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Harrison Fell
Stephen P. Holland
Andrew J. Yates

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ABSTRACT

Green hydrogen may decarbonize sectors which are difficult to electrify, and the recent Inflation Reduction Act (IRA) provides tax credits to encourage hydrogen production. We analyze a model in which hydrogen produced using electricity replaces natural gas. The electricity may be procured from dedicated renewables or from the grid with and without offsetting. In the absence of Pigouvian taxation, optimal hydrogen subsidies are positive if the unpriced externality from avoided natural gas is larger than the unpriced externality from electricity. With optimally differentiated subsidies, offsetting increases welfare. With undifferentiated subsidies, offsetting can decrease welfare, unless it is restricted to regions with higher unpriced electricity externalities. Short-run parameterization shows that the IRA's subsidy of \$3/kg-H2 is rationalized: i) by hydrogen production from dedicated renewables if the social cost of carbon (SCC) is \$500 or ii) by hydrogen production from the (relatively clean) grid in California with renewables offsetting (relatively dirty) electricity in the non-RGGI East if the SCC is \$185. Allowing offsetting of production in California with renewables in any region does not reduce welfare, but the reverse does not hold.

Harrison Fell
NC State University
Raleigh, NC 27695
United States
hfell@ncsu.edu

Stephen P. Holland
Bryan School of Business and Economics
University of North Carolina, Greensboro
P.O. Box 26165
Greensboro, NC 27402-6165
and NBER
sphollan@uncg.edu

Andrew J. Yates
Department of Economics
and Curriculum for the
Environment and Ecology
University of North Carolina at Chapel Hill
CB 3305
Chapel Hill, NC 27599
ajyates@email.unc.edu

1 Introduction

Hydrogen is a key component in efforts to decarbonize. It has potential to be used in industrial applications where electrification is not a viable option, in transportation, and in long-duration electricity storage. To help jump-start hydrogen production in the US, the recently-passed Inflation Reduction Act (IRA) provides a production tax credit (PTC) whereby hydrogen (H_2) producers can get subsidies worth up to \$3/kg-H_2.[1] Producers must prove that the life-cycle carbon emissions of their hydrogen production, inclusive of the emissions embedded in the electricity consumed in the process, falls below certain thresholds to qualify for these rather substantial production credits. Given the thresholds in place, so-called "green hydrogen", produced through electrolysis using zero emissions electricity, appears likely to be the greatest benefactor of the IRA's hydrogen subsidy.[2] What is less apparent is the optimality of these policies. Analyzing them is further complicated by the range of methods by which hydrogen producers may procure electricity. Hydrogen producers may use dedicated renewable electricity sources. They may connect to the grid, in which case electricity consumption, and therefore electricity emissions, cannot be tied directly to a specified electricity producer. Additionally, regulators may allow hydrogen producers to offset their grid-connected electricity consumption through financial instruments such as power purchase agreements (PPAs) with clean energy producers or through the purchase of renewable energy credits (RECs).[3]

In this paper, we characterize optimal hydrogen subsidies, analyze how they may vary according to procurement methods, and compare them to the IRA subsidies. To do this, we build an energy consumption model in which hydrogen produced from electrolysis competes with natural gas and either fuel may cause carbon emissions. We derive optimal uniform

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[1] To put this subsidy value in context, production costs for hydrogen via electrolysis from renewable electricity sources is approximately \$5/kg and hydrogen produced from natural gas or coal, so-called grey hydrogen, is about \$2/kg([5]).

[2] "Blue" hydrogen, hydrogen produced from natural gas with a process of steam methane reforming and including carbon capture and storage for resulting emissions, may also be able to achieve life-cycle emissions sufficiently low to qualify for PTCs under the IRA depending upon the treatment of upstream emissions from natural gas extraction and transportation.

[3] PPAs give hydrogen producers the ability to claim MWh's of clean energy through a financial settlement mechanism even though the hydrogen producer does not physically take the MWh's of clean energy through a direct transmission line with the clean energy producer. These are sometimes called virtual PPAs.

and differentiated hydrogen subsidies that depend on the producer-specific private and social costs. From this general setting, we develop four specific electricity procurement possibilities: 1) *Grid*, where hydrogen is produced with electricity withdrawn from the local grid, 2) *RenewNoGrid*, where the hydrogen producer is not connected to the electricity grid and procures all its electricity from dedicated, zero-carbon renewable generation, 3) *Offset*, where the hydrogen producer procures its electricity from the local grid but offsets its electricity usage by constructing renewable generation, which is sold to the grid possibly in a different region, and 4) *REC*, where the hydrogen producer purchases power off the local grid, but purchases Renewable Energy Credits (RECs) which may or may not be additional. We allow firms to choose the electricity procurement method and the region in which any corresponding increase in renewables occurs. We analyze the welfare consequences of these choices, for both uniform and differentiated subsidies. Finally, we parameterize the model with regionally-specific electricity generation emission rates and recent estimates of the social cost of carbon (SCC) and compare optimal subsidies to existing subsidies offered under the IRA. This analysis indicates to policy makers which procurement methods and assumptions about the SCC lead to subsidies that are in line with the IRA subsidies.

This research contributes to the on-going discussion regarding government support of hydrogen production in several ways. First, several recent studies have explored emission implications of hydrogen subsidies under various electricity procurement methods, particularly electricity offsetting provisions, at the IRA's established subsidy rates (e.g. [12], [16]). But the optimality of these subsidies and how those optimal subsidy values change under different electricity procurement methods has not been addressed. Second, the relatively generalized specification of our model allows us to demonstrate the difference in welfare under the optimal hydrogen subsidies across electricity procurement types, as opposed to making comparisons on emission outcomes alone as is more common in the dispatch modeling contexts (e.g. [13] and [12]). Finally, using optimal subsidy formulations and recent estimates of marginal emission rates from several sub-national regions, we can quantify the optimal subsidies over the different procurement types and across various possible combinations of where the hydrogen producers may draw power from the grid and where they may offset this through PPAs or RECs. This exercise displays the heterogeneity in optimal subsidy rates.

It also is important for policy makers as it shows that, while greater electricity offsetting flexibility may justify the rather large hydrogen subsidies in the IRA, the size of the optimal subsidy depends critically on the combination of where the electricity is withdrawn and where the offsetting clean energy is deployed.

Our findings for the general case show that the optimal subsidy for hydrogen is equal to the unpriced externalities associated with burning the competing fuel, in our case natural gas, less the difference between the hydrogen-producer-specific social and private costs of hydrogen production. The optimal subsidies under the more specific electricity procurement are then special cases of this general rule. The subsidy for *RenewNoGrid* collapses to the value of the unpriced emissions externality for natural gas. The *Grid* subsidy is the unpriced natural gas externality less the unpriced emissions externality associated with electricity consumption in the region the hydrogen production occurs. The subsidies for *Offset* and *REC* are the same as *Grid* plus an additional term that accounts for the unpriced emissions externality *avoided* through the production of the offsetting clean energy, correcting for the degree of additionality of this clean energy.

We next study the welfare implications when firms may choose a procurement method and region in which, for example, they purchase offsets. With optimally differentiated subsidies, allowing offsetting increases welfare relative to *Grid* and *RenewNoGrid*, because the optimal subsidies align the social and private choice of offsetting region. At best, REC's can mimic offsetting, but cannot yield any additional welfare benefit. With uniform subsidies, allowing offsetting can decrease welfare unless it is restricted to regions with higher unpriced electricity externalities.

To parameterize our model, we use estimates of regional marginal emission rates for electricity and the SCC. We find that *Grid* leads to a *negative* optimal subsidy (i.e., a hydrogen production *tax*) in all five regions of the US considered. For *RenewNoGrid*, our parameterization suggests optimal subsidies around \$1/kg-H_2 in all five regions for SCC \$185, well below the \$3 subsidy for this type of hydrogen production. In fact only when the SCC exceeds \$500 does the subsidy approach \$3. For *Offset*, the subsidy determined by our parameterization depends on where the hydrogen production is withdrawing electricity and where the offsetting clean energy is located. In this scenario, we find optimal subsidy rates as high as \$3.56 and as low as -\$1.58 kg-H_2. These results, along with the previously discussed analytic results, thus highlight that while grid-connected hydrogen production with no clean energy offsetting clearly makes it difficult to justify subsidizing hydrogen production, the push for "deliverable" clean energy, where the procured clean energy generation occurs in the same region as the hydrogen production, actually leads to optimal subsidy rates that fall well short of the IRA's subsidy rate. Indeed, our results intuitively suggest that to align optimal subsidy rates to the IRA's subsidy rates, grid-connected hydrogen production would be encouraged in regions with relatively low marginal emission rates and be offset with clean energy generation produced in relatively high-emission rate regions.

2 Model

Consider an energy use, such as a high temperature industrial process, that requires either natural gas or hydrogen because it cannot easily be electrified. Let the quantity of natural gas, Q_G, and the quantity of hydrogen, Q_H, be perfect substitutes measured in the same energy units (for example MMBtu), so that the benefit of energy use can be written $U(Q)$, where $Q \equiv Q_G + Q_H$, with $U' > 0$ and $U'' < 0$.

Natural gas is extracted directly from geologic deposits with production costs given by $C_G(Q_G)$ where $C_G' > 0$ and $C_G'' \geq 0$.[4] Because natural gas is a large market relative to hydrogen, a reasonable simplifying case has $C_G'' = 0$. Combustion of natural gas creates carbon emissions of β_G tons per MMBtu which causes external costs $\tau > 0$ per ton. These emissions are taxed at a rate t^G, and if $t^G < \tau$, natural gas taxation is less than Pigouvian.

Unlike natural gas, we assume hydrogen is not readily available from geologic deposits but can be produced through electrolysis.[5] Let q_{Hi} be hydrogen produced by firm i so that $Q_H = \sum_i q_{Hi}$. Firm i's private cost of hydrogen electrolysis is given by $PC_i(q_{Hi})$, which includes non-electricity costs and electricity procurement costs. Let the social costs be $SC_i(q_{Hi})$, which are the sum of private costs and unpriced external costs (over the life-cycle). Assume marginal costs are positive and increasing: $PC_i' > 0$, $PC_i'' > 0$, $SC_i' > 0$, and

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[4] Costs may include transporting the natural gas or hydrogen to the end use.

[5] Recent discoveries of potentially large geologic deposits of hydrogen could change this with the appropriate technological advances.

$SC_i'' > 0$. We consider subsidy policies that may allow hydrogen subsidies, s_i per MMBtu, to differ across i.

Note in this general setting we allow for arbitrary firm-specific private and social costs of hydrogen production. In the subsequent section, SC_i and PC_i will be determined by the firm's implementation of one of the four electricity procurement methods described in the introduction. Thus, i will effectively define a procurement method when we move to the more specific setting.

Returning to the general case, let welfare be defined as

$$W \equiv U(Q) - C_G(Q_G) - \tau\beta_G Q_G - \sum_i SC_i(q_{Hi}). \tag{1}$$

The first-best outcome is given by maximizing W with respect to Q_G and q_{Hi}. The first-order conditions for an interior solution can be written as

$$U'(Q) = C_G' + \tau\beta_G = SC_i'(q_{Hi}) \text{ for all } i. \tag{2}$$

Intuitively, first best requires the marginal benefit of energy consumption to equal the marginal social cost of natural gas as well as the marginal social cost of hydrogen for each i.

The market equilibrium, which depends on any subsidies, is characterized by three equations. First, energy using firms equate marginal benefits and the price price of energy p: $U'(Q) = p$. Second, natural gas producing firms equate the price of energy and the private costs of gas production: $p = C_G' + t^G\beta_G$. Third, hydrogen-producing firms equate the price of energy plus any subsidy with the private costs of hydrogen production: $p + s_i = PC_i'(q_{Hi})$. Combining these gives

$$U'(Q) = p = C_G' + t^G\beta_G = PC_i'(q_{Hi}) - s_i. \tag{3}$$

The corresponding equilibrium differentials are $U''dQ = dp$, $dp = C_G''dQ_G$, and $dp = PC_i''dq_{Hi} - ds_i$ for all i.

To characterize optimal hydrogen subsidies, s_i^*, we can think of welfare, W, as a function of the market equilibrium which is in turn a function of the subsidies. Taking the differential yields

$$dW = (U' - C'_G - \tau\beta_G)dQ_G + \sum_i \left(U' - SC'_i(q_{Hi})\right) dq_{Hi}.$$

Substitution of the market equilibrium conditions in Eq. 3 implies

$$dW = (t^G - \tau)\beta_G dQ_G + \sum_i \left(PC'_i(q_{Hi}) - s_i - SC'_i(q_{Hi})\right) dq_{Hi}. \tag{4}$$

Several insights are illustrated in Eq. 4. First, as expected, there is no need for a hydrogen subsidy when there is Pigouvian taxation of both natural gas and hydrogen. Pigouvian taxation has $t^G = \tau$ and $PC'_i(q_{Hi}) = SC'_i(q_{Hi})$ for every i, and it follows that $s_i = 0$ leads to $dW = 0$. Second, if only natural gas faces Pigouvian taxation so that $t^G = \tau$, then the optimal hydrogen subsidy for i is $s_i = PC'_i(q_{Hi}) - SC'_i(q_{Hi}) \leq 0$, i.e., the optimal hydrogen subsidy is a *tax* equal to any unpriced marginal externality from hydrogen electrolysis. Third, if natural gas taxation is not Pigouvian, i.e., if $t^G < \tau$, then a second-best policy may have positive hydrogen subsidies. From now on, we assume $t^G < \tau$.

The second-best hydrogen subsidies can be found by dividing Eq. 4 by ds_i and setting $dW/ds_i = 0$ for each i. These subsidies can be readily characterized in the special case $C''_G = 0$ where natural gas is produced at constant marginal cost. Intuitively if natural gas production has constant marginal cost, any increase in hydrogen usage exactly offsets natural gas usage so $dQ_G = -dq_{Hi}$.[6] In this case, the second best subsidy from Eq. 4 is simply:

$$s^*_i = (\tau - t^G)\beta_G - \left(SC'_i(q_{Hi}) - PC'_i(q_{Hi})\right). \tag{5}$$

This subsidy has a common component, $(\tau - t^G)\beta_G$, which is the unpriced marginal externality from natural gas, and a firm-specific component, $SC'_i(q_{Hi}) - PC'_i(q_{Hi})$, which is the firm's marginal external cost of electrolysis. The optimal subsidy for i is then the difference between these two components. Note that these optimal subsidies difference out private costs leaving only external costs, so the regulator only needs to observe the external cost.

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[6] If $C''_G = 0$, then the equilibrium differentials imply $dp = C''_G dQ_G = 0$ and hence $dQ = 0$ because $U'' dQ = dp$. Because $dp = 0$, we also have $dq_{Hi'} = 0$ for all $i' \neq i$ so $0 = dQ = dQ_G + dQ_H = dQ_G + dq_{Hi}$ which implies that $dQ_G = -dq_{Hi}$. On the other hand, if $C''_G > 0$, then $dp \neq 0$ so hydrogen does not offset natural gas exactly, and the optimal subsidy formulas are more complicated.

These optimal subsidies are differentiated across i. Alternatively, a regulator might consider a uniform subsidy. For a uniform subsidy, Eq. 4 still holds but with $s = s_i$ for all i. If $C''_G = 0$, then Eq. 4 implies

$$\frac{dW}{ds} = (t^G - \tau)\beta_G \sum_i \frac{-dq_{Hi}}{ds} + \sum_i \left(PC'_i(q_{Hi}) - s - SC'_i(q_{Hi})\right) \frac{dq_{Hi}}{ds}.$$

Setting $dW/ds = 0$ gives the optimal uniform hydrogen subsidy:

$$s^* = (\tau - t^G)\beta_G - \sum_i \alpha_i \left(SC'_i(q_{Hi}) - PC'_i(q_{Hi})\right) / \sum_i \alpha_i, \tag{6}$$

where $\alpha_i \equiv dq_{Hi}/ds = 1/PC''_i$.[7] The optimal uniform hydrogen subsidy is thus the marginal external cost of natural gas minus a weighted average across i of the marginal external cost of electrolysis with weights $1/PC''_i$. Note the subsidy to i is too large if i has large external costs and is too low if i has small external costs.

Although natural gas and hydrogen are storable across hours, electricity is not and hence the costs of electrolysis may differ across hours. The model can readily be extended to analyze hourly differences in electricity prices and emissions. If t indexes hours, then welfare in Eq. 1 becomes

$$W = U(Q) - C_G(Q_G) - \tau\beta_G Q_G - \sum_i \sum_t SC_{it}(q_{Hit})$$

where now $Q = Q_G + \sum_i \sum_t q_{Hit}$ and SC_{it} is firm i's social cost of electrolysis in hour t. The derivations of the optimal differentiated and uniform subsidy formulas now follow in a similar manner as Eqs. 5 and 6.

2.1 Graphical illustrations of the second-best subsidies

The second-best hydrogen subsidy, its deadweight loss (DWL), and hydrogen entry incentives can be illustrated graphically. Fig. 1 shows the marginal benefit, U', of energy use and the marginal costs of natural gas and hydrogen assuming only one electricity procurement type

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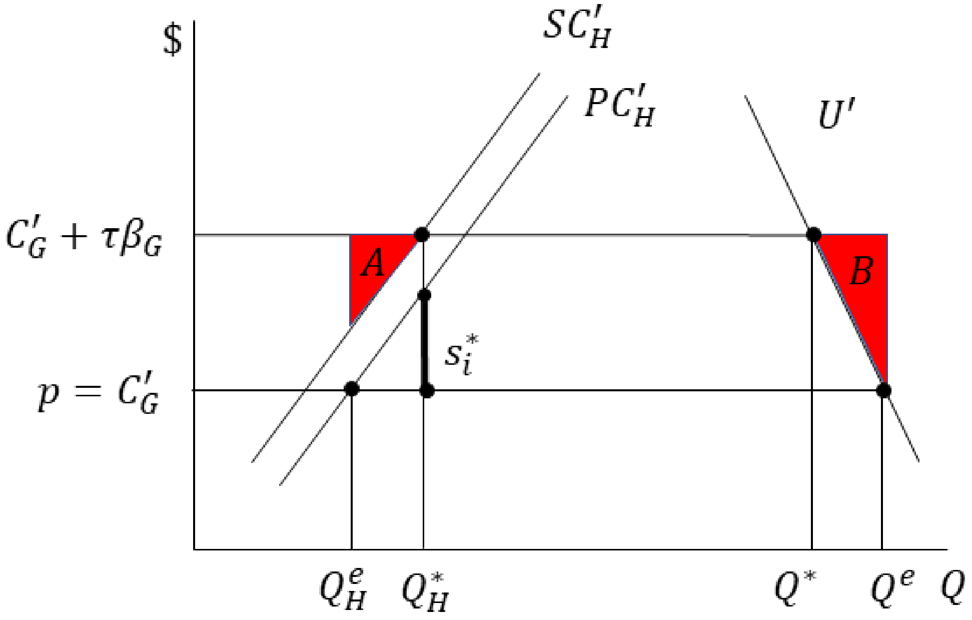
[7] If $C''_G = 0$, the equilibrium differentials imply that $dp = 0$ which further implies $dQ = 0$ so $-dQ_G = \sum dq_{Hi}$. In addition $ds = PC''_i dq_{Hi}$ for all i, so $dq_{Hi}/ds = \alpha_i$.

Figure 1: Deadweight loss of hydrogen subsidies



and no environmental taxes ($t^G = t_i^E = 0$). Following Eq. 2, first-best energy use is determined from $U'(Q^*) = C'_G + \tau\beta_G$; first-best hydrogen use is determined by $SC'_H(Q_H^*) = C'_G + \tau\beta_G$; and first-best natural gas use is the residual $Q_G^* = Q^* - Q_H^*$. Next consider the unregulated equilibrium with no carbon tax or hydrogen subsidy. Following Eq. 3 when $s_i = 0$, the equilibrium energy use is determined by $U'(Q^e) = p = C'_G$, which implies $Q^e > Q^*$ because the marginal private cost of natural gas is less than its marginal social cost. The equilibrium hydrogen quantity is determined by $PC'_H(Q_H^e) = p = C'_G$. Because both sides of this equation are lower than optimal, the equilibrium hydrogen quantity can be either two large or too small. If hydrogen electrolysis were to have very large external costs so that the gap between $SC'_H(Q_H)$ and $PC'_H(Q_H)$ were very large, the unregulated equilibrium could have *too much* hydrogen. As illustrated $Q_H^e < Q_H^*$, so the equilibrium has too little hydrogen.

The unregulated equilibrium has two sources of deadweight loss: triangles A and B in Fig. 1. Triangle B arises because $Q^e > Q^*$ and the benefit of this additional natural gas consumption is less than its social cost. Triangle A arises because $Q_H^e < Q_H^*$ so there is too little hydrogen consumption, and energy consumption from Q_H^e to Q_H^* is from natural gas instead of hydrogen. The marginal social cost of natural gas, $C'_G + \tau\beta_G$, exceeds the marginal social cost of hydrogen, SC'_H, over this range resulting in DWL triangle A.

A small hydrogen subsidy would introduce a wedge between the price and private cost, would increase Q^e_H, and reduce DWL triangle A but would have no effect on Q^e or on triangle B. In fact, the second-best hydrogen subsidy s^*_i completely eliminates DWL triangle A by subsidizing hydrogen such that Eq. 5 holds, and the equilibrium hydrogen quantity with the optimal subsidy is Q^*_H. Thus the second-best hydrogen subsidy reduces the DWL from A+B to just B.

The welfare gains from the second-best subsidy depend on the size of triangle A. If hydrogen production is perfectly clean, then $SC'_H = PC'_H$, equilibrium hydrogen production is too low, and triangle A is large. In this case, the second-best subsidy leads to a large reduction in DWL. As hydrogen production becomes dirtier, the difference between SC'_H and PC'_H increases, optimal hydrogen production decreases, and triangle A becomes smaller until the point at which the optimal subsidy, and welfare gains, become zero.

Fig. 2 illustrates welfare and hydrogen electrolysis entry incentives. If there is no hydrogen electrolysis, first-best welfare is simply area D in Fig. 2: the area below U' and above $C'_G + \tau\beta_G$.[8] The welfare gain from the entry of hydrogen electrolysis is given by triangle E: the triangle below $C'_G + \tau\beta_G$ and above SC'_H.[9] Entry of hydrogen electrolysis is socially optimal if these welfare gains are positive, which occurs if $SC'_H(0) < C'_G + \tau\beta_G$.

For an arbitrary subsidy, hydrogen entry incentives may not be optimal because the private producer surplus may not equal the welfare gains. However, the second-best hydrogen subsidy can correct these entry incentives. Fig. 3 illustrates first- and second-best hydrogen entry incentives for the case of constant external costs. The first-best entry incentive is given by area (a+b+c). If there is no subsidy, the hydrogen quantity is Q^e_H, and the private producer surplus is area (c+e). Because (c+e) is less than the welfare gain from entry (which also includes part of areas a, b, and d) the hydrogen entry incentive is too small if there is no subsidy. However, at the optimal subsidy, s^*_i, the hydrogen quantity is Q^*_H, and the private producer surplus is area (b+c+d+e), which is exactly equal to the welfare gain of

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[8] More generally this is $\int_0^{Q^*} U' - C'_G - \tau\beta_G dq$ which equals $U(Q^*) - C_G(Q^*) - \tau\beta_G Q^*$.

[9] More generally welfare gains are given by $\Delta W = \int_0^{Q^*_H} C'_G + \tau\beta_G - SC'_H(q_H) dq_H$.

Figure 2: First-best electrolysis entry incentives

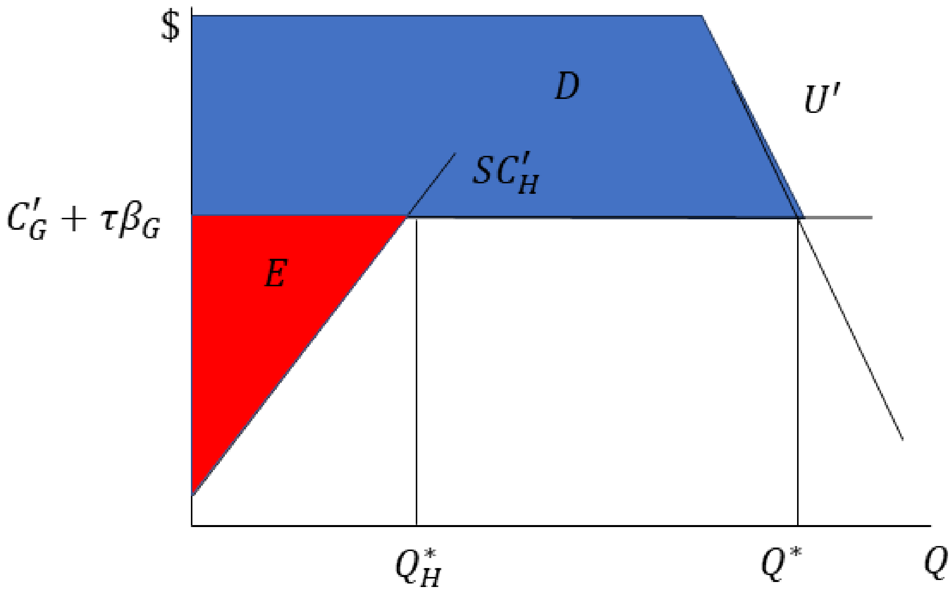
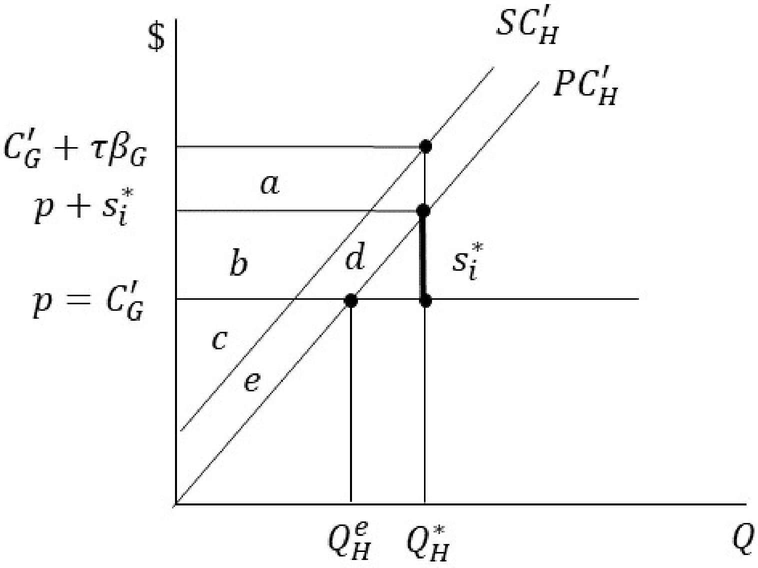


Figure 3: Entry incentives with second-best subsidy



area (a+b+c) given that the externality is constant. Thus the second-best subsidy gives exactly the correct hydrogen entry incentives.

2.2 Specific procurement methods

The electrolysis cost functions $PC_i(q_{Hi})$ and $SC_i(q_{Hi})$ are quite general. Here we create more structure for these functions and describe possible procurement types. In Section 3, we calibrate optimal subsidies based on these formulas.

Electrolysis costs depend on the cost of electricity and its emissions, both of which differ across regions. Assume there are J electricity regions. For grid electricity in region $j \in \{1, 2, ..., J\}$, assume the generation cost is c_j^E per MWh and the marginal carbon emissions rate is m_j tons carbon per MWh. If electricity is competitively supplied and carbon emissions are taxed at t_j^E, then the electricity price is

$$p_j^E = c_j^E + t_j^E m_j. \tag{7}$$

and if $t_j^E < \tau$, then electricity taxation in region j is not Pigouvian. Assume renewable (solar) generation costs $c_{Sj}(E)$ in region j where $c'_{Sj} > 0$ and $c''_{Sj} \geq 0$.[10] Finally assume Renewable Energy Certificates (RECs) from region j can be purchased at price p_j^R per MWh. The RECs may or may not be additional, so let $\delta_j \in [0, 1]$ be the additional zero-carbon, renewable electricity generation from one REC in region j.

Assume without loss of generality that the hydrogen electrolysis facility is located in electricity region 1. From the J electricity regions, we construct $2J + 1$ procurement types based on whether or how electricity used for electrolysis is offset, where the procurement types are described by the following schematic:

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[10] Renewable generation costs include both the costs of constructing the generation facility as well as any operating costs. This assumption parallels the treatment of non-electricity electrolysis costs.

$$i \in \{\underset{\substack{\uparrow \\ Grid}}{0}, \overset{\substack{RenewNoGrid \\ \downarrow}}{1}, \underbrace{2, 3, ..., J,}_{Offset} \overbrace{J+1, J+2, ..., 2J}^{REC}\}.$$

Note that i now indexes the procurement types and captures two dimensions (offset type and offset region) in a single index. Let the non-electricity cost of producing hydrogen for electrolysis facility i be $c_H(q_{Hi})$ with $c'_H > 0$ and $c''_H > 0$. Electricity required by facility i for electrolysis, E_i, depends on the conversion factor $\gamma > 0$ (measured for example in MWh per MMBtu) where $E_i \equiv \gamma q_{Hi}$.[11]

First, for $i = 0$ (*Grid*), the electrolysis facility procures electricity from the grid in region 1, but does not offset it. For this type, the carbon emissions are $m_1\gamma q_{H0}$; the social cost is $SC_0(q_{H0}) = c_H(q_{H0})+(c_1^E+\tau m_1)E_0$; and the firm's private cost is $PC_0(q_{H0}) = c_H(q_{H0})+p_1^E E_0$. The firm's marginal external cost is then $SC'_0(q_{H0}) - PC'_0(q_{H0}) = (c_1^E + \tau m_1)\gamma - p_1^E\gamma = (\tau - t_1^E)m_1\gamma > 0$ so Eq. 5 implies the optimal subsidy for *Grid* is

$$s_0^* = (\tau - t^G)\beta_G - (\tau - t_1^E)m_1\gamma, \tag{8}$$

which is the marginal external cost of natural gas minus the marginal external cost of grid electrolysis. This subsidy could be negative, e.g., if the grid electricity for electrolysis has high marginal emissions and/or if electrolysis requires substantial electricity.

For $i = 1$ (*RenewNoGrid*), the hydrogen electrolysis facility does not connect to the grid, but constructs a renewable generation facility from which it procures all its electricity. For this type, the carbon emissions are zero, so the social and private costs of hydrogen electrolysis are equal $SC_1(q_{H1}) = PC_1(q_{H1}) = c_H(q_{H1})+c_{S1}(E_1)$. The firm's marginal external cost is zero, $SC'_1(q_{H1})-PC'_1(q_{H1}) = 0$, so Eq. 5 implies the optimal subsidy for *RenewNoGrid* is

$$s_1^* = (\tau - t^G)\beta_G \tag{9}$$

which is simply the (unpriced) marginal external cost of natural gas. Note that by assumption $s_1^* > 0$.

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[11] The laws of energy conservation imply γ has a theoretical minimum. The model could easily be extended to allow the non-electricity costs, c_H, and conversion factors, γ, to differ across procurement types.

For $i \in \{2, 3, 4, ..., J\}$ (*Offset*), assume the hydrogen electrolysis facility procures its electricity from the local grid in region 1, but also constructs a renewable facility in region $j = i$, which denotes both the procurement type as well as the offsetting region. Assume the renewable facility generates ϵ MWhs of renewable generation to offset each MWh of electricity used for electrolysis. The carbon emissions from electrolysis and offsetting are then $(m_1 - m_j\epsilon)\gamma q_{Hi}$; the social cost is $SC_i(q_{Hi}) = c_H(q_{Hi}) + (c_1^E + \tau m_1)E_i - (c_j^E + \tau m_j)\epsilon E_i + c_{Sj}(\epsilon E_i)$, and the firm's private cost is $PC_i(q_{Hi}) = c_H(q_{Hi}) + p_1^E E_i - p_j^E \epsilon E_i + c_{Sj}(\epsilon E_i)$. The firm's marginal external cost can be positive (i.e., an external cost) or even negative (i.e., an external *benefit*) if offset damages are large.[12] Because $i = j$, the optimal subsidy for i is

$$s_i^* = (\tau - t^G)\beta_G - (\tau - t_1^E)m_1\gamma + (\tau - t_i^E)m_i\epsilon\gamma \text{ for all } i \in \{2, 3, 4, ..., J\}, \tag{10}$$

which is the marginal external cost of natural gas minus the direct marginal external cost of the electrolysis plus the marginal external costs offset by the renewable generation. This subsidy includes a term that is equal to the optimal renewable subsidy for the *Grid* case plus an extra term that accounts for the marginal external costs offset by the renewable generation in region i. Overall, this subsidy can even exceed the subsidy for *RenewNoGrid* if offset emissions are sufficiently large.[13]

Although we have presented Eqs. 8, 9, and 10 separately, Eq. 10 actually gives the optimal subsidy for $i \in \{0, 1, 2, ..., J\}$. To see this, first note that, in our model, building renewables and not connecting to the grid (*RenewNoGrid*) is equivalent to offsetting in the same region. Thus Eq. 10 is valid for $i = 1$. If we additionally define the "null" region 0 with $0 = p_0^E = c_0^E = c'_{S0} = m_0$, we have that Eq. 10 is also valid for $i = 0$.

Four assumptions are worthy of note here. First, we assume that the renewable facility is truly additional because the social costs are reduced by the full social costs of the additional generation $(c_j^E + \tau m_j)\epsilon E_i$. Second, the net carbon emissions of electrolysis here can be negative, i.e., if $m_1 E_i < m_j \epsilon E_i$ which can occur if marginal emissions in the offsetting region are high. Third, renewable generation need not equal electricity used in electrolysis. If $\epsilon > 1$,

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[12] We have $SC'_i(q_{Hi}) - PC'_i(q_{Hi}) = (c_1^E + \tau m_1)\gamma - (c_j^E + \tau m_j)\epsilon\gamma - p_1^E\gamma + p_j^E\epsilon\gamma = (\tau - t_1^E)m_i\gamma - (\tau - t_j^E)m_j\epsilon\gamma$.

[13] As expected, the second-best subsidy for *Offset* with electricity in the same region, i.e., $i = 1$ is the same as the *RenewNoGrid* subsidy if $\epsilon = 1$.

offsetting is more than one-to-one.[14] Finally, offsetting need not be hourly matching. For example, in the extended model with hourly differences in electricity costs, the carbon emissions of offsetting electricity use with renewables in region j would be $\sum_t m_{1t}E_{it} - \sum_t m_{jt}\epsilon_t E_{it}$. Note that assessing the emission impacts of offsetting requires accurate measurements of the marginal emissions factors.

Finally, for $i \in \{J+1, J+2, ..., 2J\}$ (REC), assume the hydrogen electrolysis facility procures its electricity from the local grid in region 1, and purchases ϵE_i MWhs of RECs from region $j = i - J$, which induce $\delta\epsilon E_i$ additional MWhs of renewable electricity in region j. The carbon emissions are $(m_1 - \delta m_j \epsilon)\gamma q_{Hi}$. The social cost is $SC_i(q_{Hi}) = c_H(q_{Hi}) + (c_1^E + \tau m_1)E_i + [c_{Sj}(\delta\epsilon E_i) - (c_j^E + \tau m_j)\delta\epsilon E_i]$, and the firm's private cost of hydrogen production and REC purchases is $PC_i(q_{Hi}) = c_H(q_{Hi}) + p_1^E E_i + p_j^R \epsilon E_i$. Together these imply that the optimal subsidy is

$$s_i^* = (\tau - t^G)\beta_G - (\tau - t_1^E)m_1\gamma + \left(\delta[c_j^E + \tau m_j - c'_{Sj}(\delta R_j)] + p_j^R\right)\epsilon\gamma, \tag{11}$$

with $j = i - J$ for all $i \in \{J+1, ..., 2J\}$. This subsidy is quite similar to the optimal *Offset* subsidy in Eq. 10 except for the final term.

Not surprisingly, carbon emissions depend crucially on δ, i.e., on the additionality of the RECs. If $\delta = 0$, the REC purchases have no effect on renewable generation and are simply a tax on hydrogen production. The second-best hydrogen subsidy offsets this REC tax. If the REC market is competitive, the REC price satisfies the condition $p_j^R = c'_{Sj}(R_j) - p_j^E = c'_{Sj}(R_j) - c_j^E - t_j^E m_j$, and the third term in Eq. 11 can be written

$$\left(c'_{Sj}(R_j) - \delta c'_{Sj}(\delta R_j) - (1-\delta)(c_j^E) + (\delta\tau - t_j^E)m_j\right)\epsilon\gamma.$$

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[14] By subsidizing hydrogen production with offsets, the regulator is effectively subsidizing renewable generation indirectly through the hydrogen subsidy. The regulator could instead apply a subsidy σ_j directly to renewable electricity in region j. In this case the renewable firm's equilibrium condition is $c'_{Sj}(E_j) = p_j^E + \sigma_j$. The social benefit from this subsidy is $(c_j^E + \tau m_j)E_j - c_{Sj}(E_j)$ which is the avoided social costs of the offset electricity minus the costs of renewable generation. Taking the first-order condition of this objective, and substituting in the firm's equilibrium condition shows that the second-best electricity subsidy is simply $\sigma_j = (\tau - t_j^E)m_j$, i.e., equals the unpriced damages from the avoided electricity consumption. As shown above, this second best subsidy is a component of the optimal hydrogen offset subsidy.

Under this condition, if $\delta = 1$, i.e., if the RECs are 1:1 additional, then the optimal subsidy is identical to the subsidy for *Offset*. Thus with competitive REC prices, the third term in the optimal subsidy ranges from $p_j^R \epsilon \gamma$ to $(\tau - t_j^E) m_j \epsilon \gamma$ depending on the additionality of the RECs.

2.3 Choice across procurement types

Up to now, we have assumed a firm in one of the procurement types has only one option for electricity procurement. More generally, electricity procurement may be a choice for the firm. For example, a firm might be able to choose whether to generate renewable electricity itself or procure electricity from the grid. Similarly, a firm may have a choice of region in which to offset emissions.

To proceed, we make two simplifying assumptions. First, assume that all offsetting is one-for-one, so that $\epsilon = 1$. Second, we assume that renewable generation has constant marginal cost, $c'_{Sj}(E_j) \equiv c'_{Sj}$ for each region j. This ensures that $\min_j \{c'_{Sj}\}$ is well-defined and is independent of the level of renewable generation in each region.

If a hydrogen electrolysis facility can choose among the $J+1$ procurement types $\{0, 1, ...J\}$, the facility will choose the procurement type, $i = j^e$, which yields the highest producer surplus. This may or may not be the procurement type with the highest welfare gains, $i = j^*$. The following lemma characterizes optimal offsetting for both the firm and social perspectives. All results are proved in the Appendix A.1.

Lemma 1. *For $J+1$ offsetting options and an arbitrary subsidy vector s, the firm's profit-maximizing procurement choice is $j^e = \text{argmin}_j \{-p_j^E \gamma + c'_{Sj} \gamma - s_j\}$ and the firm's net-of-subsidy marginal cost is $\mathcal{PC}'(q_H, s) \equiv c'_H(q_H) + p_1^E \gamma + \min_j \{-p_j^E \gamma + c'_{Sj} \gamma - s_j\}$.*

Welfare maximizing procurement is $j^* = \text{argmin}_j \{-(c_j^E + \tau m_j)\gamma + c'_{Sj} \gamma\}$ and the social marginal cost is $\mathcal{SC}'(q_H) \equiv c'_H(q_H) + (c_1^E + \tau m_1)\gamma + \min_j \{-(c_j^E + \tau m_j)\gamma + c'_{Sj} \gamma\}$.

The lemma shows that the firm chooses the procurement type with the lowest marginal cost. Thus, the firm chooses to offset in a region with cheaper renewables, more valuable offset electricity, and/or a larger subsidy. Social optimality requires offsetting in the region with the lowest social marginal cost, i.e., in a region with cheaper renewables and offset electricity with high social costs.

In general, the firm's optimal procurement need not agree with social optimality. However, the optimal differentiated subsidies align the incentives:

Result 1. *If subsidies are optimal for* $J+1$ *offsetting options, then* $j^e = j^*$ *and* $q_H^e = q_H^*$.

The result shows that the optimal differentiated subsidies can correct the incentives of the facility to choose across offsetting regions. The firm chooses the offsetting region based on the private cost of electricity, p_j^E, whereas social optimality is determined by the social cost of electricity, $c_j^E + \tau m_j$. The optimal differentiated subsidies align these incentives so that private offsetting is socially optimal.

A corollary follows directly:

Corollary 1. *If subsidies are optimal for* $J+1$ *offsetting options, then allowing offsetting to regions* $2, 3, \ldots J$ *(weakly) increases welfare relative to* Grid *or* RenewNoGrid.

This corollary is implied directly from the social optimality of the firm's choices when facing the optimally differentiated subsidies. Because the firms' choices are optimal, the regulator can weakly increase welfare by allowing the firm to choose over offsetting in additional regions.

The regulator may choose to expand choice further to allow the option to purchase RECs in each of the J regions. The following result shows this additional choice cannot increase welfare even if the subsidies are optimally differentiated across the RECs.

Result 2. *If subsidies are optimal for all* $2J+1$ *offsetting and REC options, then* $i)$ *offsets strictly welfare dominate RECs if RECs are not fully additional, i.e., if* $\delta < 1$, *and* $ii)$ *offsets and RECs are equivalent if RECs are fully additional, i.e., if* $\delta = 1$.

The result shows that if RECs are fully additional, they mimic offsetting and hence have the same optimal subsidies and the same welfare gains. This is the best case for RECs. If RECs are not fully additional, then their marginal social cost is higher and welfare is lower than with offsetting, and they would not be chosen by an optimizing firm.

These results rely on the optimal differentiated subsidies, which can make offsetting more or less attractive in different regions based on social costs. However, subsidies, including those in the IRA, may not be differentiated across regions. The absence of optimally differentiated subsidies implies that the firm and social incentives may not be aligned. Uniform subsidies affect all procurement choices the same, and so firms choose the procurement to minimize private costs, and hence offset in $j^e = \text{argmin}_j\{-p_j^E\gamma + c'_{Sj}\gamma\}$ which may or may not be the optimal procurement choice $j^* = \text{argmin}_j\{-(c_j^E + \tau m_j)\gamma + c'_{Sj}\gamma\}$. The following result provides conditions in which offsetting can increase welfare even if subsidies are not differentiated.

Result 3. *Assume the* $J+1$ *procurement options face the same (uniform) subsidy. Allowing offsetting to regions* $2, 3, ..., J$ *increases welfare relative to* Grid*. Allowing offsetting to region* $j \in \{2, 3, ..., J\}$ *cannot decrease welfare relative to* RenewNoGrid *if* $(\tau - t_1^E)m_1 < (\tau - t_j^E)m_j$.

The result first shows that offsetting increases welfare relative to *Grid*. Intuitively, the firm chooses offsetting if the market price of the renewable electricity exceeds the cost of the renewable electricity. But because the social marginal cost exceeds the market price, any chosen offsetting has social marginal cost which exceeds the renewable marginal cost and hence increases welfare relative to *Grid*.

However, not all offsetting increases welfare relative to *RenewNoGrid*. In fact, privately profitable offsetting can reduce welfare relative to *RenewNoGrid*, but the condition

$$(\tau - t_1^E)m_1 < (\tau - t_j^E)m_j$$

ensures that this does not happen. We call this the unpriced externality condition because it compares the unpriced externalities in electricity across regions. In short, if the unpriced externality in the offsetting region is larger than the unpriced externality in the home region, then offsetting cannot reduce welfare.

The unpriced externality condition is quite intuitive and can be readily implemented by a regulator. In particular, the condition compares the unpriced externality from electricity in the region of the electrolysis plant with the unpriced externality from electricity in the offsetting region. The regulator can potentially increase welfare by allowing offsetting only if the offsetting region has a larger unpriced externality from electricity, i.e., only if the grid electricity in the offsetting region is dirtier. This unpriced externality depends only on marginal emissions, the SCC, and existing taxation. These parameters can be observed by a regulator and are not readily manipulated by firms. Thus a rule allowing offsetting to regions with higher unpriced externalities from electricity likely could be readily implemented.

3 Calibration results

We parameterize the model to calculate the optimal subsidies and offsetting for different types of procurement in different regions. The optimal subsidies only depend on existing carbon prices, marginal emissions of electricity, and the social cost of carbon. Carbon is priced in California, and in the east RGGI prices carbon from electricity emissions. Marginal emissions are estimated by [7] for the three interconnections of the contiguous U.S. electricity grid (East, West, Texas).[15] As listed in Table 1, this gives five analysis regions. Appendix Table A.1 shows the assumed carbon prices and marginal emissions for the five regions. Additional baseline parameters include the social cost of carbon, $\tau = 185$ per mton, the natural gas carbon emissions rate, $\beta_G = 0.0509$ mton/MMBtu, and the electrolysis conversion factor, $\gamma = 55$ kWh/kg.

Using Eq. 10, Table 1 shows the optimal subsidies for the five regions and the six types of electricity procurement.[16] The first column shows the optimal subsidies for *Grid*. These are all negative (i.e., are taxes) which implies that the unpriced externality from grid-connected hydrogen electrolysis in any region exceeds the unpriced externality of natural gas. The subsidies are the most negative in the non-RGGI East which has the dirtiest electricity, i.e., the largest unpriced externalities from electricity. The optimal subsidies are all still negative even if marginal emissions decrease by 75% or if γ decreases to its theoretical minimum of $\gamma = 34$.

The optimal subsidies for *RenewNoGrid* are shown in the main diagonal of columns 2-6. These are the unpriced marginal externality from avoided natural gas and are \$1.08 per kg except in California (\$0.90) where natural gas faces a carbon price and has a lower unpriced

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[15] These marginal emissions may not account for all life-cycle emissions.

[16] The optimal subsidies for *REC* can be readily calculated from our results depending on their additionality.

Table 1: Optimal subsidies and unpriced externalities

Electrolysis Region	Grid	Offset region Calif.	Non-Calif. West	Texas	RGGI East	Non-RGGI East	Unpriced Electricity Externality
California	-2.94	0.90	1.65	2.07	3.12	3.56	3.84
Non-Calif. West	-3.50	0.34	1.08	1.50	2.55	2.99	4.58
Texas	-3.93	-0.09	0.65	1.08	2.13	2.57	5.01
RGGI East	-4.98	-1.14	-0.39	0.03	1.08	1.52	6.06
Non-RGGI East	-5.42	-1.58	-0.83	-0.41	0.64	1.08	6.50

Notes: Subsidies, s_i, are in \$ per kg of hydrogen. SCC is $\tau = 185$ per mton. Offsetting has $\epsilon = 1$. "Unpriced Electricity Externality" is $(\tau - t_i^E)m_i\gamma$ in \$ per kg of hydrogen.

externality. These *RenewNoGrid* subsidies are positive, because the renewable electricity has zero emissions. Note however, that they are all substantially below \$3, which is the legislated subsidy amount.

The off-diagonals of columns 2-6 show the optimal subsidies for *Offset* in the indicated region. For offsetting, the optimal subsidies can be positive or negative. In fact, several combinations exceed the actual \$3 subsidy. The largest subsidy is for electrolysis in California offset by renewable generation in the non-RGGI East. Electrolysis in California uses electricity with the lowest unpriced electricity externality and offsets it with renewables in the non-RGGI East which has the largest unpriced electricity externality. The carbon emissions from offsetting (shown in Appendix Table A.3) are negative for this case reflecting marginal emissions that are highest in the East and lowest in the West. On the other hand, the most negative subsidy is for hydrogen electrolysis in the non-RGGI East (using dirty electricity) offset with renewables in California (offsetting clean electricity).

Corollary 1 implies that with these optimal subsidies, any offsetting adopted by electrolysis facilities increases welfare. If subsidies are uniform, there is no such guarantee and offsetting can decrease welfare. Result 3 provides conditions under which allowing offsetting increases welfare with a uniform subsidy. Namely, offsetting in a region with a higher unpriced externality from electricity cannot decrease welfare. The unpriced electricity externality is shown in the final column of Table 1.

Result 3 implies that hydrogen electrolysis with a uniform subsidy in California which is offset with renewable electricity in any region does not decrease welfare. Because electricity sector carbon emissions in California are relatively low and and are priced, the unpriced externality in California is \$3.84 which is the lowest in the country. Result 3 implies that offsetting anywhere in the country, that is profitable for a California firm, will not reduce welfare. The result does not imply that with uniform subsidies the California electrolysis firm will choose the welfare maximizing offsetting, but only that its choice cannot lower welfare.

On the other hand, Result 3 provides no such assurances for an electrolysis facility in the Non-RGGI East. This region has the highest unpriced electricity externality so offsetting to any region under uniform subsidies has the potential to decrease welfare. Whether or not it reduces welfare depends on the relative social costs. For other regions, Result 3 can provide additional guidance. For example, if a hydrogen electrolysis facility in Texas is allowed to offset in the RGGI or Non-RGGI East, then offsetting cannot decrease welfare. However, offsetting in California and the Non-California West could decrease welfare.[17]

The optimal subsidies only depend on a small number of parameters. Of these, the SCC is the most uncertain. Table 2 shows the optimal subsidies for different SCCs. With a lower SCC of \$100, the unpriced externalities are smaller so the *RenewNoGrid* and *Grid* subsidies are smaller in absolute value. For a higher SCC of \$500, the *RenewNoGrid* subsidies are larger and, in fact, this SCC justifies the \$3 subsidy in the IRA. However, this high SCC also implies large negative subsidies for grid-connected electrolysis.

Table 2: Optimal subsidies: Sensitivity to SCC

	τ = 100		τ = 185		τ = 500	
Electrolysis Region	Renewable NoGrid	Grid	Renewable NoGrid	Grid	Renewable NoGrid	Grid
California	0.41	-1.33	0.90	-2.94	2.74	-8.90
Non-Calif. West	0.58	-1.89	1.08	-3.50	2.92	-9.47
Texas	0.58	-2.12	1.08	-3.93	2.92	-10.62
RGGI East	0.58	-2.49	1.08	-4.98	2.92	-14.20
Non-RGGI East	0.58	-2.93	1.08	-5.42	2.92	-14.64

Notes: Subsidies, s_i, are in \$ per kg of hydrogen.

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[17] Result 3 can also be seen from the optimal subsidies: offsetting in any region with a larger optimal subsidies cannot decrease welfare.

The estimates of marginal emissions in [7] are based on the existing grid.[18] However, for investment in a long-lived electrolysis facility, a longer-run estimate of marginal emissions might be more appropriate. [8] present estimates of long-run marginal emissions in thirteen EIA regions. These estimates are long run marginal emissions because they allow all technologies to enter or exit fully in response to a load shock. The long run marginal emissions and current carbon taxes for the thirteen regions are shown in Appendix Table A.2.

Table 3 shows the optimal subsidies based on these long-run estimates. The *RenewNoGrid* subsidies are the unpriced marginal externality from natural gas and are the same as above. The *Grid* subsidies are all negative, indicating that even in the long-run the marginal externality from grid-connected electrolysis exceeds the marginal externality from natural gas. The table also presents the optimal subsidies based on the "best" offset in the dirtiest regions with the highest unpriced externality (Carolinas, MidWest, SouthEast, or Tennessee) and the "worst" offset in the cleanest region (Central). Offsetting with renewable electricity in the best region, can rationalize the \$3 subsidy for example, if electrolysis in Central is offset with renewable generation in the Carolinas. However, offsetting with renewable electricity in the cleanest region (Worst Offset), yields negative optimal subsidies for electrolysis in most regions.

4 Implications for implementation of the IRA hydrogen subsidies

Much of the discussion regarding the implementation of hydrogen subsidies has been centered around design elements more related to the *Offset* and *REC* methods of procurement. Those concerned about the environmental integrity of hydrogen support have pushed to make grid-connected hydrogen electrolysis be eligible for a subsidy only if the hydrogen producer can prove that its electricity consumption can be offset by purchases of electricity from zero-emissions sources that are "additional" (the clean energy produced is produced only because of the purchase agreement from hydrogen producers), "deliverable" (the hydrogen production

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[18] [7] show that marginal emissions have not been falling in recent years despite substantial changes in the grid.

Table 3: Optimal subsidies for long-run marginal emissions using EIA regions

Electrolysis Region	Renewable NoGrid	Grid	Best Offset	Worst Offset	Unpriced Externality
California	0.90	-1.14	2.29	0.06	2.05
Carolinas	1.08	-2.36	1.08	-1.16	3.44
Central	1.08	-0.12	3.32	1.08	1.20
Florida	1.08	-2.35	1.09	-1.14	3.42
MidAtlantic	1.08	-2.13	1.31	-0.93	3.21
MidWest	1.08	-2.36	1.08	-1.16	3.44
New England	1.08	-2.13	1.31	-0.93	3.21
NorthWest	1.08	-1.43	2.01	-0.23	2.51
New York	1.08	-2.13	1.31	-0.93	3.21
SouthEast	1.08	-2.36	1.08	-1.16	3.44
SouthWest	1.08	-0.78	2.66	0.42	1.86
Tennessee	1.08	-2.36	1.08	-1.16	3.44
Texas	1.08	-0.38	3.06	0.82	1.46

Notes: Subsidies, s_i, are in \$ per kg of hydrogen. SCC is $\tau = 185$ per mton. Offsetting has $\epsilon = 1$. "Best Offset" offsets with Carolinas, Midwest, or SouthEast which have highest local externality. "Worst Offset" offsets with Central which has lowest unpriced externality. "Unpriced Externality" is $(\tau - t_i^E)m_i\gamma$ in \$ per kg of hydrogen.

and clean energy are done in the same region, which implies that they have the same marginal emissions rate), and "time-matching" (the electricity consumed by the hydrogen producer temporally matches the production from the clean energy facility it is purchasing power from).[19] On the other hand, those hoping to make hydrogen production financially viable argue for a more flexible offsetting design ([6] and [14]).

Our results suggest that restrictive deliverability rules may not be welfare maximizing and often lead to optimal subsidies below the maximum-IRA-defined \$3/kg-H_2. Our analytic results suggest that with optimal differentiated subsidies, the *Offset* scenario welfare dominates the *RenewNoGrid* scenario, which can be viewed as the strictest implementation of the additional, deliverable, and time-matching qualifiers. Our numerical analysis finds that optimal hydrogen subsidies are the largest when the hydrogen production occurs in regions with relatively low marginal emissions rate and is offset by clean electricity produced in regions with relatively high marginal emission rates. Even then, when we consider the

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[19] See [4], [15], and [17].

"best" offsetting scenario for each of the 13 regions modeled only two regions have optimal subsidies greater than \$3/kg-H_2.

Of course, these optimal hydrogen subsidies with relaxed spatial electricity offsets require accurate, spatially-specific estimates of marginal emission rates. In addition, these marginal emission rates will change over time. There are several methods for obtaining these marginal emission rates. Econometric models can be used to retrospectively assess the marginal emissions associated with increasing load for a certain time segment (e.g. the marginal emissions rate of load for each hour of the day). Similarly, one can estimate, based on historic data, the marginal emissions avoided from an additional MWh of clean energy added to the grid. The marginal emission rates can also be obtained through simulated dispatch modeling (e.g.[3]). The advantage of the simulation-based methods is that they can be used to assess marginal emission rates for hypothetical sets of generating units and load level, allowing one to obtain prospective estimates. This can be useful for determining appropriate subsidies for hydrogen producers entering long-term PPAs. The disadvantage of this approach, however, is that the modeler must make assumptions about plant operations and simplifications of the transmission network to feasibly estimate the effect over the time frequency and spatial scales needed. Provided these methods can be implemented reliably, the welfare gains from allowing more flexible offsetting rules can be achieved while still maintaining environmental integrity.

With respect to additionality, our *REC* procurement scenario clearly show that the optimal subsidy declines with declining additionality of the REC-generating clean energy. The difficulty, of course, is assessing the degree of additionality. Determining the additionality of the clean energy is further complicated by fact that the IRA also provides generous direct production and investment subsidies for various forms of clean energy generation. That is, to assess an additionality claim by a hydrogen producer would require regulators to disentangle the causal effect of the hydrogen producer's procurement agreement with a clean energy generator from the other forms of direct subsidies received by the given generator. Thus, simply determining that a hydrogen producer is meeting the additionality requirements because it contracts with a relatively new clean energy source, such as is done in the European Union, would appear to discount the role that the various direct subsidies have in encouraging investment in clean energy additions.[20] To truly assess the additionality question within the *Offset* or *REC* scenarios that we explore, one would need to more explicitly model the market for PPA's and/or REC's to determine how the addition of hydrogen producers affects the equilibrium prices in these markets. One would then further need to model how these updated PPA and REC prices affect the investment in clean electricity sources. This in-depth modeling is beyond the scope of this paper, but is also not accounted for in the large energy systems models that have analyzed the IRA, as those models do not explicitly calculate PPA and REC market equilibriums.[21] In addition, increasing REC prices may also affect the intensive margins of renewable electricity producers. For example, [10] and [1] find that US Federal PTC increases production from existing wind generators relative to those generators that do not receive the PTC.

Our results also speak to the efficiency loss of uniform subsidies, such as those offered under the IRA.[22] With a constant subsidy and some form of offsetting allowed, hydrogen producers will be incentivized to procure clean electricity in regions with low renewable energy costs (e.g. places with high wind and solar potential) and relatively high electricity prices. This may lead to a quantitative and spatial misallocation of renewable energy facilities relative to what would occur under optimal differentiated subsidies, which adjust for marginal emission differences between where the hydrogen is produced and the clean energy is generated.

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[20] As part of the European Commission's "Fit for 55" plan, they provided various incentives for green hydrogen production. To qualify for these incentives, hydrogen producers must purchase electricity from qualifying, clean electricity generators that are no more than three years old (see https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/electric-power/021323-ec-proposes-phasing-in-additionality-rules-on-renewable-hydrogen-to-2028).

[21] For example, the analyses of the IRA by [9] and [11] use large energy system models with fixed energy demand or fixed energy service demand, that seek the cost minimizing path of energy provision subject to the IRA and other regulatory provisions. These models do not explicitly model PPA contract markets or REC markets and, thus, are not well suited to assessing additionality concerns of offsetting electricity use in hydrogen production via PPAs or RECs.

[22] While the IRA has a tiered system of subsidies, the subsidy is constant for all producers with an assessed emissions intensity at, or below, 0.45 kgCO2e/kg hydrogen.

5 Conclusion

In this paper we consider a model that compares the use of natural gas versus clean hydrogen as an energy source for industrial processes. Although the model is quite general, we highlight the model mechanisms by analyzing four salient electricity procurement types. For each type we determine a theoretical formula for second best subsidies. Calibrating the model shows that most of the time the second best subsidies are lower than those suggested in the IRA.

There are several other issues policy makers would consider which we do not address specifically in our model. One of these issues is hydrogen transportation costs. With strict deliverability requirements, hydrogen producers will be incentivized to build electrolyzers in regions with high solar and wind generation potential. However, if these regions do not geographically align with the hydrogen demand centers and hydrogen transportation costs are high, then restrictive deliverability rules will likely stymie hydrogen investments. Such concerns are more than hypothetical. For example, a potential end use for hydrogen is its application in making steel.[23] About 40 percent of the US steel production comes from facilities in Indiana and Ohio[24], with both states being hundreds of miles east of the wind-intensive regions of Iowa and Minnesota and neither having significant solar potential.

We have also assumed a rather straightforward substitution pattern where hydrogen production offsets natural gas. But, as noted, hydrogen may have numerous end uses. In the short term, the most obvious end use for green hydrogen is the replacement of existing hydrogen derived primarily from natural gas using steam methane reformation (i.e., grey hydrogen). The emissions intensity of grey hydrogen is about twice that of natural gas.[25] Thus, the optimal subsidies under the *RenewNoGrid* procurement method effectively double for each region if green hydrogen offsets grey hydrogen. For the *Offset* procurement case, the grey-to-green hydrogen substitution would result in higher "Best Offset" subsidies as well, ranging from \$2.21-\$4.45/kg-H_2 and passing the IRA's \$3/kg-H_2 mark in five of the 13 regions modeled.[26]

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[23] See https://www.smithsonianmag.com/smart-news/green-steel-produced-first-time-180978550/.

[24] See https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-iron-steel.pdf

[25] Grey hydrogen generates about 12 kg-CO2/kg-H_2, which translates to a CO2 per MMBtu intensity of 230 lbs-CO2/MMBtu, compared to 112 lbs-CO2/MMBtu for natural gas

[26] Other end uses could easily be modeled within this framework by simply inserting the emissions intensity of the competing fuel (β_g).

Finally, the motivation for subsidizing green hydrogen production may go beyond its direct emissions-abatement potential. As with other nascent technologies, innovation market failures, learning-by-doing possibilities, and the potential for economies of scale may keep green hydrogen investment below socially optimal levels, even if it is subsidized at its optimal rate based on its resulting emission reductions.[27] We do not include these additional features to our model, but given that we consistently find the optimal subsidy to be below \$3/kg-H_2 in many regions based on emission reductions from displacing natural gas, these additional features would have to be quite large in many cases to warrant the subsidy rate offered in the IRA.

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[27] See [2] for a recent review of policies to address climate-related, market innovation failures.

References

[1] Joseph E. Aldy, Todd D. Gerarden, and Richard L. Sweeney. Investment versus output subsidies: Implications of alternative incentives for wind energy. *Journal of the Association of Environmental and Resource Economists*, 10(4):981–1018, 2023.

[2] Sarah C. Armitrage, Noel Bakhtian, and Adam B. Jaffe. Innovation market failures and the design of new climate policy instruments. Working Paper 31622, National Bureau of Economic Research, 2023.

[3] Thomas A. Deetjen and Inês L. Azevedo. Reduced-order dispatch model for simulating marginal emissions factors for the United States power sector. *Environmental Science & Technology*, 53(17):10506–10513, 2019. PMID: 31436968.

[4] Dan Esposito, Eric Gimon, and Mike O'Boyle. Smart design of 45v hydrogen production will reduce emissions and grow the industry. *Energy Innovation Policy & Technology LLC*, April 11 2023.

[5] Dolf Gielen, Priyank Lathwal, and Silvia Carolina Lopez Rocha. Unleashing the power of hydrogen in the clean energy transition. `https://blogs.worldbank.org/energy/unleashing-power-hydrogen-clean-energy-transition`, 2023. Accessed on April 25, 2023.

[6] Evan Halper. How a tax break meant to curb climate change could make it worse. *The Washington Post*, Mar 3 2023.

[7] Stephen P. Holland, Matthew J. Kotchen, Erin T. Mansur, and Andrew J. Yates. Why marginal CO2 emissions are not decreasing for US electricity: Estimates and implications for climate policy. *Proceedings of the National Academy of Sciences*, 119:doi.org/10.1073/pnas.2116632119, 2023.

[8] Stephen P Holland, Erin T Mansur, and Andrew J Yates. Decarbonization and electrification in the long run. Working Paper 30082, National Bureau of Economic Research, May 2022.

[9] Jesse D. Jenkins, Erin N. Mayfield, Jamil Farbes, Ryan Jones, Neha Ptankar, Qingyu Xu, and Greg Schivley. Preliminary report: The climate and energy impacts of the Inflation Reduction Act of 2022. Technical report, Princenton University Zero Lab, 2022.

[10] Owen Kay and Michael Ricks. Time-limited subsidies: Optimal taxation with implications for renewable energy subsidies. Working paper, 2023.

[11] John Larsen, Ben King, Hannah Kolus, Naveen Dasari, Galen Hiltbrand, and Whitney Jones. A turning point for US climate progress: Assessing the climate and clean energy provisions in the Inflation Reduction Act. Technical report, Rhodium Group, 2022.

[12] Wilson Ricks, Qingyu Xu, and Jesse D. Jenkins. Minimizing emissions from grid-based hydrogen in the United States. *Environmental Research Letters*, 18:014025, 2023.

[13] Oliver Ruhnau and Johanna Schiele. Flexible green hydrogen: The effect of relaxing simultaneity requirements on project design, economics, and power sector emissions. *Energy Policy*, 182:113763, 2023.

[14] Oliver Ruhnau and Johanna Schiele. Flexible green hydrogen: The effect of relaxing simultaneity requirements on project design, economics, and power sector emissions. *Energy Policy*, 182:113763, 2023.

[15] Leah Stokes. Before we invest billions in this clean fuel, let's make sure it's actually clean. *The New York Times*, April 14 2023.

[16] Melany Vargas, Kara McNutt, and Chris Seiple. Green hydrogen: What the Inflation Reduction Act means for production economics and carbon intensity. *Wood Mackenzie: Opinion*, 2023. Accessed on April 25, 2023.

[17] Gernot Wagner and Danny Cullenward. Get tax right or clean hydrogen will be bigger boondoggle than biofuels. *The Washington Post*, April 27 2023.

Appendix

A.1 Proofs

Proof of Lemma 1

Lemma 1 *For* $J+1$ *offsetting options and an arbitrary subsidy vector* s*, the firm's profit-maximizing procurement choice is* $j^e = \text{argmin}_j\{-p^E_j\gamma + c'_{Sj}\gamma - s_j\}$ *and the firm's net-of-subsidy marginal cost is* $\mathcal{PC}'(q_H, s) \equiv c'_H(q_H) + p^E_1\gamma + \min_j\{-p^E_j\gamma + c'_{Sj}\gamma - s_j\}$.

Welfare maximizing procurement is $j^* = \text{argmin}_j\{-(c^E_j + \tau m_j)\gamma + c'_{Sj}\gamma\}$ *and the social marginal cost is* $\mathcal{SC}'(q_H) \equiv c'_H(q_H) + (c^E_1 + \tau m_1)\gamma + \min_j\{-(c^E_j + \tau m_j)\gamma + c'_{Sj}\gamma\}$.

Proof: Define $j^e \equiv \text{argmin}_j\{-p^E_j\gamma + c'_{Sj}\gamma - s_j\}$. Define the profit function for procurement method j and arbitrary hydrogen production q as $\pi_j(q) \equiv pq - c_H(q) - p^E_1\gamma q + p^E_j\gamma q - c'_{Sj}\gamma q + s_j q$. For every j and arbitrary q, we have $\pi_j(q) \le \pi_{j^e}(q)$ because

$$\pi_j(q) = \int_0^q p - c'_H(t) - p^E_1\gamma + p^E_j\gamma - c'_{Sj}\gamma + s_j dt$$

$$\le \int_0^q p - c'_H(t) - p^E_1\gamma + p^E_{j^e}\gamma - c'_{Sj^e}\gamma + s_{j^e} dt = \pi_{j^e}(q)$$

where the inequality follows from the definition of j^e. Define $q^e_j \equiv \text{argmax}_q\, \pi_j(q)$. Using the inequality above, we have $\pi_j(q^e_j) \le \pi_{j^e}(q^e_j) \le \pi_{j^e}(q^e_{j^e})$ for every j. But this implies that $\pi_{j^e}(q^e_{j^e})$ is the profit maximum, and the firm's profit-maximizing procurement choice is j^e.

The firm's net-of-subsidy marginal cost is then

$$\mathcal{PC}'(q_H, s) \equiv c'_H(q_H) + p^E_1\gamma - p^E_{j^e}\gamma + c'_{Sj^e}\gamma - s_{j^e}$$

$$= c'_H(q_H) + p^E_1\gamma + \min_j\{-p^E_j\gamma + c'_{Sj}\gamma - s_j\}.$$

For welfare maximizing procurement, define $j^* \equiv \text{argmin}_j\{-(c^E_j + \tau m_j)\gamma + c'_{Sj}\gamma\}$. Parallel to above, define the welfare gain for procurement method j and arbitrary hydrogen production q as $W_j(q) \equiv (C'_G + \tau\beta_G)q - c_H(q) - (c^E_1 + \tau m_1)\gamma q + (c^E_j + \tau m_j)\gamma q - c'_{Sj}\gamma q$. As above, taking the integral implies that $W_j(q) \le W_{j^*}(q)$ for every j, which implies that j^* is the welfare maximizing procurement choice. ■

Proof of Result 1

Result 1 *If subsidies are optimal for* $J+1$ *offsetting options, then* $j^e = j^*$ *and* $q^e_H = q^*_H$.

Proof: Substitution of the optimal subsidies from Eq. 10 into $j^e = \text{argmin}_j\{-p^E_j\gamma + c'_{Sj}\gamma - s_j\}$ implies:

$$j^e = \underset{j}{\text{argmin}}\{-p^E_j\gamma + c'_{Sj}\gamma - \big((\tau - t^G)\beta_G - (\tau - t^E_1)m_1\gamma + (\tau - t^E_j)m_j\gamma\big)\}$$

$$= \underset{j}{\text{argmin}}\{-p^E_j\gamma + c'_{Sj}\gamma - (\tau - t^E_j)m_j\gamma\}.$$

Using Eq. 7, we have

$$= \operatorname*{argmin}_{j}\{-(c_j^E + t_j^E m_j)\gamma + c'_{Sj}\gamma - (\tau - t_j^E)m_j\gamma\}$$

$$= \operatorname*{argmin}_{j}\{-(c_j^E + \tau m_j)\gamma + c'_{Sj}\gamma\} = j^*.$$

The equilibrium hydrogen production, q_H^e, is determined by $C'_G + t^G\beta_G = \mathcal{PC}'(q_H^e, s^*)$ which implies:

$$C'_G = \mathcal{PC}'(q_H^e, s^*) - t^G\beta_G$$
$$= c'_H(q_H^e) + p_1^E\gamma - p_{j^e}^E\gamma + c'_{Sj^e}\gamma - s_{j^e} - t^G\beta_G.$$

Using Eq. 7, we have

$$= c'_H(q_H^e) + p_1^E\gamma - p_{j^e}^E\gamma + c'_{Sj^e}\gamma - \Big((\tau - t^G)\beta_G - (\tau - t_1^E)m_1\gamma + (\tau - t_{j^e}^E)m_{j^*}\gamma\Big) - t^G\beta_G$$

$$= c'_H(q_H^e) + (c_1^E + \tau m_1)\gamma - (c_{j^e}^E + \tau m_{j^e})\gamma + c'_{Sj^e}\gamma - \tau\beta_G. \tag{12}$$

Because the welfare optimizing hydrogen production, q_H^*, is determined by $C'_G + \tau\beta_G = \mathcal{SC}'(q_H^*)$, we have

$$C'_G = \mathcal{SC}'(q_H^*) - \tau\beta_G$$
$$= c'_H(q_H^*) + (c_1^E + \tau m_1)\gamma - (c_{j^*}^E + \tau m_{j^*})\gamma + c'_{Sj^*}\gamma - \tau\beta_G.$$

Comparing this equation with Eq. 12 and recalling that $j^e = j^*$ implies that $q_H^e = q_H^*$. ■

Proof of Corollary 1

Corollary 1 *If subsidies are optimal for* $J + 1$ *offsetting options, then allowing offsetting to regions* $2, 3, ...J$ *(weakly) increases welfare relative to* Grid *or* RenewNoGrid.

Proof: If the regulator allows offsetting to a set of regions and if all subsidies are optimal, then Result 1 implies that the firm chooses the socially optimal procurement and produces the welfare maximizing hydrogen quantity. This implies that the firm chooses offsetting to one of regions $2, 3, ...J$ if and only if it increases social welfare. Therefore allowing offsetting cannot reduce welfare and weakly increases welfare relative to *Grid* or *RenewNoGrid.*■

Proof of Result 2

Result 2 *If subsidies are optimal for all* $2J + 1$ *offsetting and REC options, then* $i)$ *offsets strictly welfare dominate RECs if RECs are not fully additional, i.e., if* $\delta < 1$, *and* $ii)$ *offsets and RECs are equivalent if RECs are fully additional, i.e., if* $\delta = 1$.

Proof: For offsetting the social marginal cost is

$$\mathcal{SC}'(q_H) = c_H(q_{Hi}) + (c_1^E + \tau m_1)\gamma + \min_j\{-(c_j^E + \tau m_j)\gamma + c'_{Sj}\gamma\}$$

and for *REC* the social marginal cost is

$$\mathcal{SC}'(q_H) = c_H(q_{Hi}) + (c_1^E + \tau m_1)\gamma + \min_j\{-(c_j^E + \tau m_j)\gamma\delta + c'_{Sj}\gamma\delta\}.$$

Because the null region has $-(c_0^E+\tau m_0)\gamma+c'_{S0}\gamma=0$, we have $\min_j\{-(c_j^E+\tau m_j)\gamma+c'_{Sj}\gamma\}\le 0$, and it follows that the social marginal cost for offsetting is less than for *REC* and is equal if $\delta=1$. Noting that lower social marginal cost has higher welfare demonstrates the result.

Proof of Result 3

Result 3 *Assume the* $J+1$ *offsetting options face the same (uniform) subsidy. Allowing offsetting to regions* $2,3,...,J$ *increases welfare relative to* Grid. *Allowing offsetting to region* $j\in\{2,3,...,J\}$ *cannot decrease welfare relative to* RenewNoGrid *if* $(\tau-t_1^E)m_1<(\tau-t_j^E)m_j$.

Proof: With a uniform subsidy $s_j=s$ for all j, the formula in Lemma 1 simplifies to $j^e=\operatorname{argmin}_j\{-p_j^E+c'_{Sj}\}$. Because $-p_0^E+c'_{S0}=0$ by the definition of the null region, it must be that $-p_j^E+c'_{Sj}<0$ if the firm offsets in region j. But because $p_j^E<c_j^E+\tau m_j$ this implies that $-(c_j^E+\tau m_j)+c'_{Sj}<0$. Since $-(c_0^E+\tau m_0)+c'_{S0}=0$ by the definition of the null region, applying the welfare optimizing procurement formula in Lemma 1 shows that offsetting to region j increases welfare relative to *Grid*.

Suppose $(\tau-t_1^E)m_1<(\tau-t_j^E)m_j$, the firm chooses procurement in region j relative to *RenewNoGrid*, and that this choice decreases welfare. Relative to *RenewNoGrid*, the formula $j^e=\operatorname{argmin}_j\{-p_j^E+c'_{Sj}\}$ implies the firm chooses procurement in region j if $-p_j^E+c'_{Sj}<-p_1^E+c'_{S1}$ or equivalently if

$$p_1^E-p_j^E<c'_{S1}-c'_{Sj}. \tag{13}$$

Applying the welfare optimizing formula in Lemma 1 shows that this *lowers* welfare if $-(c_1^E+\tau m_1)+c'_{S1}<-(c_j^E+\tau m_j)+c'_{Sj}$ or equivalently

$$c'_{S1}-c'_{Sj}<(c_1^E+\tau m_1)-(c_j^E+\tau m_j). \tag{14}$$

Eqs. 13 and 14 imply $(p_1^E-p_j^E)<(c_1^E+\tau m_1)-(c_j^E+\tau m_j)$. Using Eq. 7, we have $(\tau-t_j^E)m_j<(\tau-t_1^E)m_1$ which contradicts the assumption.

A.2 Appendix Tables

Table A.1: Taxes and marginal emissions

Region	t_i^G	t_i^E	m_i
California	30	30	0.4505
Non Calif. West	0	0	0.4505
Texas	0	0	0.4923
RGGI East	0	12.5	0.6384
Non RGGI East	0	0	0.6384

Notes: t_i^G and t_i^E are carbon prices ($/mton) in AB32 and RGGI. m_i is mton/MWh from [7].

Table A.2: Taxes and long-run marginal emissions for EIA regions

Region	t_i^G	t_i^E	m_i	m_i
California	30	30	0.338	0.240
Carolinas	0	0	0.338	0.338
Central	0	0	0.338	0.118
Florida	0	0	0.338	0.337
MidAtlantic	0	12.5	0.338	0.338
MidWest	0	0	0.338	0.338
New England	0	12.5	0.338	0.338
NorthWest	0	0	0.338	0.247
New York	0	12.5	0.338	0.338
SouthEast	0	0	0.338	0.338
SouthWest	0	0	0.338	0.183
Tennessee	0	0	0.338	0.338
Texas	0	0	0.332	0.143

Notes: t_i^G and t_i^E are carbon prices (\$/mton) in AB32 and RGGI. m_i is mton/MWh from [8] for baseline and 25% reduction in renewable costs.

Table A.3: Carbon emissions rates

		Offset region				
Electrolysis			Non-Calif.	Texas	RGGI East	Non-RGGI
Region	Grid	California	West	Texas	RGGI East	East
California	0.0248	0	0	-0.002	-0.010	-0.010
Non-Calif. West	0.0248	0	0	-0.002	-0.010	-0.010
Texas	0.0271	0.002	0.002	0	-0.008	-0.008
RGGI East	0.0351	0.010	0.010	0.008	0	0
Non-RGGI East	0.0351	0.010	0.010	0.008	0	0

Notes: Emissions are in mton per kg of hydrogen. To receive the full subsidy, electrolysis emissions must be less than 0.45 kg CO2 per kg of hydrogen or 0.00045 mton per kg.