implemented through various types of REFIT programs. As argued in the introduction, we exclude from consideration here implementing such subsidies through grants or projects, as such an approach encourages rent-seeking and bureaucratic intervention rather than providing incentives, based on actual renewable energy produced. As we will see, REFIT policies implemented using TGCs allow a more efficient market-based approach for the government to provide subsidies to renewable energy sources in a manner which avoids these problems. Under a REFIT/TGC approach, the government can purchase TGCs on the open market. We describe and evaluate the efficiency of two different approaches, per-unit subsidy and direct-buy, to implementing the government purchases. Each of these policies could be financed from general revenues or from taxes on the non-green power sector.

It is important to note that in all of the following policy analysis, it is assumed that the consumers' utility functions are unchanged, i.e., given by (1). Crucially, the "social effect" of buying green power persists even as the government makes interventions in the market. We note that this ignores the possibility of "crowding out" of individual altruism by government subsidy (see Frey and Oberholzer-Gee (1997)). Analysis of this and other behavioral "anomalies" would be interesting avenues for research, but we ignore these here.

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[12] We are considering here only the case in which every consumer has both $x(\theta)$, $y(\theta) > 0$. An appropriate inequality system would obtain if for some consumers $x(\theta) = 0$ or $y(\theta) = 0$ were optimal.

Traditional Producer and Consumer Subsidies Financed from General Revenue

Suppose the government offers a per-unit subsidy of h to the producers of green power. The new green power supply function becomes $c_G(Q_G) - h$. Accordingly, the market equilibrium conditions become

$$c_N(X(p, g)) = p; \quad c_G(Y(g)) - h = p + g \tag{13}$$

Since the government cannot spend more than its renewable energy budget B (and it is assumed that the budget is small enough that it does spend all of it), then there is an additional condition that

$$B = hY(g) \tag{14}$$

Proposition 1: An increase in the subsidy h increases equilibrium Y, decreases equilibrium X, and decreases both p and g in equilibrium.

The effects of a per-unit consumer subsidy for any green power purchased would be similar. A per-unit consumer subsidy would shift the demand curves for X and Y from $X(p, g)$ to $X(p, g\text{-}k)$ and from $Y(g)$ to $Y(g\text{-}k)$. The resulting market equilibrium would be determined from (10) by

$$c_N(X(p, g–k)) = p; \qquad c_G(Y(g–k)) = p + g \tag{15}$$

The effect of "k" plays essentially the same role as the "$–h$" in (13), with the same effect on the output of green and non-green power. If the government has budget B available for this subsidy, then there is the additional constraint that

$$B=kY(g–k) \tag{16}$$

Proposition 2: An increase in the subsidy k increases equilibrium Y and decreases equilibrium X.

If the government always spends its entire budget B on subsidy, then define the equilibrium X and Y as a function of B as $X^S(B)$ and $Y^S(B)$. Then we have the following corollary:

Corollary 1: For either type of subsidy, an increase in the government budget B increases equilibrium Y and decreases equilibrium X.

Government Direct Purchase of TGCs, Financed from General Revenue

Having set up the TGC market, the government has an additional option for encouraging green power. It could simply enter the market and buy TGCs without actually consuming the associated electricity. (Additionally, one can imagine non-profit organizations buying TGCs in a similar manner, as the American Lung Association has done in the market for sulfur emissions rights.)

If the government purchases a TGC without consuming the associated electricity, then it is as if this residual electricity were "converted" from green to non-green, at least in the eyes of a consumer. The government's buying activity can be viewed as an increase in green power demand and a simultaneous increase in the supply of non-green power. However, this increased supply of non-green power does not, in actual fact, add to the external pollution effect $G(X)$. The formulation of this problem is that government chooses to buy some number of TGCs ψ. Consumers' value functions are then given by

$$U(x+y,\theta) + V(y, G(X-\psi),\theta) + M \tag{17}$$

where the term $G(X-\psi)$ makes it clear that the ψ units appear as non-green power to the consumer but do not actually cause any pollution externality.

The solution to the consumers' problems produces demand functions for non-green and green power as before, X and Y. However, the actual production of green power includes the units purchased by the government, i.e., green power generators produce $Y+\psi$ units. And since the government does not actually consume the ψ units of electricity, they get added to the supply of non-green power. Thus non-green generators need only produce $X-\psi$ units to satisfy demand.

The solution to the consumer's problem is the same as before. Market equilibrium is determined by the quantities $X(\psi)$ and $Y(\psi)$ that solve the equilibrium conditions

$$c_N(X(p, g) - \psi) = p \qquad c_G(Y(g) + \psi) = p + g \tag{18}$$

where ψ is the number of TGCs purchased by the government. In a budget constrained environment, the price of TGCs is $g(\psi)$, the solution to (18), so the number of TGCs ψ that would be purchased by the government with a total budget B would be determined by

$$B = g(\psi)\cdot\psi \tag{19}$$

Proposition 3: An increase in the government direct buy ψ decreases (crowds out) private consumption of green power Y but increases the total amount of green power produced, $Y+\psi$. An increase in ψ increases X, the apparent amount of non-green power sold, but actual production of non-green power, $X-\psi$, will fall.

Corollary 2: An increase in the government budget decreases (crowds out) private Y. This effect is less than one for one, so an increase in the government budget increases total green power $Y+\psi$.

Comparison of Policies

How do the subsidy and direct buy policy instruments compare with one another? Two issues are present. First is the effect of alternative policies in reducing $G(X)$, for a given budget (i.e., for a given B, which yields smaller non-green power, $X^S(B)$ or $X^D(B)$?). More generally, accounting for changes in demand for green power under the two regimes as well as for non-green power, which of the two regimes yields greater overall welfare (as measured by (6))?

It is not possible to say in general whether $X^S(B)$ is larger or smaller than $X^D(B)$. Nor is it possible to say anything in general about the comparative welfare effects at equilibrium of these two policies. The effectiveness of the policies depends on the elasticities of demand and supply, where the elasticity of demand, in turn, depends on the distribution of consumer types as well as the form of the utility function.

For the case where the supply curves are horizontal and consumer types are well-behaved, we can make the comparison more definitely.

Proposition 4: Suppose the c_N' and c_G' are constant. Let $\varepsilon_G = -\frac{\partial Y}{\partial g}\frac{g}{Y}$ be the elasticity of demand for green power with respect to the price of TGCs. Then a budget B spent on a direct buy of TGCs will result in more green power (and therefore less non-green power) than the same budget spent on a subsidy if and only if $\varepsilon_G < 1$.

This proposition suggests that direct government intervention in the TGC market and the supply side (as in the REFIT programs focused on suppliers) would be particularly

effective in regions where consumers are relatively unresponsive to price changes in making their green power decisions. One such market could be comprised of green-power buyers who are mostly committed environmentalists and therefore not much influenced by price considerations. However, a market might also have this feature if most people were not interested in TGCs (or perhaps were unaware of the impact of their energy purchases on G(X) and therefore generally unconcerned about green power). Thus, a TGC market could be an effective tool for government intervention even in markets where consumers do not participate extensively. Of course, determining the optimal "budget" and associated subsidies for the case of an uninformed public in whose name the government is to act remains a deep puzzle for public economics.[13]

4. Institutional Considerations and Discussion

There are a number of institutional considerations that will be important in the ultimate design of TGC markets. We discuss these below under several headings: alternative forms of the TGC market; engendering and maintaining public trust in the institution; and efficiency issues in the public-private partnership likely to emerge in regulating environmental aspects of electrical power.

Alternative Forms of the TGC Market

As noted in our introduction, a number of different forms of credit and constraints to promote renewables have emerged as policy instruments, including REFIT-type credits and RPS-type constraints. The basic issue we have addressed here is that any efficient approach to these credits or constraints will require authentication of the actual production and delivery of energy. We have argued that the TGC approach can accomplish this authentication and provide simultaneously the basic instrument for targeting per unit energy subsidies to renewable energy sources. The traditional approach is to determine the per unit subsidy for energy produced by administrative fiat, e.g. as a direct payment to the renewable generators per kWh produced or through some pricing formula relative to other energy sources (e.g., at level of 90% of final retail price as in the

[13] See Sen (1995) and Thaler and Sunstein (2003) for an introduction to this topic. In the context of renewable energy, see the discussion of this and related dynamic problems of supporting the right tempo

German case. Even if subsidies are determined in part by administrative or political policies, using TGCs would to implement credits would allow the price for renewables to be integrated with the overall power market. Issues such as transmission, location of facilities, reliability and timing of power injections would then all be dealt with, as they should be, through the normal rules of the market, not by administrative fiat.

A number of hybrid solutions, including many that follow the REFIT model, can be implemented through the TGC approach. The rationale for doing this is two-fold. First, and foremost, it is to enlist the discipline of the market in an-going fashion to provide proper motivation for investor choices of renewable technology. After all, these need to fit as part of an overall portfolio of generation technology choices, including for the foreseeable future a significant percentage of non-green power. Secondly, if renewables are to be valued as part of market-level portfolio management, as foreseen by Awerbuch and Berger (2002) and others in the electric power area (e.g., Kleindorfer and Li (2005)), then their price must be determined in a transparent manner and as free as possible from short-term political whims. Note that, per our discussion following equation (12), the green power market is economically efficient, and the market failure that we are trying to correct through TGCs comes from the externality in the non-green power market. Thus, any type of subsidy to green power is a second-best solution to the real problem. However, in the absence of a Pigouvian tax on non-green power, government intervention in the green power market can be a reasonable corrective for the externality associated with the pollution caused by non-green power. As this externality is not likely to disappear, non-green power will continue to have lower private costs than its full social costs, so a continuing intervention makes sense if the transactions costs of implementing such an intervention do not outweigh the benefits. If the intervention is implemented through a well-functioning TGC market, it should be relatively free of "grantsmanship" and other transactions costs as compared with other types of government policies.[14]

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for technological change in Newell et al. (2006).

[14] See also Finon and Perez (2007) for a detailed argument on this issue.

Maintaining Public Trust

Another issue that has been raised, and is critically important for environmental disclosure, is verifiability and understandability of the institutions designed to facilitate environmental disclosure. There remain significant concerns about public understanding and acceptance of the TGC mechanism, possibly rooted in a general mistrust of large energy firms in the wake of the Enron bankruptcy and the general disregard of former monopolistic firms of consumer rights. In our view, this matter needs to be taken seriously, but it only will be if there are proper means of authenticating energy actually produced by one or another renewable generation facility. TGCs, if properly monitored, can help to reinforce both the measurement of renewable energy produced, as well as who is consuming this energy. From the point of both economic and social accountability, TGCs can play an important and positive role.

Efficiency Issues

We have pointed on several occasions to the key efficiency aspect of TGCs, and that is its confluence with market discipline and conduct. It is also compatible with various regulatory interventions and tax/subsidy schemes, without the typical grantsmanship that underlies these approaches to date in a world of project-based subsidies and continues to be associated with any purely administrative approach to the problem of determining appropriate levels of renewable energy credits. As pointed out, a number of designs are feasible within the context of TGC itself, and we have not provided any ranking of these alternative designs. The primary reason is that it is not likely that there is a dominant design, but rather that the particular approach to the implementation of TGCs will depend on the relative importance of several factors that could affect the desirable structure of the TGC market. Some of the principle factors include deadweight losses, externalities and the perceived need to promote price stability for renewables as an infant industry.

Deadweight losses: Both the subsidy and the direct purchase schemes may be financed out of general tax revenue, with the generation of this tax revenue creating a deadweight loss $D(B)$, a function of the level of the subsidy budget for renewables. As this deadweight loss increases, these schemes become less attractive relative to the simultaneous tax on non-green power and subsidy to

green power. Furthermore, even among the schemes that depend on general tax revenue, which scheme is optimal will depend on the demand and cost parameters. As deadweight loss increases, it becomes more costly to implement a government intervention, and therefore picking the optimal intervention becomes even more crucial if specific welfare improvements are to be achieved.

Magnitude of the externality: The economic motivation for any of the government interventions discussed above is the reduction of the pollution externality $G(X)$. If the magnitude of this externality increases for given X, the optimal level of government intervention will clearly increase, i.e. for tax revenue-financed interventions, the optimal budget, B, will increase. We do not conjecture that the ranking of the different schemes is sensitive to the size of the externality, but the magnitude of the difference between the best and worst schemes could very well increase. In any case, the major implication of non-green power externalities and their correction through government intervention is that it will be critical to continue to assess the cost of these externalities and the willingness-to-pay at a societal level to control them. The TGC mechanism provides a transparent approach that reflects the total cost of government intervention in a manner that could facilitate the necessary political and public discussion to address this matter in an on-going, open manner.

Price Stabilization and Investment Recovery: A key issue raised by both renewable energy investors and certain environmental groups is the need for assurance for long-term capital recovery of investments in renewables. Indeed, as noted above, this is one of the primary reasons for the support of the renewable energy investors for REFIT-type programs. In the context of TGCs, the government could guarantee minimum or limit maximum prices for the TGCs, and do so over some extended period of time, to assure increased stability in the renewables sector and to encourage investment. However, the history of such interventions (e.g., minimum price controls in agriculture and price caps in electric power markets) is dotted with many examples of economic inefficiency, both in the short run and in terms of long-run technology choices (see e.g., Newell

et al., 2006). If subsidies are to be provided by the government for renewables, then using TGCs would at least assure a level playing field through the market (in terms of kWh of energy actually produced and used).

Infant industries: It is possible that some green power generation techniques, such as wave and tidal power, are in such early stages of the innovation process that they would not emerge from private entrepreneurship even in the presence of RPS and/or REFIT policies supported by TGCs. As such, they might qualify as "infant industries" needing additional government subsidies to be successful. The presence of the TGC market would still be a great benefit to avoiding "grantsmanship" in this context, however. Because a TGC market provides information on the currently prevailing cost differences between green and non-green power across a range of technologies, it provides a baseline competitive cost level for any new green power source. Arguments for additional subsidies could then be made, based exclusively on non-environmental infant industry arguments such as imperfections in capital markets, lack of coordination in complementary investments, or other positive externalities such as technology spillovers.

TGCs are, in the end, a direct result of the increasing interest by people everywhere in environmental disclosure. This has driven both energy consumers and environmentalists to be concerned with a credible measurement of the environmental attributes of the power supplied and consumed. What we have analyzed here are several approaches, under the general heading of Tradable Green Certificates, for achieving the requisite balance between the efficiency of market-based approaches and public trust, and their mutual compatibility with the usual instruments of tax/subsidy by the government in addressing externalities.

A number of issues remain open at this point. We have focused on market-based energy payments. One could also examine supplementary capacity payments for renewables, just as such capacity payments have been introduced for generation capacity in general. Hopefully, such capacity payments would themselves be market based, e.g.,

based on auctions of desired renewable capacity quotas as suggested by Lesser and Su (2007), rather than set administratively. In any case, there is a natural integration of TGC markets and market-based capacity payments, just as there is for normal power markets and capacity payments. A second issue is the treatment of peak-load effects. In principle, there is no problem making the TGC prices time-dependent or seasonal, and the normal clearing mechanism for power markets underlying the above analysis would apply straightaway. The integration of TGCs with long-term contracting, portfolio selection involving renewables and derivative instruments based on TGCs are interesting further topics to be explored. There is obviously much left to be said on this subject.

Appendix

Comparative Statics Results

The first order conditions for a consumer who buys positive quantities of both non-green and green power are

$$U_1(x+y,\theta) = p \qquad\qquad U_1(x+y,\theta) + V_1(y,G(X),\theta) = p + g \tag{A1}$$

Differentiating (A1) with respect to p (treating $G(X)$ as fixed) gives

$$U_{11}\left(\frac{\partial x}{\partial p}+\frac{\partial y}{\partial p}\right)=1 \qquad\qquad U_{11}\left(\frac{\partial x}{\partial p}+\frac{\partial y}{\partial p}\right)+V_{11}\frac{\partial y}{\partial p}=1 \tag{A2}$$

Solving both equations in (A2) simultaneously implies that

$$V_{11}\frac{\partial y}{\partial p}=0 \Rightarrow \frac{\partial y}{\partial p}=0 \tag{A3}$$

The left equation in (A2) combined with (A3) and the assumption that $U_{11}<0$ implies

$$\frac{\partial x}{\partial p}=\frac{1}{U_{11}}<0 \tag{A4}$$

Differentiating (A1) with respect to g gives

$$U_{11}\left(\frac{\partial x}{\partial g}+\frac{\partial y}{\partial g}\right)=0 \qquad\qquad U_{11}\left(\frac{\partial x}{\partial g}+\frac{\partial y}{\partial g}\right)+V_{11}\frac{\partial y}{\partial g}=1 \tag{A5}$$

Solving the two equations in (A4) simultaneously gives

$$\frac{\partial y}{\partial g}=\frac{1}{V_{11}}<0 \tag{A6}$$

Then (A6) and (A5) together imply that

$$\frac{\partial x}{\partial g}=-\frac{1}{V_{11}}>0 \tag{A7}$$

Note that (A6) and (A7) together mean that

$$\frac{\partial x}{\partial g}+\frac{\partial y}{\partial g}=0 \tag{A8}$$

Finally, if we solve (A1) simultaneously and differentiate with respect to G, the pollution level, we get

$$V_{11}\frac{\partial y}{\partial G}+V_{12}=0 \tag{A9}$$

Since we have assumed that V_{12} is close to zero, then y (and x) are approximately invariant with G.

Lemma 1: If V_{12}=0, all the comparative static properties of the individual demand functions x and y are preserved in the market demand functions X and Y.

Proof: Differentiating (9) with respect to p and recalling that x is assumed to change very little with G,

$$\frac{\partial X}{\partial p} = \int \left(\frac{\partial x}{\partial p} + \frac{\partial x}{\partial G} \frac{\partial G}{\partial X} \frac{\partial X}{\partial p} \right) dF(\theta) = \int \frac{\partial x}{\partial p} dF(\theta) \tag{A11}$$

Since $\partial x/\partial p \leq 0$, (A11) implies $\partial X/\partial p \leq 0$. By similar reasoning with respect to g,

$$\frac{\partial X}{\partial g} = \int \frac{\partial x}{\partial g} dF(\theta) \tag{A12}$$

The results for $Y(p,g)$ are analogous.

Proposition 1: An increase in the subsidy h increases equilibrium Y and decreases equilibrium X.

Proof: The derivatives of the equilibrium conditions in (13) with respect to h are

$$c'_N \left(\frac{\partial X}{\partial p} \frac{dp}{dh} + \frac{\partial X}{\partial g} \frac{dg}{dh} \right) = \frac{dp}{dh} \tag{A13}$$

$$c'_G \left(\frac{\partial Y}{\partial g} \frac{dg}{dh} \right) - 1 = \frac{dp}{dh} + \frac{dg}{dh} \tag{A14}$$

Solving (A13) for dg/dh gives

$$\frac{dg}{dh} = \frac{dp}{dh} A \tag{A15}$$

where

$$A = \left(1 - c'_N \frac{\partial X}{\partial p} \right) \left(c'_N \frac{\partial X}{\partial g} \right)^{-1} \tag{A16}$$

From the comparative statics, $\partial X/\partial p < 0$ and $\partial X/\partial g > 0$. The marginal cost function, c_N, is upward sloping, implying $c_N' > 0$.[15] Together these conditions imply $A>0$. Substituting (A15) into (A14) gives

$$\frac{dp}{dh} = -\left(1 + A - c'_G A \frac{\partial Y}{\partial g} \right)^{-1} \tag{A17}$$

[15] To simplify the proofs, we ignore the limiting case of constant marginal costs.

The right hand side of (A17) is negative because $\partial Y/\partial g < 0$. Combining this result with (A15) implies that

$$\frac{dg}{dh} < 0 \qquad\qquad \frac{dp}{dh} < 0 \tag{A18}$$

Returning to (A13) and simplifying,

$$c_N'\left(\frac{\partial X}{\partial p}\right) = \frac{dp}{dh} \tag{A19}$$

Since c_N' is positive, (A19) implies that $dX/dh < 0$. It remains to consider dY/dh. This is given by

$$\frac{dY}{dh} = \frac{\partial Y}{\partial g}\frac{dg}{dh} \tag{A20}$$

Both terms on the right hand side of (A20) are negative, so $dY/dh > 0$.■

Proposition 2: An increase in the subsidy k increases equilibrium Y and decreases equilibrium X.

Proof: The derivatives of (15) with respect to k are

$$c_N'\left(\frac{\partial X}{\partial p}\frac{dp}{dk} + \frac{\partial X}{\partial g}\left(\frac{dg}{dk} - 1\right)\right) = \frac{dp}{dk} \tag{A21}$$

$$c_G'\left(\frac{\partial Y}{\partial g}\left(\frac{dg}{dk} - 1\right)\right) = \frac{dp}{dk} + \frac{dg}{dk} \tag{A22}$$

Solving (A21) for dg/dk gives

$$\frac{dg}{dk} = A\frac{dp}{dk} + 1 \tag{A23}$$

where A is defined by (A16). Substituting (A23) into (A22) and rearranging gives

$$\frac{dp}{dk} = -\left(1 + A - c_G' A\frac{\partial Y}{\partial g}\right)^{-1} \tag{A24}$$

Since $\partial Y/\partial g < 0$, every term on the right hand side of (A24) is positive, hence the whole expression is negative: $dp/dk < 0$. Rewriting (A21) gives

$$c_N'\left(\frac{\partial X}{\partial k}\right) = \frac{dp}{dk} \tag{A25}$$

and since $dp/dk < 0$, it must be that $dX/dk < 0$. Substituting (A23) into dY/dk gives

$$\frac{dY}{dk} = \frac{\partial Y}{\partial g}\frac{dp}{dk}A \tag{A26}$$

which is positive: $dY/dk>0$. ■

Corollary: An increase in the government budget increases equilibrium Y and decreases equilibrium X.

Proof: Differentiate (13) with respect to B:

$$c'_G\left(\frac{dY}{dB}\right)-\frac{dh}{dB}=\left(\frac{dp}{dh}+\frac{dg}{dh}\right)\frac{dh}{dB}$$

In the case of a producer subsidy, differentiate (14) with respect to B:

$$\frac{dh}{dB}=\frac{1}{Y(p,g)+h\frac{\partial Y}{\partial g}\frac{dg}{dh}} \tag{A27}$$

All terms are positive by (A18), and an increase in h decreases X as shown in Proposition 1.

Substitute (A27) and simplify with (A15) and (A17):

$$\frac{dY}{dB}=\frac{A\frac{\partial Y}{\partial g}}{h\frac{\partial Y}{\partial g}A-Y\left(1+A-c'_G A\frac{\partial Y}{\partial g}\right)} \tag{A28}$$

All terms are negative, so dY/dB is positive. In the case of a consumer subsidy, the proof is very similar. ■

Proposition 3: An increase in the government direct buy ψ decreases (crowds out) private consumption of green power Y but increases the total amount of green power produced, $Y+\psi$. An increase in ψ increases X, the apparent amount of non-green power sold, but actual production of non-green power, $X-\psi$, will fall.

Proof: The derivatives of (18) with respect to ψ are:

$$c'_N\left(\frac{\partial X}{\partial p}\frac{dp}{d\psi}+\frac{\partial X}{\partial g}\frac{dg}{d\psi}-1\right)=\frac{dp}{d\psi} \tag{A29}$$

$$c'_G\left(\frac{\partial Y}{\partial g}\frac{dg}{d\psi}+1\right)=\frac{dp}{d\psi}+\frac{dg}{d\psi} \tag{A30}$$

This proof first shows that $dp/d\psi < 0$, and then that $dp/d\psi + dg/d\psi > 0$. These facts can then be used to derive all the stated results about $dX/d\psi$ and $dY/d\psi$.

Solving (A29) for $dg/d\psi$ gives

$$\frac{dg}{d\psi} = A\frac{dp}{d\psi} + \left(\frac{\partial X}{\partial g}\right)^{-1} \tag{A31}$$

where A is defined in (A16); it was shown following (A16) that $A>1$. Substitute (A31) into (A30), and use the comparative static result (A8):

$$\frac{dp}{d\psi} = \frac{-1}{\frac{\partial X}{\partial g}\left(1 + A - c'_G A\frac{\partial Y}{\partial g}\right)} \tag{A32}$$

All terms in the denominator are positive, so $dp/d\psi < 0$.

Next we turn to the sign of $dp/d\psi + dg/d\psi$. Using (A31) gives

$$\frac{dp}{d\psi} + \frac{dg}{d\psi} = (1 + A)\frac{dp}{d\psi} + \left(\frac{\partial X}{\partial g}\right)^{-1} \tag{A33}$$

Substitute (A32) into (A33) and simplify

$$\frac{dp}{d\psi} + \frac{dg}{d\psi} = \frac{c'_G A}{1 + A - c'_G A\frac{\partial Y}{\partial g}} \tag{A34}$$

The numerator and denominator are both positive so, $dp/d\psi + dg/d\psi > 0$, and from the previous result that $dp/d\psi < 0$, it is now shown that $dg/d\psi > 0$.

The first claim of the proposition is that the government direct buy crowds out private consumption of Y. The effect of ψ on Y is given by

$$\frac{dY}{d\psi} = \frac{\partial Y}{\partial g}\frac{dg}{d\psi} \tag{A37}$$

Since $dg/d\psi > 0$, (A37) is negative.

The second claim of the proposition is that the crowding out is less than one for one. The fact that the sum $dp/d\psi + dg/d\psi > 0$ implies that both sides of (A30) must be positive. For the left hand side of (A30) to be positive requires that $\frac{dY}{d\psi} + 1 > 0$, which proves the claim.

The third claim of the proposition is that increasing ψ increases the apparent amount of non-green power sold, X. The effect of ψ on X is given by

$$\frac{dX}{d\psi} = \frac{\partial X}{\partial p}\frac{dp}{d\psi} + \frac{\partial X}{\partial g}\frac{dg}{d\psi} \tag{A39}$$

Since $dp/d\psi < 0$ and $dg/d\psi > 0$, both terms of (A39) are positive, and $dX/d\psi > 0$.

The fourth claim of the proposition is that although X is increased, the actual production of non-green power is reduced. The fact that $dp/d\psi < 0$ implies that both sides of (A29) are negative. For the left hand side of (A29) to be negative requires that $\frac{dX}{d\psi} - 1 < 0$, which proves the claim. ■

Corollary: An increase in the government budget decreases (crowds out) private Y. This effect is less than one for one, so an increase in the government budget increases total green power $Y+\psi$.

Proof: Differentiate (18) with respect to B:

$$c'_G\left(\frac{dY}{dB} + \frac{d\psi}{dB}\right) = \left(\frac{dp}{d\psi} + \frac{dg}{d\psi}\right)\frac{d\psi}{dB} \tag{A41}$$

Differentiate (19) with respect to B:

$$\frac{d\psi}{dB} = \frac{1}{\frac{dg}{d\psi}\psi + g(\psi)} \tag{A42}$$

From proposition 3, the denominator is positive. Substitute (A42) into (A41) and simplify with (A32) and (A34):

$$\frac{dY}{dB} + \frac{d\psi}{dB} = \frac{A}{\psi c'_G A + \psi\left(\frac{\partial X}{\partial g}\right)^{-1} + g\left(1 + A - c'_G A\frac{\partial Y}{\partial g}\right)} \tag{A43}$$

All terms are positive, so (A43) is positive. Thus an increase in B increases ψ which decreases Y by Proposition 3, but it increases $Y+\psi$. ■

Proposition 4: A budget B spent on a direct buy of TGCs will result in more green power (and therefore less non-green power) than the same budget spent on a subsidy if and only if the demand for green power is inelastic with respect to the price of TGCs.

Proof: A direct buy causes a larger increase in Y if (A43) is greater than (A28) when both are evaluated where $\psi=h=0$ initially. That comparison readily simplifies to:

$$1 > -\frac{\partial Y}{\partial g}\frac{g}{Y} \tag{A44}$$

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