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The EU electricity market: Renewables targets, Tradable Green Certificates and electricity trade☆

Ourania Karakosta [a], Dimitra Petropoulou [b,*]

[a] Department of Economics, University of Ioannina, Ioannina 451 10, Greece
[b] Department of Economics, London School of Economics, London, WC2A 2AE, United Kingdom

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ABSTRACT

Several EU member states have introduced national systems of Tradable Green Certificates (TGCs), which stipulate the percentage of total energy consumption to be obtained from renewable sources. The Renewable Energy Directive sets a binding EU-wide target of 32% but without imposing legally binding national targets. To assess incentives for the choice of national percentage requirements we develop a two-country, Cournot duopoly model of the electricity market, with one "green" and one "black" supplier in each country. We show that nationally determined percentage requirements do not align with the EU-welfare maximising renewable energy target due to cross-country externalities arising from trade in electricity and the market price of TGCs and examine the direction of misalignment. Our results cast doubts on the feasibility of EU renewable energy policy in the absence of binding national targets and inform how national targets should be shaped.

1. Introduction

In recent years, many countries have promoted the production of electricity from renewable energy sources, such as wind, solar and biomass. European Union (EU) member states, many U.S. states and Australia, among others, require a share of total electricity to come from renewable energy. In 2008, the EU's Renewable energy directive set a binding target of 20% of EU energy consumption must come from renewable sources by 2020. This was complemented with legally binding national targets for EU countries, ranging from a 10% requirement for Malta to a 49% requirement for Sweden, jointly intended to achieve the EU-wide target.

The revised Renewable Energy Directive establishes a binding EU target of at least 32% for 2030 without imposing legally binding national targets. That is, the 32% target is binding only upon the EU as a whole. The absence of binding national targets raises questions as to whether nationally determined percentage requirements can be expected to jointly meet the stipulated EU target and how international linkages influence incentives for the choice of percentage requirements. The objective of this paper is to explore the international spillovers arising from the non-cooperative setting of the percentage requirements for green electricity. More precisely, what is the impact that the domestic percentage requirement for green electricity has on the welfare of other countries? How does the equilibrium percentage requirement chosen non-cooperatively by national policymakers compare to that chosen by a supranational authority, such as the EU? Under what circumstances will national policymakers over- or under-regulate, relative to the global optimum?

To implement their renewable energy targets many countries have introduced a system of Tradable Green Certificates (TGCs), also known as Renewable Energy Certificates or Renewable Portfolio Standards (in the U.S), or Renewable Obligation Certificates (in the UK)[1] (see, for example, Amundsen and Mortensen (2001), Linares et al. (2008), Amundsen and Bergman (2012)). This is a market-based regulatory system where "green" producers are issued with a certificate per unit of production, which can be sold at the prevailing certificate price. In turn "black" electricity producers and importers are required to purchase a specific number of certificates from green producers per unit of electricity injected into the grid. This creates a market for green certificates, while the stipulated percentage of total energy consumption to be obtained from renewable sources serves as an important policy instrument (the "percentage requirement"). The percentage requirement influences the level of green and black electricity production, and thus the level of environmental damage. At the same time, there exist important international linkages between countries through the

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* Corresponding author.
E-mail addresses: okarakosta@uoi.gr (O. Karakosta), d.petropoulou@lse.ac.uk (D. Petropoulou).

[1] Other policy instruments used by governments to promote green electricity include feed-in tariffs (i.e., subsidies to green producers) and tax incentives.

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development of interconnectors between national grids that have facilitated international trade in electricity, the flows of which contribute to energy consumption and thus national targets. Moreover, there is the potential for integration of TGC markets, such as the Swedish–Norwegian common electricity certificate market introduced in January 2012.

An important question arising from the widespread introduction of TGC markets is how policy-makers determine the optimal percentage requirement in the presence of international linkages. This paper develops a two-country, Cournot duopoly model of the electricity market, in order to analyse incentives for national renewable energy policy decisions in an open economy setting. It builds on the one-country framework of Currier and Rassouli-Currier (2012) to explore how international linkages through integrated TGC markets and international trade in electricity impact on national decision making. While the related literature treats the percentage requirement as an exogenous parameter, we endogenise the choice of percentage requirement in an open economy setting.

Each country is assumed to have one renewable electricity supplier ("green") and one fossil fuel electricity supplier ("black"), where carbon emissions from black electricity contribute to an environmental damage function. In such a framework nationally determined percentage requirements do not align with the global-welfare maximising renewable energy target due to cross-country externalities arising from trade in electricity and the market price of TGCs. We identify these externalities and illustrate the forces at work. In particular, international links between electricity markets cause the domestic percentage requirement to impact foreign welfare through (a) profits of overseas electricity suppliers, (b) overseas pollution damage and (c) the market price of TGC. We show that, under some circumstances, these externalities drive national decision-makers to under-regulate relative to the global optimum, suggesting serious limitations to the feasibility of 2030 EU renewables target in the absence of binding national targets.

A growing literature has explored the effects of TGC markets. One of the earliest contributions is Mozumder and Marathe (2004), which discusses the tradable renewable energy certificates market in different countries and examine the gains from trade in these certificates. The first to endogenise the TGC market percentage requirement of green electricity in a single country with a Cournot duopoly with one green and one black producer is Currier and Rassouli-Currier (2012). They do not obtain an analytical solution for the optimal percentage requirement, but Currier (2013) presents a regulatory adjustment process that computes the optimal percentage requirement iteratively in a Cournot oligopoly.

Other contributions to the literature explore TGC markets in multi-country frameworks. Amundsen and Nese (2009) show that the percentage requirement guarantees only an increase in the *share* of green electricity in total consumption, while the absolute *level* of green electricity may rise or fall (though black electricity strictly falls). Their findings hold under autarky and when electricity, or both electricity and TGCs, are traded between two countries. More recently, Aune et al. (2012) assume a perfectly competitive energy market with free trade, and evaluate the cost efficiency of meeting the overall EU target under three scenarios, (i) common national targets and integrated TGC markets, (ii) differentiated national targets and integrated TGC markets, and (iii) differentiated national targets with segmented TGC markets. They find that a common renewable target combined with an integrated market in green certificates leads to the most efficient solution. Both these contributions, however, treat the renewable targets are exogenous and so cannot shed light on how international linkages impact on national versus international decision-making.

Sun (2016) draws from Aune et al. (2012) and Currier and Rassouli-Currier (2012) to analyse a perfectly competitive electricity market[2] with two countries, where the percentage requirement is chosen optimally in a common TGC market. While the percentage requirement is endogenous, the focus of the analysis is on a welfare comparison between a common certificate market (with a single optimally chosen share) and a number of different scenarios, such as the case where there are only black producers regulated by a CO_2 emissions standard. In contrast, we employ an imperfectly competitive framework and allow country shares to be distinct,[3] modelling integration of TGC markets in terms of a common price for certificates; this allows national versus international decision-making regarding percentage requirements to be explicitly contrasted.

Several papers model the interaction of TGC markets with other policy instruments. For example, Amundsen and Nese (2009) show that the emission permit price/emission tax affects the TGC price, impacting on green electricity generation. Menanteau et al. (2003) show that a feed-in tariff system is superior a TGC system in terms of installed capacity and incentive effects. Tamas et al. (2010) compare feed-in tariff and TGC systems in an oligopolistic market and show that for a wide range of parameter values both black and green energy output is higher, while social welfare is lower, under a feed-in tariff. Sun and Nie (2015) show that, when a monopoly first chooses R&D and then the quantity of energy, a feed-in tariff is more efficient than TGCs as a means of increasing the quantity of renewable energy and stimulating cost-reducing R&D input to reduce costs. Finally, Von der Fehr and Ropenus (2017) model the case of a dominant electricity producer of both conventional and renewable energy that faces a fringe of price-taking producers of renewable energy, and explore whether the dominant firm squeezes competitor margins by distorting certificates prices. Furthermore, they compare this outcome with the case in which renewables are regulated by a feed-in tariff.

We contribute to the literature by focusing on the externalities arising from the non-cooperative setting of the percentage requirements for green electricity in a two-country setting. With international trade in electricity between two countries and segmented TGCs markets, a change in the share of renewables in one country reduces the exports of the foreign non-renewable energy producer and so impacts the pollution level abroad as well as the profit of foreign firms. We show the direction of the resulting externality depends on the environmental parameter, with the possibility of national policy-makers either over-regulating (when damage is low) or under-regulating (when damage is high) relative to the global welfare maximising percentage requirement. In the case of integrated TGCs markets, a change in the domestic share of renewables affects the price of the green certificates, which in turn impacts foreign welfare. The resulting positive externality results in under-regulation by each policy-makers relative to the global welfare-maximising percentage requirement.

The rest of the paper is structured as follows. Section 2 introduces the benchmark closed economy model with segmented TGC markets. Section 3 analyses the choice of percentage requirements with international trade in electricity and segmented TGCs market, while Section 4 explores the choice of percentage requirements with integrated market for TGCs. In Section 5 we analyse transboundary pollution before examining the impact of cross-country heterogeneity in Section 6. Section 7 concludes.

[2] The literature has explored how market structure affects the impact of TGC markets. Zhou and Tamas (2010) examine how mergers between green and black electricity companies affect the performance of the TGC system. Tanaka and Chen (2013) examine how the market power of suppliers affects the way electricity price and the certificate price change with the percentage requirement. Zhou and Liu (2015) show that where regional suppliers are small relative to the national market green power output decreases with the renewable energy percentage but increases with the TGC price.

[3] Note, integration of TGC markets does not require national percentage requirements to converge. For example, Sweden aims for a 50.2% share of renewables in consumption of electricity by 2020, while Norway aims for 67.5% by 2020, even though they share a common market for green certificates since January 2012.

2. The benchmark model

This section outlines the benchmark model, where TGC markets are segmented, there is no international trade in electricity and environmental damage from black electricity is contained within the country in which it is produced. In these distinct circumstances, where international links are severed, we show that policy-makers in each country choose the renewable percentage requirement optimally, and in doing so jointly maximise global welfare. Subsequent sections sequentially relax these assumptions.

Consider two countries, Home and Foreign, denoted by $j \in \{H, F\}$. Each country has an electricity industry served by two firms: a "black" producer, whose electricity production is generated by fossil-fuels (y_j), and one "green" producer, whose electricity production is generated from renewable energy sources (x_j). The total supply of electricity is denoted by $q_j \equiv x_j + y_j$. Black and green electricity are produced under constant marginal cost technology, where $c_{xj} > c_{yj}$; that is, green electricity is costlier to generate than black electricity. For simplicity, we abstract from uncertainty in production and assume firms do not face any capacity constraints.

Black electricity production gives rise to environmental damage, which is assumed to be contained within the country it is produced. In particular, let the damage function be symmetric across countries and given by $D(y_j) = \frac{b}{2}y_j^2$, for which $D' > 0$ and $D'' > 0$.

Demand for electricity in each country follows from consumer maximisation of consumer surplus, $V_j \equiv U(q_j) - p_j q_j$, where U denotes total consumer utility from electricity consumption, assumed symmetric across countries, and p_j denotes the price of electricity by final consumers in country j. Note that consumers do not distinguish between green and black electricity. In particular, let $U(q_j) = f q_j - \frac{q_j^2}{2}$, so maximisation of consumer surplus in each market gives rise to inverse demand functions $p_j(q_j) = f - q_j$.

For now, assume the TGC markets are segmented, where p_{cj} denotes the price of green certificates in country j. In each country, the green producer is issued with a certificate per unit of production, which can be sold at the prevailing certificate price. At the same time, both producers in each country are required to surrender α_j TGCs per unit of production, at a cost of $\alpha_j p_{cj}$. It follows that the supply of green certificates is x_j, while total demand for green certificates is $\alpha_j (x_j + y_j)$. TGC market clearing thus implies $x_j = \alpha_j (x_j + y_j)$, from which it follows that:

$$\alpha_j = \frac{x_j}{x_j + y_j}. \tag{1}$$

Hence $\alpha_j \in [0, 1]$ reflects the percentage requirement policy instrument in j, which pins down the share of renewable electricity in total consumption.

The profit functions of green and black producers are thus given by (2)–(3), where the TGC system implies a transfer from the black to the green producer. Assuming Cournot behaviour, each firm chooses quantity to maximise profit, given the percentage requirement and the quantity of their competitor.

$$\Pi_{G_j} = p_j (x_j + y_j) x_j - c_{x_j} x_j + (1 - \alpha_j) p_{cj} x_j \tag{2}$$

$$\Pi_{Bj} = p_j (x_j + y_j) y_j - c_{y_j} y_j - \alpha_j p_{cj} y_j. \tag{3}$$

So the green producer sells $(1 - \alpha_j) x_j$ certificates at the prevailing certificate price p_{cj} while the black producer needs to buy $\alpha_j y_j$ certificates.

Social welfare in j is denoted by W_j and defined as the sum of consumer surplus and profits net of environmental damage. It follows that when the TGC market clears[4]:

$$W_j \equiv V_j + \Pi_{G_j} + \Pi_{B_j} - D_j = U(q_j) - c_{x_j} x_j - c_{y_j} y_j - D(y_j). \tag{4}$$

[4] This is as in Proposition 1 of Currier and Rassouli-Currier (2012).

Policy-makers in Home and Foreign regulate the share of renewables electricity by unilaterally setting the percentage requirement in stage 1, prior to the strategic interaction of electricity producers. They select α_H and α_F, respectively, to maximise national welfare, anticipating firms' quantity decision. The subgame perfect equilibrium of electricity quantities and percentage requirements is found by backward induction.

2.1. The regulated Cournot equilibrium

Firms compete in quantities in stage 2, given stage 1 percentage requirement levels. Maximising profits and solving the first order conditions, assuming TGC clearing, gives rise to stage 1 production levels, as well as electricity and green certificates prices in Home and Foreign as functions of the percentage requirement and core parameters. These are given by:

$$y_j = \frac{(1-\alpha_j)}{2} \frac{f - (1-\alpha_j) c_{y_j} - \alpha_j c_{x_j}}{1 - \alpha_j + \alpha_j^2}, \tag{5}$$

$$x_j = \frac{\alpha_j}{2} \frac{f - (1-\alpha_j) c_{y_j} - \alpha_j c_{x_j}}{1 - \alpha_j + \alpha_j^2}, \tag{6}$$

$$q_j = \frac{1}{2} \frac{f - (1-\alpha_j) c_{y_j} - \alpha_j c_{x_j}}{1 - \alpha_j + \alpha_j^2} \tag{7}$$

$$p_{cj} = \frac{1}{2} \frac{(2\alpha_j - 1) f + (2 - \alpha_j) c_{x_j} - (1 + \alpha_j) c_{y_j}}{1 - \alpha_j + \alpha_j^2}, \tag{8}$$

$$p_j = \frac{1}{2} \frac{\left(2\alpha_j^2 - 2\alpha_j + 1\right) f + \alpha_j c_{x_j} + (1 - \alpha_j) c_{y_j}}{1 - \alpha_j + \alpha_j^2}. \tag{9}$$

Let f be sufficiently large such that $f > \alpha_j c_{xj} + (1 - \alpha_j) c_{yj}$ $\forall \alpha_j$, ensuring green and black electricity production is non-negative in both countries. Note that electricity production and price where $p_{cj} = 0$ correspond to the unregulated Cournot equilibrium in Home and Foreign without a TGC market. It follows from (8) that the corresponding proportion of green electricity is $\alpha_j^C \equiv \frac{f - 2c_{xj} + c_{yj}}{2f - c_{xj} - c_{yj}}$. If we further assume $f > 2c_{xj} - c_{yj} > c_{xj}$, then[5] $\alpha_j^C \in (0, 1)$, so the policy space for the percentage requirement of the TGC system is $\alpha_j \in \left[\frac{f - 2c_{xj} + c_{yj}}{2f - c_{xj} - c_{yj}}, 1\right]$ where $p_{cj} \geq 0$, and similarly for Foreign. Finally, electricity price is positive for all parameter values.[6]

Substituting (5)–(9) into (2), (3), V_j and D_j, gives profits of the green and black producers, consumer surplus and environmental damage as functions of exogenous parameters and the percentage requirement.

$$\Pi_{Gj} = \frac{\alpha_j^2 \left(f - (1-\alpha_j) c_{yj} - \alpha_j c_{xj}\right)^2}{4 \left(1 - \alpha_j + \alpha_j^2\right)^2}, \tag{10}$$

$$\Pi_{Bj} = \frac{(1-\alpha_j)^2 \left(f - (1-\alpha_j) c_{yj} - \alpha_j c_{xj}\right)^2}{4 \left(1 - \alpha_j + \alpha_j^2\right)^2}, \tag{11}$$

$$V_j = \frac{\left(f - (1-\alpha_j) c_{yj} - \alpha_j c_{xj}\right)^2}{8 \left(1 - \alpha_j + \alpha_j^2\right)^2}, \tag{12}$$

$$D_j = b \frac{(1-\alpha_j)^2 \left(f - (1-\alpha_j) c_{yj} - \alpha_j c_{xj}\right)^2}{8 \left(1 - \alpha_j + \alpha_j^2\right)^2}. \tag{13}$$

[5] We can rewrite the lower bound on α_j as $\alpha_j^C \equiv \frac{f - 2c_{xj} + c_{yj}}{2f - c_{xj} - c_{yj}} = \frac{f - 2c_{xj} + c_{yj}}{(f - 2c_{xj} + c_{yj}) + (f + c_{xj} - 2c_{yj})}$, which is between 0 and 1 if (i) $f > 2c_{xj} - c_{yj}$ and (ii) $f > 2c_{yj} - c_{xj}$. However, since $c_{xj} > c_{yj}$, it follows that (ii) is satisfied when (i) holds. Thus $f > 2c_{xj} - c_{yj}$ is a sufficient condition for $\alpha_j^C \in (0, 1)$.

[6] It follows from (9) that $p_j > 0$ provided $f > -\frac{(1-\alpha)c_{yj} + \alpha c_{xj}}{2\alpha_j^2 - 2\alpha_j + 1}$; this condition is always satisfied since $f > 0$.

From (5)–(13) we can assess how the choice of percentage requirement in stage 1 affects the stage 2 equilibrium. As in related work (see Currier and Rassouli-Currier (2012) and Amundsen and Nese (2009), the following Lemmas show that an increase in the percentage requirement unambiguously lowers the production of black electricity, while the relationship between the percentage requirement and green electricity is non-monotonic. The combined effect is for total production of electricity to be non-monotonic in α_j, and similarly the electricity price since $p_j = f - q_j$. As the production of black electricity shrinks, so does the level of environmental damage.

From (2)–(3) we can see that an increase in the percentage requirement acts as if to shock the marginal cost of the black producer upwards and that of the green producer downwards. This shifts market share towards green electricity, while the market power of the green producer grows. For weak regulation, total electricity production rises and electricity prices fall with the percentage requirement, while with strong regulation the monopoly power afforded the green producer constrains production driving up the price of electricity and lowering consumer surplus.

More specifically:

Lemma 1. *Black electricity production, profit and environmental damage are strictly decreasing with the percentage requirement.*

Proof. $\frac{dy_j}{d\alpha_j} = -\frac{\alpha_j(2-\alpha_j)(f-c_{xj})+\left(1-\alpha_j^2\right)(c_{xj}-c_{yj})}{2(1-\alpha_j+\alpha_j{}^2)^2} < 0$, $\frac{d\Pi_{Bj}}{d\alpha_j} = -\frac{(1-\alpha_j)(f-(1-\alpha_j)c_{yj}-\alpha_j c_{xj})\left[\alpha_j(2-\alpha_j)(f-c_{xj})+\left(1-\alpha_j^2\right)(c_{xj}-c_{yj})\right]}{2(1-\alpha_j+\alpha_j{}^2)^3} < 0$ and $\frac{dD_j}{d\alpha_j} = -\frac{b(1-\alpha_j)(f-(1-\alpha_j)c_{yj}-\alpha_j c_{xj})\left[\alpha_j(2-\alpha_j)(f-c_{xj})+\left(1-\alpha_j^2\right)(c_{xj}-c_{yj})\right]}{4(1-\alpha_j+\alpha_j{}^2)^3} < 0$ since $\alpha_j \in (0,1)$, $c_{xj} > c_{yj}$, $f > \alpha_j c_{xj} + \left(1-\alpha_j\right)c_{yj}$ $\forall \alpha_j$ and $f > c_{xj}$. ■

Lemma 2. *Green electricity production and profit increase with the percentage requirement over the interval*
$\alpha_j \in [\frac{f-2c_{xj}+c_{yj}}{2f-c_{xj}-c_{yj}}, \frac{\left((f-c_{yj})(f-c_{xj})+(c_{xj}-c_{yj})^2\right)^{\frac{1}{2}}+c_{yj}-c_{xj}}{f-c_{xj}})$
and decrease over the interval $\alpha_j \in (\frac{\left((f-c_{yj})(f-c_{xj})+(c_{xj}-c_{yj})^2\right)^{\frac{1}{2}}+c_{yj}-c_{xj}}{f-c_{xj}}, 1]$.

Proof. $\frac{dx_j}{d\alpha_j} = \frac{\left(1-\alpha_j^2\right)(f-c_{xj})+(1-2\alpha_j)(c_{xj}-c_{yj})}{2(1-\alpha_j+\alpha_j{}^2)^2} = 0$ and $\frac{d\Pi_{Gj}}{d\alpha_j} = \frac{\alpha_j(f-(1-\alpha_j)c_{yj}-\alpha_j c_{xj})\left[\left(1-\alpha_j^2\right)(f-c_{xj})+(1-2\alpha_j)(c_{xj}-c_{yj})\right]}{2(1-\alpha_j+\alpha_j{}^2)^3} = 0$ at $\alpha_j = \frac{\left((f-c_{yj})(f-c_{xj})+(c_{xj}-c_{yj})^2\right)^{\frac{1}{2}}-(c_{xj}-c_{yj})}{f-c_{xj}} \in (\frac{f-2c_{xj}+c_{yj}}{2f-c_{xj}-c_{yj}}, 1]$ and $\alpha_j = \frac{-\left((f-c_{yj})(f-c_{xj})+(c_{xj}-c_{yj})^2\right)^{\frac{1}{2}}-(c_{xj}-c_{yj})}{f-c_{xj}} < 0$; discard the negative root; $\frac{dx_j}{d\alpha_j} > 0$ and $\frac{d\Pi_{Gj}}{d\alpha_j} > 0$ if $\alpha_j \in [\frac{f-2c_{xj}+c_{yj}}{2f-c_{xj}-c_{yj}}, \frac{\left((f-c_{yj})(f-c_{xj})+(c_{xj}-c_{yj})^2\right)^{\frac{1}{2}}+c_{yj}-c_{xj}}{f-c_{xj}})$, $\frac{dx_j}{d\alpha_j} < 0$ and $\frac{d\Pi_{Gj}}{d\alpha_j} < 0$ if $\alpha_j \in (\frac{\left((f-c_{yj})(f-c_{xj})+(c_{xj}-c_{yj})^2\right)^{\frac{1}{2}}+c_{yj}-c_{xj}}{f-c_{xj}}, 1]$. ■

Lemma 3. *Total electricity production and consumer surplus increase (and the price of electricity decreases) with the percentage requirement over the interval* $\alpha_j \in [\frac{f-2c_{xj}+c_{yj}}{2f-c_{xj}-c_{yj}}, \frac{f-c_{yj}-\left((f-c_{yj})(f-c_{xj})+(c_{xj}-c_{yj})^2\right)^{\frac{1}{2}}}{c_{xj}-c_{yj}})$ *and decrease (increases) over the interval* $\alpha_j \in (\frac{f-c_{yj}-\left((f-c_{yj})(f-c_{xj})+(c_{xj}-c_{yj})^2\right)^{\frac{1}{2}}}{c_{xj}-c_{yj}}, 1]$.

Proof. $\frac{dq_j}{d\alpha_j} = \frac{(1-2\alpha_j)(f-c_{yj})-\left(1-\alpha_j^2\right)(c_{xj}-c_{yj})}{2(1-\alpha_j+\alpha_j{}^2)^2} = 0$ and $\frac{dV_j}{d\alpha_j} = \frac{(f-(1-\alpha_j)c_{yj}-\alpha_j c_{xj})\left[(1-2\alpha_j)(f-c_{yj})-\left(1-\alpha_j^2\right)(c_{xj}-c_{yj})\right]}{4(1-\alpha_j+\alpha_j{}^2)^3} = 0$ at $\alpha_j = \frac{f-c_{yj}-\left((f-c_{yj})(f-c_{xj})+(c_{xj}-c_{yj})^2\right)^{\frac{1}{2}}}{c_{xj}-c_{yj}} \in (\frac{f-2c_{xj}+c_{yj}}{2f-c_{xj}-c_{yj}}, 1]$ and $\alpha_j = \frac{f-c_{yj}+\left((f-c_{yj})(f-c_{xj})+(c_{xj}-c_{yj})^2\right)^{\frac{1}{2}}}{c_{xj}-c_{yj}} > 1$; discard the root which exceeds 1;
$\frac{dq_j}{d\alpha_j} > 0$ and $\frac{dV_j}{d\alpha_j} > 0$ if $\alpha_j \in [\frac{f-2c_{xj}+c_{yj}}{2f-c_{xj}-c_{yj}}, \frac{f-c_{yj}-\left((f-c_{yj})(f-c_{xj})+(c_{xj}-c_{yj})^2\right)^{\frac{1}{2}}}{c_{xj}-c_{yj}})$; $\frac{dq_j}{d\alpha_j} < 0$ and $\frac{dV_j}{d\alpha_j} < 0$ if $\alpha_j \in (\frac{f-c_{yj}-\left((f-c_{yj})(f-c_{xj})+(c_{xj}-c_{yj})^2\right)^{\frac{1}{2}}}{c_{xj}-c_{yj}}, 1]$. Conversely for electricity price since $\frac{dp_j}{d\alpha_j} = -\frac{dq_j}{d\alpha_j}$. Note $\frac{\left((f-c_{yj})(f-c_{xj})+(c_{xj}-c_{yj})^2\right)^{\frac{1}{2}}+c_{yj}-c_{xj}}{f-c_{xj}} > \frac{f-c_{yj}-\left((f-c_{yj})(f-c_{xj})+(c_{xj}-c_{yj})^2\right)^{\frac{1}{2}}}{c_{xj}-c_{yj}} > \frac{f-2c_{xj}+c_{yj}}{2f-c_{xj}-c_{yj}}$. ■

Lemma 4. *The price of certificates is strictly increasing with the percentage requirement.*

Proof. $\frac{dp_{cj}}{d\alpha_j} = 0$ at $\alpha_j = \frac{f-2c_{xj}+c_{yj}}{2f-c_{xj}-c_{yj}} - \frac{\left[3\left((f-c_{yj})(f-c_{xj})+(c_{xj}-c_{yj})^2\right)\right]^{\frac{1}{2}}}{2f-c_{xj}-c_{yj}} < \frac{f-2c_{xj}+c_{yj}}{2f-c_{xj}-c_{yj}}$ and $\alpha_j = \frac{f-2c_{xj}+c_{yj}}{2f-c_{xj}-c_{yj}} + \frac{\left[3\left((f-c_{yj})(f-c_{xj})+(c_{xj}-c_{yj})^2\right)\right]^{\frac{1}{2}}}{2f-c_{xj}-c_{yj}} > 1$ when $f > 2c_{xj} - c_{yj}$;

hence $\frac{dp_{cj}}{d\alpha_j} = \frac{(2\alpha_j(1-\alpha_j)+1)(f-c_{xj})+\left(2-2\alpha_j-\alpha_j^2\right)(c_{xj}-c_{yj})}{2(1-\alpha_j+\alpha_j{}^2)^2} > 0$ over the interval $\alpha_j \in \left[\frac{f-2c_{xj}+c_{yj}}{2f-c_{xj}-c_{yj}}, 1\right]$. ■

2.2. Non-cooperative vs world welfare maximising percentage requirements

Anticipating the effects on the stage 2 equilibrium, policy-makers in each country non-cooperatively choose the percentage requirements in stage 1 to maximise W_j. Substituting (10)–(13) allows national welfare to be expressed in terms of core parameters and the percentage requirement:

$$W_j\left(\alpha_j\right) = \frac{\left(f-\left(1-\alpha_j\right)c_{yj}-\alpha_j c_{xj}\right)^2}{8\left(1-\alpha_j+\alpha_j^2\right)^2} \times \left[3-4\alpha_j\left(1-\alpha_j\right)-b\left(1+\alpha_j^2-2\alpha_j\right)\right] \tag{14}$$

The optimal percentage requirement $\alpha_j^*\left(f,b,c_{xj},c_{yj}\right)$ solves $\frac{dW_j}{d\alpha_j} = 0$ and satisfies the second order conditions for a maximum. The complexity of the first order condition does not allow us to present a closed form solution for α_j^*.

Fig. 1 illustrates the choice of percentage requirement in the benchmark model *à la* Currier and Rassouli-Currier (2012), for parameter values[7] $f = 100$, $c_{xj} = 6$, $c_{yj} = 2$, $b = \frac{8}{11}$. The solid arc corresponds to all the combinations of x_j and y_j that are feasible given TGC market clearing ("the equilibrium locus"), with varying α_j. In the unregulated Cournot equilibrium, $\alpha_j^C = \frac{f-2c_{xj}+c_{yj}}{2f-c_{xj}-c_{yj}} = 0.47$, electricity price is $p_j = 36$, while certificates have no value. W^C denotes the isowelfare contour at this unregulated equilibrium, where[8] $\left(x_j, y_j\right) = (30, 34)$. It can be seen that the unregulated equilibrium does not maximise social welfare; the optimal percentage requirement is that which gives rise

[7] We use the same parameter values as Currier and Rassouli-Currier (2012) as a benchmark against which to compare the analysis in subsequent sections.

[8] Note the unregulated equilibrium is to the left of the diagonal as the producers differ in their marginal cost, giving the lower-cost black producer a larger initial market share.

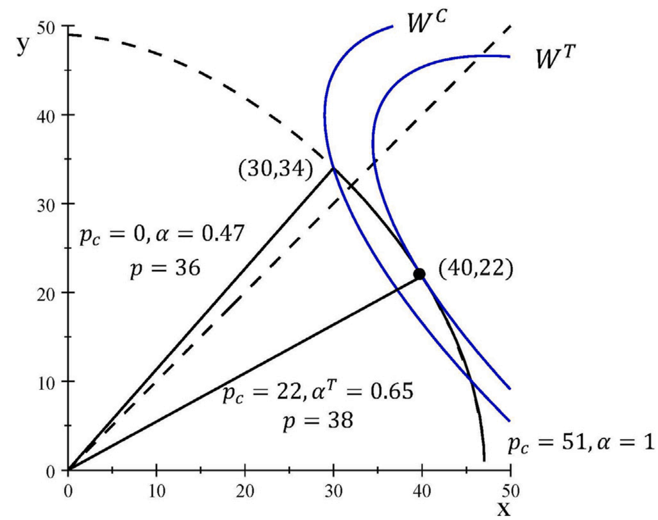

Fig. 1. Optimal choice of percentage requirement, for parameter values $f = 100$, $c_x = 6$, $c_y = 2$ and $b = \frac{8}{11}$.

to a tangency between the isowelfare contour W^T and the equilibrium locus. The optimal percentage requirement is $\alpha_j^* = 0.65$, which results in production $(x_j, y_j) = (40, 22)$, and higher electricity and certificate prices.

So far we have focused on the decision of national policy-makers. An important question is whether a world-welfare maximising authority would select the same national targets as the local authorities. Since markets in the benchmark model are segmented by construction, it is straightforward to see that the global authority chooses exactly the same percentage requirements as national policy-makers. That is, if world welfare is denoted by $W \equiv W^H + W^F$, then $\alpha_H^* = \arg\max W = \arg\max W^H$, and similarly for Foreign. The reason for this is that the home percentage requirement does not affect foreign welfare and therefore $\frac{dW^F}{d\alpha_H} = 0$.

Therefore if TGC markets are segmented and there is no trade in electricity, then the global welfare maximising percentage requirements are identical to the non-cooperative equilibrium national percentage requirements. According to this benchmark result, it makes no difference if the EU sets individual binding targets for all EU Member States or if the member states choose their renewable energy targets on their own. This stems from the fact that in the benchmark model there are no cross-country externalities. In practice, however, there are externalities arising for example from trade in electricity or when TGC markets are integrated. In what follows we analyse the effect of the domestic percentage requirement on the welfare of foreign countries through these channels and explore whether the non-cooperative national percentage requirements are higher or lower than those that maximise global welfare.

3. International trade in electricity

This section allows international trade in electricity between Home and Foreign, while maintaining the assumption of segmented TGC markets. We address whether the non-cooperative national percentage requirements over- or under-shoot those that maximise global welfare in the presence of international trade. Since the two electricity markets are segmented, firm decisions regarding over quantity of electricity supplied domestically and abroad are independent. For simplicity, we assume no tariffs, transport costs, or restrictions to the volume that can be traded.[9]

Let x_{ij} and y_{ij} denote green and black electricity, respectively, produced in country i and consumed in country j, where $i, j \in \{H, F\}$. Pollution is generated from domestic black production, encompassing both domestic sales and exports:

$$D_H = b\frac{\left(y_{HH} + y_{HF}\right)^2}{2} \text{ and } D_F = b\frac{\left(y_{FF} + y_{FH}\right)^2}{2}, \tag{15}$$

while consumer surplus arises from consumption of domestic production and imports:

$$q_H = x_{HH} + x_{FH} + y_{HH} + y_{FH} \text{ and } q_F = x_{FF} + x_{HF} + y_{FF} + y_{HF}. \tag{16}$$

The TGC market clearing conditions are now:

$$x_{HH} + x_{FH} = \alpha_H \left(x_{HH} + x_{FH} + y_{HH} + y_{FH}\right)$$
$$x_{FF} + x_{HF} = \alpha_F \left(x_{FF} + x_{HF} + y_{FF} + y_{HF}\right)$$

such that the percentage requirement $\alpha_H = \frac{x_{HH}+x_{FH}}{x_{HH}+x_{FH}+y_{HH}+y_{FH}}$ and $\alpha_F = \frac{x_{FF}+x_{HF}}{x_{FF}+x_{HF}+y_{FF}+y_{HF}}$ reflect the share of renewable electricity in total consumption.[10]

For purposes of tractability, assume marginal costs are identical across countries. The profit functions of green and black producers in Home and Foreign are thus given by:

$$\begin{aligned}\Pi_{G_H} = &\left[\left(p_H - c_x\right) x_{HH} + \left(1 - \alpha_H\right) p_{cH} x_{HH}\right] \\ &+ \left[\left(p_F - c_x\right) x_{HF} + \left(1 - \alpha_F\right) p_{cF} x_{HF}\right]\end{aligned} \tag{17}$$

$$\begin{aligned}\Pi_{G_F} = &\left[\left(p_F - c_x\right) x_{FF} + \left(1 - \alpha_F\right) p_{cF} x_{FF}\right] \\ &+ \left[\left(p_H - c_x\right) x_{FH} + \left(1 - \alpha_H\right) p_{cH} x_{FH}\right]\end{aligned} \tag{18}$$

$$\begin{aligned}\Pi_{BH} = &\left[\left(p_H - c_y\right) y_{HH} - \alpha_H p_{cH} y_{HH}\right] \\ &+ \left[\left(p_F - c_y\right) y_{HF} - \alpha_F p_{cF} y_{HF}\right]\end{aligned} \tag{19}$$

$$\begin{aligned}\Pi_{BF} = &\left[\left(p_F - c_y\right) y_{FF} - \alpha_F p_{cF} y_{FF}\right] \\ &+ \left[\left(p_H - c_y\right) y_{FH} - \alpha_H p_{cH} y_{FH}\right].\end{aligned} \tag{20}$$

Policy-makers in Home and Foreign select α_H and α_F in stage 1. Given these percentage requirements, firms maximise their profits in stage 2 by the appropriate choice of quantities. We solve using backwards induction.

3.1. The regulated Cournot equilibrium

Maximising profits and solving the first order conditions, assuming TGC clearing, gives rise to stage 1 production, trade flows and consumption:

$$x_{HH} = x_{FH} = \alpha_H \frac{f - \left(1 - \alpha_H\right) c_y - \alpha_H c_x}{3 - 2\alpha_H + 2\alpha_H{}^2} \tag{21}$$

$$x_{FF} = x_{HF} = \alpha_F \frac{f - \left(1 - \alpha_F\right) c_y - \alpha_F c_x}{3 - 2\alpha_F + 2\alpha_F{}^2} \tag{22}$$

$$y_{HH} = y_{FH} = \left(1 - \alpha_H\right) \frac{f - \left(1 - \alpha_H\right) c_y - \alpha_H c_x}{3 - 2\alpha_H + 2\alpha_H{}^2} \tag{23}$$

$$y_{FF} = y_{HF} = \left(1 - \alpha_F\right) \frac{f - \left(1 - \alpha_F\right) c_y - \alpha_F c_x}{3 - 2\alpha_F + 2\alpha_F{}^2} \tag{24}$$

$$q_j = \frac{2\left(f - \left(1 - \alpha_j\right) c_y - \alpha_j c_x\right)}{3 - 2\alpha_j + 2\alpha_j{}^2}. \tag{25}$$

Certificate and electricity prices are:

$$p_{cj} = \frac{\left(2\alpha_j - 1\right) f + \left(3 - \alpha_j\right) c_x - \left(\alpha_j + 2\right) c_y}{3 - 2\alpha_j + 2\alpha_j{}^2} \tag{26}$$

[9] In practice, there is a binding upper limit to the amount of electricity that can be traded, determined by investment in grid interconnectors. We abstract from this here, for tractability, and because a cap on trade flows is not expected to qualitatively change the results.

[10] With international trade, production and consumption of electricity in a country may differ. Since the EU sets percentage requirements as a share of consumption, we also follow this convention here.

$$p_j = \frac{\left(1 - 2\alpha_j + 2{\alpha_j}^2\right) f + 2\left(1 - \alpha_j\right) c_y + 2\alpha_j c_x}{3 - 2\alpha_j + 2{\alpha_j}^2}. \tag{27}$$

At the unregulated equilibrium $p_{cj} = 0$, where $\alpha_j = \frac{f-3c_x+2c_y}{2f-c_x-c_y}$. Assuming $f > 3c_x - 2c_y$, the policy space is $\alpha_j \in \left[\frac{f-3c_x+2c_y}{2f-c_x-c_y}, 1\right]$. Moreover:

$$\Pi_{Gj} = \alpha_H^2 \left(\frac{f - \left(1-\alpha_H\right) c_y - \alpha_H c_x}{3 - 2\alpha_H + 2{\alpha_H}^2}\right)^2 + \alpha_F^2 \left(\frac{f - \left(1-\alpha_F\right) c_y - \alpha_F c_x}{3 - 2\alpha_F + 2{\alpha_F}^2}\right)^2 \tag{28}$$

$$\Pi_{Bj} = \left(1-\alpha_H\right)^2 \left(\frac{f - \left(1-\alpha_H\right) c_y - \alpha_H c_x}{3 - 2\alpha_H + 2{\alpha_H}^2}\right)^2 + \left(1-\alpha_F\right)^2 \left(\frac{f - \left(1-\alpha_F\right) c_y - \alpha_F c_x}{3 - 2\alpha_F + 2{\alpha_F}^2}\right)^2 \tag{29}$$

$$D_j = \frac{b}{2}\left(\left(1-\alpha_H\right)\frac{f - \left(1-\alpha_H\right) c_y - \alpha_H c_x}{3 - 2\alpha_H + 2{\alpha_H}^2} + \left(1-\alpha_F\right)\frac{f - \left(1-\alpha_F\right) c_y - \alpha_F c_x}{3 - 2\alpha_F + 2{\alpha_F}^2}\right)^2 \tag{30}$$

$$V_j = 2\frac{\left(f - \left(1-\alpha_j\right) c_y - \alpha_j c_x\right)^2}{\left(3 - 2\alpha_j + 2{\alpha_j}^2\right)^2}. \tag{31}$$

The impact of a change in α_j on production streams, prices, profits, pollution and consumer surplus follows the same pattern as in Lemma 1–Lemma 4. In particular, $\frac{dy_{HH}}{d\alpha_H} = \frac{dy_{FH}}{d\alpha_H} < 0$ and[11] $\frac{\partial y_{FF}}{\partial \alpha_F} = \frac{\partial y_{HF}}{\partial \alpha_F} < 0$, so an increase in the percentage requirement unambiguously lowers black domestic sales and black electricity imports. In contrast, an increase in the share of renewables in a country has an ambiguous effect on both green domestic sales and green imports,[12] and in turn on profits; it does, however, reduce environmental damage both at home and abroad, as it restricts both domestic black production and black electricity imports.

3.2. Non-cooperative percentage requirements

Anticipating stage 2, policy-makers non-cooperatively choose percentage requirements in stage 1 to maximise W_j. Substituting (28)–(31) gives national welfare equations:

$$W_H = \frac{\left(f - \left(1-\alpha_H\right) c_y - \alpha_H c_x\right)^2}{3 - 2\alpha_H + 2\alpha_H^2} + \left(1 - 2\alpha_F + 2\alpha_F^2\right)\left(\frac{f - \left(1-\alpha_F\right) c_y - \alpha_F c_x}{3 - 2\alpha_F + 2\alpha_F^2}\right)^2 - \frac{b}{2}\left(\sum_{j=H,F}\frac{\left(1-\alpha_j\right)\left(f - \left(1-\alpha_j\right) c_y - \alpha_j c_x\right)}{3 - 2\alpha_j + 2\alpha_j^2}\right)^2 \tag{32}$$

$$W_F = \frac{\left(f - \left(1-\alpha_F\right) c_y - \alpha_F c_x\right)^2}{3 - 2\alpha_F + 2{\alpha_F}^2} + \left(1 - 2\alpha_H + 2{\alpha_H}^2\right)\left(\frac{f - \left(1-\alpha_H\right) c_y - \alpha_H c_x}{3 - 2\alpha_H + 2{\alpha_H}^2}\right)^2 - \frac{b}{2}\left(\sum_{j=H,F}\frac{\left(1-\alpha_j\right)\left(f - \left(1-\alpha_j\right) c_y - \alpha_j c_x\right)}{3 - 2\alpha_j + 2{\alpha_j}^2}\right)^2. \tag{33}$$

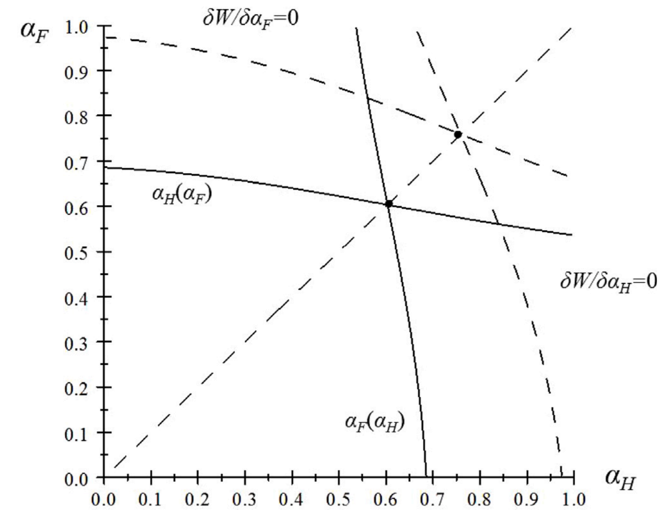

Fig. 2. Non-cooperative and socially optimal percentage requirements with free trade; drawn for parameter values $f = 100$, $c_x = 6$, $c_y = 2$ and $b = \frac{8}{11}$.

$\frac{\partial W_H}{\partial \alpha_H} = 0$ and $\frac{\partial W_F}{\partial \alpha_F} = 0$ implicitly give the reaction functions $\alpha_H\left(f, c_y, c_x, b, \alpha_F\right)$ and $\alpha_F\left(f, c_y, c_x, b, \alpha_H\right)$, which can be solved jointly for the non-cooperative equilibrium percentage requirements. The first order conditions are again too complex for closed form solutions.

Fig. 2 illustrates the reaction functions $\alpha_H\left(\alpha_F\right)$ and $\alpha_F\left(\alpha_H\right)$ for parameter values $f = 100$, $c_x = 6$, $c_y = 2$ and $b = \frac{8}{11}$. Solving these gives non-cooperative equilibrium percentage requirements $\alpha_H^* = \alpha_F^* = 0.60$, which corresponds to welfare levels $W_F = W_H = 4044$ and $D_F = D_H = 329$. This illustrates that opening to trade is welfare-improving relative to the benchmark model where welfare levels were 3814, but can give rise to higher levels of environmental damage, despite percentage requirements being higher under free trade. Intuitively, opening to free trade increases both green and black electricity generation, increasing environmental damage; this provides an incentive to regulate more heavily, mitigating the effects to an extent.

3.3. World welfare maximising percentage requirements

Now suppose a federal authority were to choose the percentage requirements for Home and Foreign to maximise world welfare $W = W_H + W_F$. These socially optimal shares, denoted by α_H^{SO} and α_F^{SO} solve $\frac{\partial W}{\partial \alpha_H} = 0$ and $\frac{\partial W}{\partial \alpha_F} = 0$, respectively. First order conditions $\frac{\partial W}{\partial \alpha_H} = 0$ and $\frac{\partial W}{\partial \alpha_F} = 0$ are illustrated in Fig. 2 for the case where $f = 100$, $c_x = 6$, $c_y = 2$ and $b = \frac{8}{11}$. World welfare is maximised where $\alpha_H^{SO} = \alpha_F^{SO} = 0.76$, illustrating that national policy-makers choose inefficiently low percentage requirements. Interestingly, environmental damage at the social optimum is $D_F = D_H = 110$, which is even lower than in the autarky equilibrium.

The inefficiency in national decision-making stems from the positive impact of an increase in a country's percentage requirement on its trading partner, which is not accounted for. To see this, we perturb W_H with a change in α_F. We appeal to symmetry in order to simplify by evaluating $\frac{\partial W_H}{\partial \alpha_F}$ where $\alpha_H = \alpha_F$:

$$\frac{\partial W_H}{\partial \alpha_F} = \underbrace{\frac{2\left(f - \left(1-\alpha_F\right) c_y - \alpha_F c_x\right)}{\left(3 - 2\alpha_F + 2{\alpha_F}^2\right)^3}}_{\text{positive}}$$

[11] $\frac{dy_{HH}}{d\alpha_H} = \frac{dy_{FH}}{d\alpha_H} = -\frac{2\alpha_H(1-\alpha_H)(f-c_y)+2\alpha_H(f-3c_x+2c_y)+(f-\alpha_H c_x-(1-\alpha_H)c_y)+(3+\alpha_H)(c_x-c_y)}{(3-2\alpha_H+2{\alpha_H}^2)^2} < 0$ and analogously for $\frac{\partial y_{FF}}{\partial \alpha_F} = \frac{\partial y_{HF}}{\partial \alpha_F} < 0$.

[12] $\frac{dx_{HH}}{d\alpha_H} = \frac{dx_{FH}}{d\alpha_H} = \frac{3f-2f{\alpha_H}^2+6\alpha_H c_y+2c_x\alpha_H^2-6\alpha_H c_x}{(3-2\alpha_H+2{\alpha_H}^2)^2} = \underbrace{\frac{\alpha_H}{1-\alpha_H}\frac{dy_{FH}}{d\alpha_H}}_{\text{negative}} + \underbrace{\frac{1}{\left(1-\alpha_H\right)^2} y_{FH}}_{\text{positive}}$ and similarly for $\frac{dx_{FF}}{d\alpha_F} = \frac{dx_{HF}}{d\alpha_F}$.

$$\widetilde{b}=\frac{f+3c_x-4c_y-2{\alpha_F}^3\left(c_x-2f+2c_y\right)-6{\alpha_F}^2\left(f-2c_x+c_y\right)-9\alpha_F\left(c_x-c_y\right)}{(1-\alpha_F)\left[2\alpha_F(1-\alpha_F)\left(f-c_y\right)+2\alpha_F\left(f+2c_y-3c_x\right)+f-\alpha_F c_x-(1-\alpha_F)c_y+(3+\alpha_F)(c_x-c_y)\right]}. \quad (35)$$

Box I.

$$\begin{aligned}&\times[2{\alpha_F}^3\left(c_x-2f+c_y\right)+6{\alpha_F}^2\left(f-2c_x+c_y\right)+9\alpha_F\left(c_x-c_y\right)\\&-3c_x+4c_y-f+b(1-\alpha_F)[(1-\alpha_F)2\alpha_F\left(f-c_y\right)\\&+2\alpha_F(f+2c_y-3c_x)\\&+\left(f-\alpha_F c_x-(1-\alpha_F)c_y\right)+(3+\alpha_F)(c_x-c_y)]]. \quad (34)\end{aligned}$$

The first term is positive, while the second is positive provided $b>\widetilde{b}$ where[13] $\widetilde{b}$ is as given in Box I.

Hence, provided b is sufficiently large, the externality on Home from a change in the percentage requirement in Foreign is positive.[14] Intuitively, a rise in the share of renewables in Foreign does not affect consumer surplus in Home. It does, however, reduce the pollution level in Home (by reducing black exports) and affects the profits of both firms. If the positive effect of the reduced pollution is strong enough to overcome negative effects on profits, then the overall effect on Foreign welfare is positive.

These results are summarised by:

Proposition 1. *If there is free trade in electricity and TCG markets are segmented, then the global welfare maximising percentage requirements are higher than the non-cooperative percentage requirements provided the environmental damage parameter is sufficiently large.*

The following numerical examples based on Proposition 1 shows that externalities can take either sign. Suppose that the damage function parameter is $b=\frac{8}{11}$ and the other parameters are $c_x=6,\ c_y=2$, and $f=100$. In this case the externalities are positive and (49) gives $\frac{\partial W_H}{\partial \alpha_F}=1183>0$. Therefore an increase in the non cooperative optimal percentage requirements is welfare improving.

If however $b=\frac{1}{11}$ while the other parameters are the same as in the previous example ($c_x=6,\ c_y=2$, and $f=100$), then the world welfare maximising percentage requirements are lower than the non cooperative ones ($\alpha_H^*=\alpha_F^*=0.46$ and $\alpha_F=\alpha_H=0.47$). In this case the externalities are negative ($\frac{\partial W_H}{\partial \alpha_F}=-19$) and national policy-makers choose inefficiently high percentage requirements. The reason for this result is that a rise in the share of renewables in the other country does not reduce domestic pollution much (because of the low value of the damage function parameter b and therefore the positive effect of the reduced pollution is not strong enough to overcome the negative effects on the joint profits of the two domestic firms.

4. Integrated TGC markets

This section explores the efficiency of national decision making where TGC markets are integrated. We maintain the assumption of no trade in electricity, while additional imposing symmetric costs across countries for tractability. Integration of the market for certificates implies a common certificates price, such that $p_{cH}=p_{cF}=p_c$. The percentage requirements of the two countries may vary, with the overall equilibrium requirement given by:

$$x_H+x_F=\alpha_H\left(x_H+y_H\right)+\alpha_F\left(x_F+y_F\right). \quad (36)$$

Maximising (2)–(3) gives:

$$\begin{aligned}x_j&=\frac{1}{3}\left[f-2c_x+c_y+\left(2-\alpha_j\right)p_c\right]\\y_j&=\frac{1}{3}\left[f-2c_y+c_x-\left(1+\alpha_j\right)p_c\right]. \quad (37)\end{aligned}$$

4.1. The regulated Cournot equilibrium

Solving the first order conditions given (36) yields stage 1 production and prices for Home, with analogous equations for Foreign given in Box II.

Moreover, we can compute profits, consumer surplus and environmental damage for Home are (analogous equations arise for Foreign):

$$\Pi_{GH}=x_H^2 \text{ and } \Pi_{BH}=y_H^2 \quad (43)$$

$$V_H=\frac{1}{72}\left(\frac{\left(1-2\alpha_F+2\alpha_H\right)\alpha_F\left(2f-c_x-c_y\right)-6\left(f-c_y\right)-\alpha_H\left(2f-7c_x+5c_y\right)}{\left(1-\alpha_H+{\alpha_H}^2\right)+\left(1-\alpha_F+{\alpha_F}^2\right)}\right)^2 \quad (44)$$

$$\begin{aligned}D_H=&\frac{b}{72\left[\left(1-\alpha_H+{\alpha_H}^2\right)+\left(1-\alpha_F+{\alpha_F}^2\right)\right]}[6\left(f-c_y\right)-\alpha_F\left(4f+c_x-5c_y\right)\\&+2\alpha_F^2\left(f+c_x-2c_y\right)-\alpha_H\left(2f+5c_x-7c_y\right)+3\alpha_H^2\left(c_x-c_y\right)\\&+\alpha_F\alpha_H\left(c_x+c_y-2f\right)]^2 \quad (45)\end{aligned}$$

4.2. Non-cooperative percentage requirements

Anticipating stage 2, policy-makers non-cooperatively choose percentage requirements in stage 1 to maximise W_j, where $W_j=V_j+\Pi_{Gj}+\Pi_{Bj}-D_j$. The conditions $\frac{\partial W_H}{\partial \alpha_H}=0$ and $\frac{\partial W_F}{\partial \alpha_F}=0$ implicitly give reaction functions $\alpha_H\left(f,c_y,c_x,b,\alpha_F\right)$ and $\alpha_F\left(f,c_y,c_x,b,\alpha_H\right)$, which can be solved jointly for the non-cooperative equilibrium percentage requirements. While too complex for closed form solutions, it can be shown numerically that α_H and α_F are once again strategic substitutes, and increasing in f, b and c_y and decreasing in c_x.

Fig. 3 illustrates the reaction functions $\alpha_H\left(\alpha_F\right)$ and $\alpha_F\left(\alpha_H\right)$ for parameter values $f=100$, $c_x=6$, $c_y=2$ and $b=\frac{8}{11}$. Solving these gives non-cooperative equilibrium percentage requirements $\alpha_H^*=\alpha_F^*=0.55$, which corresponds to welfare levels $W_F=W_H=3774$, and $D_F=D_H=298$. Percentage requirements and national welfare are thus lower, and pollution higher, than in the benchmark model where TGC markets are segmented. Weaker regulation also implies certificate have a lower price. The analysis demonstrates that integration of TGC markets can be welfare-reducing when policy-makers act non-cooperatively. Each policymaker fails to account for the impact of their domestic policy decision on welfare abroad; by raising the common certificate price, an increase in the percentage requirement in one country has the effect of curtailing black production and environmental damage abroad, while enhancing green production abroad. The failure to account for this externality results in under-regulation by each country, with detrimental effects on both pollution and overall welfare.

[13] To arrive at this result we appeal to the fact that the second term in the denominator of (50), that is $\left[2\alpha_F(1-\alpha_F)\left(f-c_y\right)+2\alpha_F\left(f+2c_y-3c_x\right)+f-\alpha_F c_x-(1-\alpha_F)c_y+(3+\alpha_F)(c_x-c_y)\right]$, is positive. We know that $f-\alpha_F c_x-(1-\alpha_F)c_y>0$ so that green electricity production x_{FF} to be non-negative. For $\alpha_H=0$ and $\alpha_H=1$ it becomes $f>c_y$ and $f>c_x$. Moreover, we have assumed that $f-3c_x+2c_y>0$ so as the proportion of green electricity in the unregulated Cournot equilibrium $\frac{f-3c_x+2c_y}{2f-c_x-c_y}$ to be positive.

[14] An analogous condition also applies for $\frac{\partial W_F}{\partial \alpha_H}>0$.

$$x_H = \frac{2\alpha_F^2\left(f-2c_x+c_y\right)+2\alpha_F\left(f+c_x-2c_y\right)-3\alpha_H^2\left(c_x-c_y\right)+\left(2-\alpha_F\right)\alpha_H\left(2f-c_x-c_y\right)}{6\left(1-\alpha_H+{\alpha_H}^2\right)+\left(1-\alpha_F+{\alpha_F}^2\right)} \tag{38}$$

$$y_H = \frac{1}{6\left[\left(1-\alpha_H+{\alpha_H}^2\right)+\left(1-\alpha_F+{\alpha_F}^2\right)\right]}\left[-\alpha_F\left(4f+c_x-5c_y\right)+2\alpha_F^2\left(f+c_x-2c_y\right)\right. \tag{39}$$
$$\left.-\ \alpha_H\left(2f+5c_x-7c_y\right)+3\alpha_H^2\left(c_x-c_y\right)+\alpha_F\alpha_H\left(-2f+c_x+c_y\right)+6\left(f-c_y\right)\right]$$

$$q_H = \frac{1}{6}\frac{6\left(f-c_y\right)+\alpha_H\left(2f-7c_x+5c_y\right)+\left(2\alpha_F-2\alpha_H-1\right)\alpha_F\left(2f-c_x-c_y\right)}{\left(1-\alpha_H+{\alpha_H}^2\right)+\left(1-\alpha_F+{\alpha_F}^2\right)} \tag{40}$$

$$p_H = \frac{1}{6\left[\left(1-\alpha_H+{\alpha_H}^2\right)+\left(1-\alpha_F+{\alpha_F}^2\right)\right]}\left[6\left(f+c_y\right)-\alpha_F\left(4f+c_x+c_y\right)\right. \tag{41}$$
$$\left.+\ 2\alpha_F^2\left(f+c_x+c_y\right)-\alpha_H\left(8f-7c_x+5c_y\right)+6f\alpha_H^2+2\alpha_F\alpha_H\left(2f-c_x-c_y\right)\right]$$

$$p_c = \frac{1}{2}\frac{2f\left(\alpha_H+\alpha_F-1\right)+\left(4-\alpha_H-\alpha_F\right)c_x-\left(2+\alpha_H+\alpha_F\right)c_y}{\left(1-\alpha_H+{\alpha_H}^2\right)+\left(1-\alpha_F+{\alpha_F}^2\right)} \tag{42}$$

Box II.

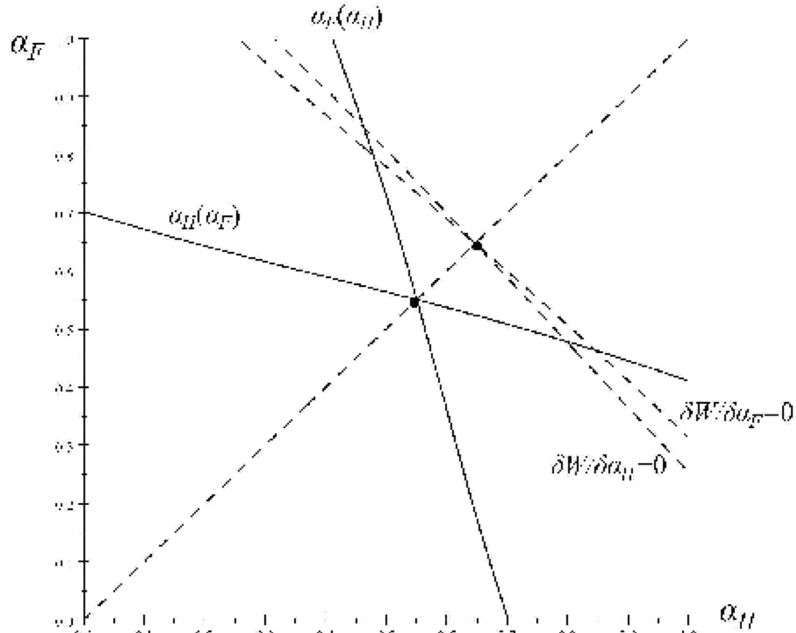

Fig. 3. Non-cooperative and socially optimal percentage requirements with integrated TGC markets; drawn for parameter values $f = 100$, $c_x = 6$, $c_y = 2$ and $b = \frac{8}{11}$.

4.3. World welfare maximising percentage requirements

If a federal authority were to choose the percentage requirements to maximise world welfare, then α_H^{SO} and α_F^{SO} would again solve $\frac{\partial W}{\partial \alpha_H} = 0$ and $\frac{\partial W}{\partial \alpha_F} = 0$, respectively. First order conditions $\frac{\partial W}{\partial \alpha_H} = 0$ and $\frac{\partial W}{\partial \alpha_F} = 0$ are illustrated in Fig. 3 for the case where $f = 100$, $c_x = 6$, $c_y = 2$ and $b = \frac{8}{11}$. World welfare is maximised where $\alpha_H^{SO} = \alpha_F^{SO} = 0.65$, which again implies more stringent regulation than national policy-makers choose. Welfare at the social optimum is again 3814, restoring the welfare level to that of the benchmark model.

The inefficiency in national decision-making stems from the impact of an increase in a country's percentage requirement on foreign welfare, through the effect on the certificates price. The price of certificates is increasing with the percentage requirement, entering negatively in the foreign black firm's profit and positive in the foreign green firm's profit. The output response to this price change is beneficial to foreign overall if the welfare gain from reduction in pollution more than offsets any negative effect on profits. To see this, we perturb W_H with a change in α_F and appeal to symmetry in order to simplify by evaluating $\frac{\partial W_H}{\partial \alpha_F}$ where $\alpha_H = \alpha_F$:

$$\frac{\partial W_H}{\partial \alpha_F} = \underbrace{\frac{f-\left(1-\alpha_H\right)c_y-\alpha_H c_x}{24\left(1-\alpha_H+\alpha_H^2\right)^3}}_{\text{positive}} \times \underbrace{\left[\left(1-\alpha_H^2\right)\left(f+c_x-2c_y\right)+\alpha_H\left(2-\alpha_H\right)\left(f-2c_x+c_y\right)\right]}_{\text{positive}}$$
$$\left[b\left(1-{\alpha_H}^2\right)+2\alpha_H-1\right]. \tag{46}$$

The first two terms are strictly positive, so the direction of the cross-country externality depends on the sign of the third term. The two roots of $b\left(1-{\alpha_H}^2\right)+2\alpha_H-1=0$ are $\frac{1-\sqrt{1-b+b^2}}{b}$ and $\frac{1+\sqrt{1-b+b^2}}{b}$, where the latter exceeds 1 and can be discarded. Furthermore, $\frac{1-\sqrt{1-b+b^2}}{b} < \frac{f-2c_x+c_y}{2f-c_x-c_y}$ is satisfied when $b > \frac{\left(c_x-c_y\right)\left(2f-c_x-c_y\right)}{\left(f-c_x\right)\left(f+c_x-2c_y\right)}$, which is the range of damage parameter values under which the policy-maker chooses to regulate.[15] If follows that $b\left(1-a^2\right)+2a-1$ is positive for the entire parameter space $\alpha_H \in [\frac{f-2c_x+c_y}{2f-c_x-c_y}, 1]$ and so for all relevant parameter values the externality is positive. Hence, a federal government would increase the percentage requirement of green electricity in both countries so as to increase global welfare. These findings are summarised by:

Proposition 2. *If TCG markets are integrated and there is no trade in electricity, then the global welfare maximising percentage requirements are higher than the non-cooperative percentage requirements.*

5. Transboundary pollution

Our analysis thus far has assumed that environmental damage arises from domestic pollution only. Indeed, in the context of climate change, environmental damage is not restricted to the country generating pollution, but arises as a function of total greenhouse gas emissions and concentration. In this section we explore the impact of transboundary pollution where a country is impacted by pollution overseas.

To focus on the effect of transboundary pollution as a mechanism, we first assume segmented TGC markets and there is no trade in electricity. Suppose welfare in country j is affected from the environmental damage created by black production from both countries:

$$W_j = V_j + \Pi_{G_j} + \Pi_{B_j} - D\left(y_j\right) - \beta D\left(y_i\right) \tag{47}$$

The parameter $\beta \in [0,1]$ reflects the degree of transboundary pollution, capturing the impact of pollution overseas on domestic welfare. The limit case of $\beta = 0$ reflects the case where environmental damages is purely local, whereas $\beta = 1$ reflects the case where aggregate global damage impacts on domestic welfare.

As we have seen, the non-cooperative behaviour of countries creates externalities through several channels. Here we see transboundary pollution creates a new avenue for such avenues. Specifically, a rise in the share of renewables in one country reduces the environmental damage created domestically (from Lemma 1 we know that $\frac{\partial D_j}{\partial a_j} < 0$), which in turn results in less transboundary pollution impacting the other country.

The effect of a change in the domestic percentage requirement on the welfare of the other country is given by, after using (47),

$$\frac{\partial W_j}{\partial a_i} = -\beta \frac{\partial D_i}{\partial a_i} > 0 \tag{48}$$

Therefore an increase in a country's percentage requirement reduces the level of the transboundary pollution (by reducing the environmental damage level of domestic black production), resulting in higher welfare in the other country. This externality is unaccounted for in national decision-making, resulting in inefficiently low national percentage requirements. It therefore follows that even with segmented TCG markets and no trade in electricity, the global welfare maximising percentage requirements are higher than the non-cooperative percentage requirements in the presence of transboundary pollution.

Underregulation in the context of a "public bad" such as greenhouse gas emissions is not new. What is novel is an exploration of how international trade in electricity impacts on policy incentives in the face of transboundary pollution; we now turn to this case.

With only local pollution ($\beta = 0$), we have seen that a rise in the share of renewables in Foreign decreases the exports of the Home country, creating a positive effect in Home through reduced local pollution. When the environmental damage parameter is sufficiently large, $b > \widetilde{b}$, this positive effect can overcome the negative effects on profits. Now consider that in addition there is transboundary pollution, where $\beta \in (0,1]$. This gives rise to an additional positive effect on Home welfare through the direct impact through Foreign environmental damage reduction. A rise in the share of renewables in Foreign decreases the production of the black firm in Foreign, lowering Foreign environmental damage and impacting on Home welfare directly. For a sufficiently high environmental damage parameter b the externality is positive. Solving:

$$\begin{aligned}\frac{\partial W_H}{\partial \alpha_F} = \underbrace{\frac{4\left(f-\left(1-\alpha_F\right)c_y-\alpha_F c_x\right)}{\left(3-2\alpha_F+2\alpha_F{}^2\right)^3}}_{\text{positive}} & [2\alpha_F{}^3\left(c_x-2f+2c_y\right) \\ & + 6\alpha_F{}^2\left(f-2c_x+c_y\right)+9\alpha_F\left(c_x-c_y\right) \\ & - 3c_x+4c_y-f+2b(1-\alpha_F)[(1-\alpha_F)2\alpha_F\left(f-c_y\right) \\ & + 2\alpha_F(f+2c_y-3c_x) \\ & + \left(f-c_y\right)+3(c_x-c_y)]].\end{aligned} \tag{49}$$

Solving (49) gives[16]:

$$b > \frac{1}{2}\widetilde{b} \tag{50}$$

where $\widetilde{b}$ is the value of the environmental damage parameter needed for the externality to be positive in the case of local pollution. Hence, transboundary pollution results in a broader parameter range for which externalities are positive; in particular, the threshold damage parameter is half as large as where pollution is purely local.

Now consider the integrated TGC markets, where we found in Section 4 that the effect of an increase in a country's percentage requirement on foreign welfare is positive with local pollution. This externality continues to be positive if pollution becomes transboundary pollution, but is larger in magnitude as welfare is affected both indirectly through the impact of a change in the certificates price, and directly through transboundary pollution. Transboundary pollution does not alter the incentives, except to magnify the externalities present and thus enlarge the disparity between national policy decisions and those that are globally optimal.

6. Cross-country heterogeneity

Our analysis thus far has assumed the benchmark case of symmetric countries. An important question is how cross-country heterogeneity in production costs or damage functions shapes policy decisions and thus welfare. We explore this question through a series of numerical simulations to offer a sensitivity analysis of our findings to parameter changes.

6.1. Differences in the damage functions

First we focus on cross-country differences in the damage function when there is international trade in electricity. Electricity that is created from nonrenewable energy sources can give rise to different degrees of pollution; for example, burning coal for energy results in more emissions than burning natural gas. This can be incorporated

[15] To see this we set $\alpha_H = \frac{f-2c_x+c_y}{2f-c_x-c_y}$ in $\frac{\partial W_H}{\partial \alpha_H} = 0$ and solve for b to find the value of the damage parameter that must prevail in order for the optimal percentage requirement to correspond to the Cournot equilibrium (no regulation). This corresponds to $b = \frac{(c_x-c_y)(2f-c_x-c_y)}{(f-c_x)(f+c_x-2c_y)}$. From there it is straightforward to show that $b > \frac{(c_x-c_y)(2f-c_x-c_y)}{(f-c_x)(f+c_x-2c_y)}$ must hold in order for the optimal non-cooperative percentage requirement to fall within our policy space.

[16] To arrive at this result we appeal to the fact that the second term in the denominator of (50), that is $2\alpha_F(1-\alpha_F)\left(f-c_y\right)+2\alpha_F\left(f+2c_y-3c_x\right)+\left(f-c_y\right)+3(c_x-c_y)$, is positive. We know that for $\alpha_H = 0$ and $\alpha_H = 1$ it becomes $f > c_y$. Moreover, we have assumed that $f-3c_x+2c_y > 0$ so as the proportion of green electricity in the unregulated Cournot equilibrium $\frac{f-3c_x+2c_y}{2f-c_x-c_y}$ to be positive.

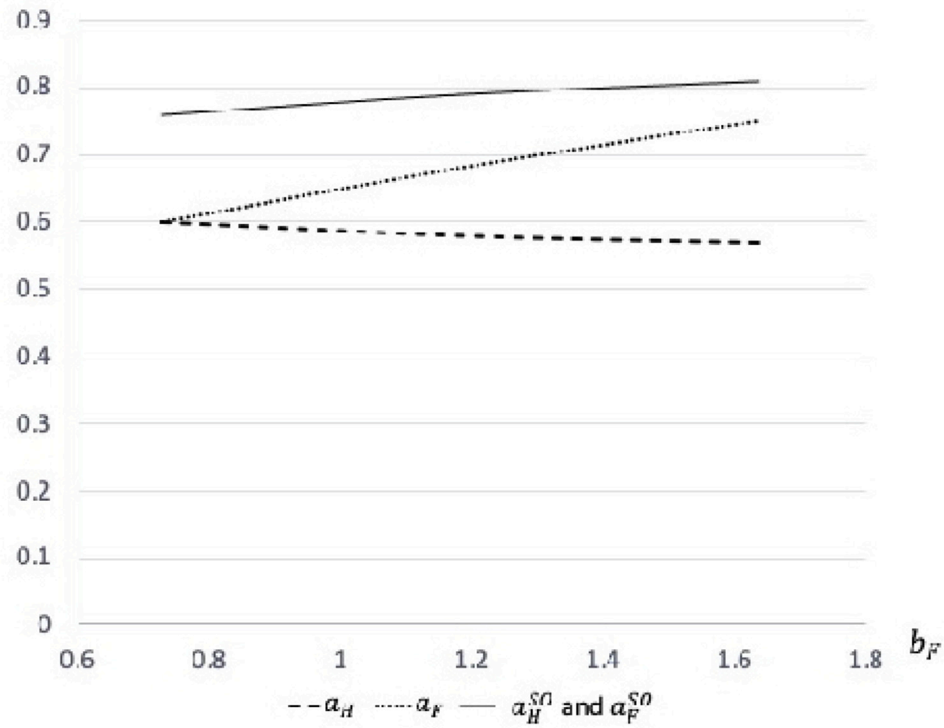

Fig. 4. Non-cooperative and socially optimal percentage requirements with free trade; drawn for parameter values $f = 100$, $c_x = 6$, $c_y = 2$ and $b_H = \frac{8}{11}$.

into our model by assuming a different damage parameter $b_j > 0$ for each country $j = \{H, F\}$. In particular, the damage functions are asymmetric, such that $D_H = b_H \frac{(y_{HH}+y_{HF})^2}{2}$ and $D_F = b_F \frac{(y_{FF}+y_{FH})^2}{2}$, where $b_F \geq b_H > 0$.

The appendix provides the analysis of the impact of an increase in a country's percentage requirement on its trading partner in the context of free trade and asymmetric damage parameters. Results are similar to those in Proposition 1, in that the global welfare maximising percentage requirements are higher than the non-cooperative percentage requirements provided the environmental damage parameters are sufficiently large. However the threshold values differ from those in Proposition 1 due to the asymmetry in damage.

We conduct a simulation where we keep b_H fixed at $\frac{8}{11}$ as in earlier examples, but raise b_F above b_H to examine the impact on the global optimum percentage requirement and the non-cooperative percentage requirements under free trade. These are illustrated in Fig. 4. The first observation is that despite heterogeneity in damage functions the globally optimal percentage requirements remain symmetric. This emerges because percentage requirements are defined in consumption and free trade in electricity serves to equalise consumption patterns across countries and in turn globally optimal percentage requirements. Despite a common optimal percentage requirement in a freely trading EU, welfare differs across countries because of the asymmetric damage function entering into national welfare. Within the range of valid parameter assumptions in the model, we continue to observe positive cross-country externalities, that cause national decision-makers to under-regulate relative to the global optimum. Moreover, we observe a divergence between the non-cooperative requirement percentages across the two countries as the Foreign country's damage parameter rises, with the country with most damage regulating more strictly. However, we also observe that the while Foreign's non-cooperative requirement ratio approaches the global optimum, that of Home gets progressively further away.

Intuitively, a rise in the share of renewables in Home a_H reduces the pollution level in Foreign through a reduction in its black exports. This positive external effect is larger, the greater is b_F. When this effect is large enough to overcome the negative effects on profits, an increase in the share of renewables in Home is beneficial to Foreign. The larger the parameter b_F, the greater the positive externality through the damage function of Home's requirement ratio, and thus the larger the misalignment between non-cooperative and globally optimal regulation levels. A similar argument applies to the incentives of the Foreign country when setting a_F.

The policy implication of these findings are that decision-makers in relatively low damage countries will not factor into their decision-making how their national requirement ratio interacts with trade incentives to create positive benefits in high damage countries. This suggests that more stringent regulation in relatively low emissions regions would confer welfare benefits through a reduction of emissions in higher emissions regions. In fact, from a global perspective if trade in electricity were completely free, then there would be no need for regional variation in requirement ratios. The role of free trade here is key, as it is the driving mechanism for uniform optimal percentage requirements across regions.

We now turn to the case of integrated TGC markets where the black supplier of electricity in one country has a larger negative impact on the environment than the one in the other country (for example, where oil or coal is used rather than cleaner natural gas). In the absence of trade the damage functions are $D_H = b_H \frac{y_H^2}{2}$ and $D_F = b_F \frac{y_F^2}{2}$, and we further assume $b_F \geq b_H > 0$.

We again conduct a simulation where we keep b_H fixed at $\frac{8}{11}$ but raise b_F above b_H to examine the effects on the global optimum percentage requirement and the non-cooperative percentage requirements, under integrated TGC markets. These are illustrated in Fig. 5. In the absence of international trade we see we no longer have a convergence of the socially optimal national targets. Instead we find that it is optimal for the country with the more polluting black industry to set a more stringent percentage requirement, with the reverse true for the country with the relatively cleaner black industry.

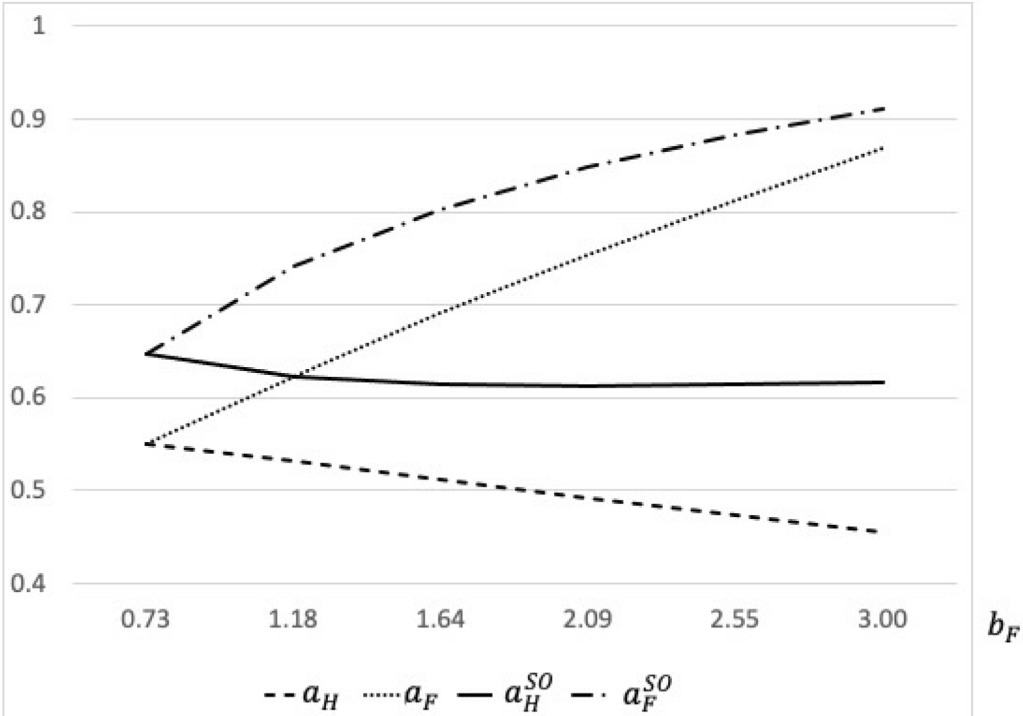

Fig. 5. Non-cooperative and socially optimal percentage requirements with integrated TGC markets; drawn for parameter values $f = 100$, $c_x = 6$, $c_y = 2$ and $b_H = \frac{8}{11}$.

The externality incurred on the Home country by a change in the optimal percentage requirement of electricity from renewable sources in Foreign becomes much more complicated here, because of the break in symmetry here. It can be shown numerically that optimal a_i is increasing in b_i but decreasing in b_j. Both externalities $\frac{\partial W_H}{\partial a_F}$ and $\frac{\partial W_F}{\partial a_H}$ are increasing in b_H and b_F, so the non cooperative percentage requirements always lie below the cooperative ones. Moreover, as b_F increases, the Foreign non cooperative percentage requirement converges to the world welfare maximising percentage requirement.

6.2. Production cost asymmetries

This section explores the effect of heterogeneity in green production costs across countries. Some countries are likely to have a cost advantage in solar or wind-powered electricity production, by virtue of their geographical location or climate. We keep damage functions symmetric and explore the effect of asymmetric green production costs in the case of free trade in electricity and integrated TGC markets. We assume country specific green production cost parameters c_{xH} and c_{xF}, where $c_{xH} \geq c_{xF} > c_y$.

The simulation carried out increases the cost of green electricity production in Home, keeping that of Foreign fixed. The resulting socially optimal and non-cooperative requirement percentages are illustrated in Fig. 6.

We again observe that free trade gives rise to convergence in the socially optimal percentage requirements, while global welfare maximising percentage requirements continue to be higher than non-cooperative percentage requirements for this range of parameter values. We also observe a growing divergence between the two non-cooperative percentage requirements as the cost of green production rises in Home, with the Foreign non-cooperative percentage requirement converging to the social optimum and the Home non-cooperative percentage requirement getting father from it.

Intuitively, higher Home green production costs impacts the share of green production in Home, as well as exports to Foreign, weakening the incentive to regulate in Home. Moreover, the impact of Foreign's percentage requirement on Home profits is progressively smaller as Home green production costs are higher, reducing the size of the externality on Home and thus narrowing the gap between the non-cooperative and socially optimal percentage requirements in Foreign.

A policy implication from this simulation emerges. If the cost of green electricity production were to fall in regions where it is relatively high, perhaps through technological advance, then – assuming free trade in electricity – the socially optimal renewables policy target would become more stringent for all countries.

A similar simulation is carried out for the case of integrated TGC markets, where the effect of higher Home green production costs on socially optimal and non-cooperative percentage requirements is explored. This is illustrated in figure Fig. 7. Here the picture is again more complex, due to non-monotonicity in green production and profits, which for a high degree of heterogeneity could even lead to Foreign setting a higher than optimal percentage requirement.

The consistent pattern that emerges, however, across the two simulations is that higher green production costs in one country tends to lower socially optimal percentage requirements in general, while dramatically lowering the non-cooperative percentage requirement of the high cost country. That is, in the absence of a socially optimal binding target, we can expect higher cost countries to fall short when choosing their percentage requirement. At the same time, technological innovations that lower the cost of green electricity production in regions where they are relatively high, will result in more stringent socially optimal percentage requirements.

7. Conclusions

The former Renewable Energy Directive of the EU set individual binding targets for all EU Member States, the sum of which should lead to a share of 20% renewable energy in the EU 'gross final consumption of energy' by 2020. The revised Renewable Energy Directive sets an EU-wide target of 32% renewables in total EU energy consumption by 2030, without imposing legally binding national targets. The absence

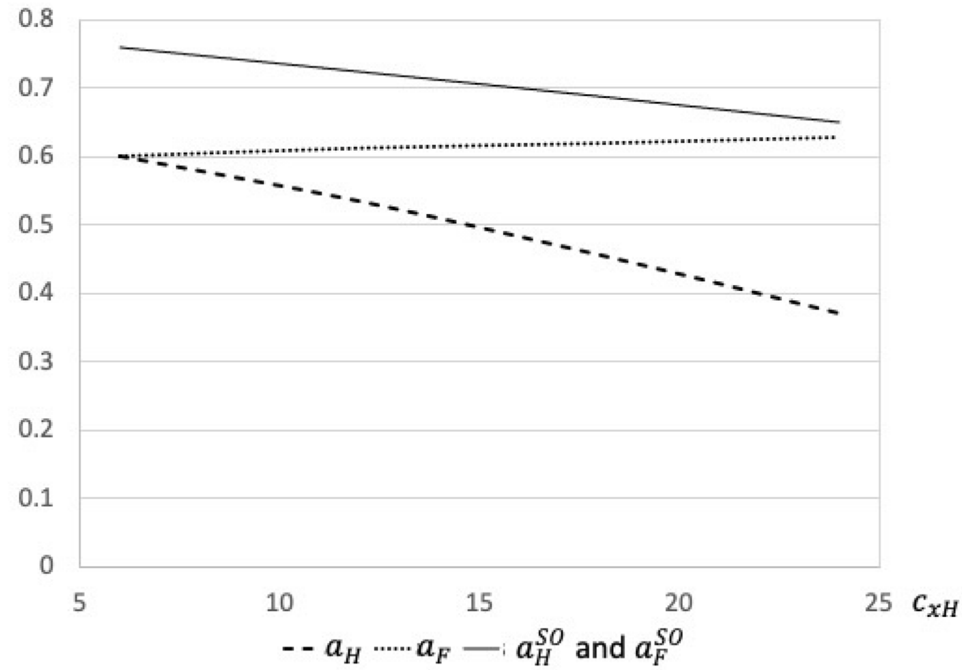

Fig. 6. Non-cooperative and socially optimal percentage requirements with free trade; drawn for parameter values $f = 100$, $c_{xF} = 6$, $c_y = 2$ and $b = \frac{8}{11}$.

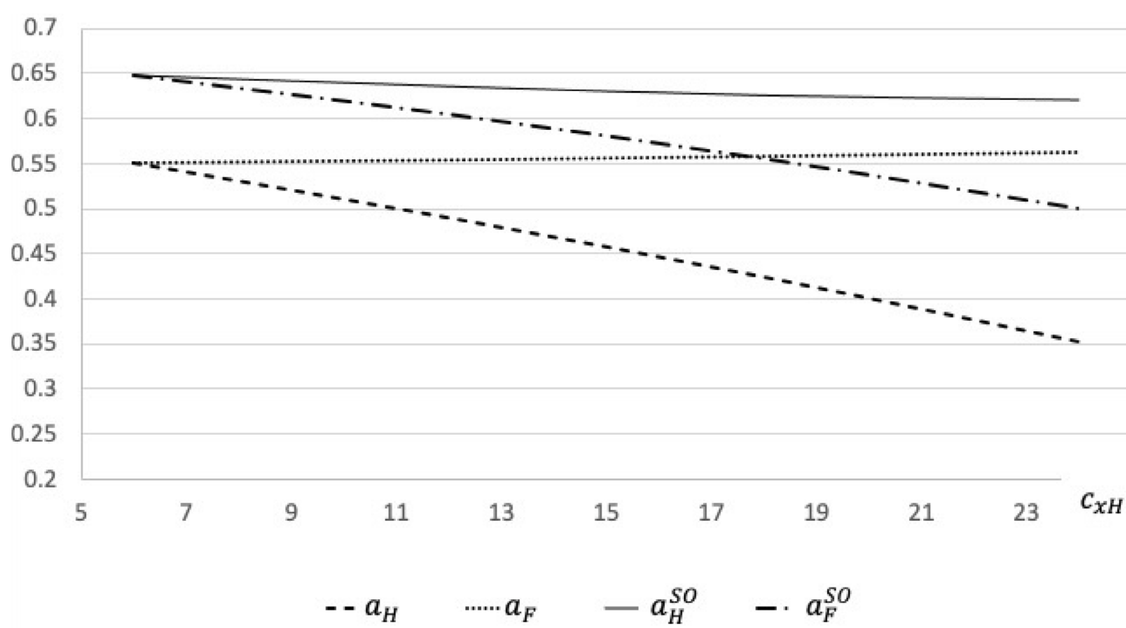

Fig. 7. Non-cooperative and socially optimal percentage requirements with integrated TGC markets; drawn for parameter values $f = 100$, $c_{xF} = 6$, $c_y = 2$ and $b = \frac{8}{11}$.

of binding national targets raises questions as to whether national policy incentives over the choice of percentage requirement can be expected to jointly meet the stipulated EU target. Opening to trade in electricity, as well as integrating national TGC markets, have in fact been put forth as possible mechanisms for aligning national and EU incentives.

This paper explores whether this is indeed the case in a two-country framework in which countries employ a system of Tradable Green Certificates. The national targets on renewable energy are met through TGC percentage requirements. In contrast to much of the related literature, which treats the percentage requirement as an exogenous parameter, we endogenise the choice of percentage requirement in an open economy setting. In our framework governments first choose the percentage requirement of total electricity that must be obtained from renewable sources and then, one "green" and one "black" supplier in each country compete in quantities.

We show that nationally determined percentage requirements do not align with the global-welfare maximising renewable energy targets set by a federal authority. Integration of TGC markets and free trade in electricity generate cross-country externalities, which are unaccounted for in national decision making. Transboundary pollution also serves as a mechanism for cross-country externalities, reinforcing the positive externalities from regulation in both the free trade and integrated TGC cases.

$$\frac{\partial W_H}{\partial a_F} = -2\left(f - c_y - a_F\left(c_x - c_y\right)\right)\frac{f + 3c_x - 4c_y - 9a_F\left(c_x - c_y\right) - 6a_F^2\left(f + c_y\right) + 12a_F^2 c_x + \left(2f - c_x - c_y\right)2a_F^3}{\left(-2a_F + 2a_F^2 + 3\right)^3}$$
$$+ b_H\left(\left(1 - a_H\right)\frac{f - \left(1 - a_H\right)c_y - a_H c_x}{3 - 2a_H + 2a_H^2} + \left(1 - a_F\right)\frac{f - \left(1 - a_F\right)c_y - a_F c_x}{3 - 2a_F + 2a_F^2}\right)$$
$$\frac{\left(2a_F(1 - a_F)\left(f - c_y\right) + 2a_F\left(f + 2c_y - 3c_x\right) + f - a_F c_x - (1 - a_F)c_y + (3 + a_F)(c_x - c_y)\right)}{\left(3 - 2a_F + 2a_F^2\right)^2}$$

Box III.

$$b_H > \frac{2\left(f - c_y - a_F c_x + a_F c_y\right)\frac{f+3c_x-4c_y-9a_F c_x+9a_F c_y-6fa_F^2+4fa_F^3+12a_F^2 c_x-6a_F^2 c_y-2a_F^3 c_x-2a_F^3 c_y}{\left(-2a_F+2a_F^2+3\right)^3}}{\left(\left(1 - a_H\right)\frac{f-(1-a_H)c_y-a_H c_x}{3-2a_H+2{a_H}^2} + \left(1 - a_F\right)\frac{f-(1-a_F)c_y-a_F c_x}{3-2a_F+2{a_F}^2}\right)\frac{\left(2a_F(1-a_F)\left(f-c_y\right)+2a_F\left(f+2c_y-3c_x\right)+f-a_F c_x-(1-a_F)c_y+(3+a_F)(c_x-c_y)\right)}{\left(3-2a_F+2a_F^2\right)^2}}.$$

Box IV.

When the TGCs market is integrated between countries, a positive externality arises through the change in the price of the green certificates, causing the non-cooperative Nash equilibrium percentage requirements chosen by national policy-makers to be inefficiently low compared to those that would maximise EU welfare. Moreover, heterogeneity across countries in terms of the damage function or green production costs leads to heterogeneous socially optimal percentage requirements. The findings suggest that all other things equal, countries with relatively higher costs of green electricity production, or with relatively higher environmental damage arising from black production (e.g. through coal rather than natural gas) should face relatively more stringent targets.

In contrast, we show that barrier-free international trade in electricity leads to convergence in the socially optimal percentage requirements across countries, even where the countries are heterogeneous in terms of damage functions or production cost. This is a theoretical benchmark — in practice we are very far from free trade in electricity due to the relatively small infrastructural capacity for international exchange in electricity, so one would not expect targets to be common across countries. Even if EU socially optimal targets were to converge across countries through trade, we show that international trade flows create a channel for cross-country externalities causing non-cooperative percentage requirements to be too low, for a sufficiently high damage parameter.

Overall, our findings identify serious limitations to the feasibility of the new EU renewable energy policy in the absence of binding national targets, and point to factors that can shape national targets. In particular, countries in which electricity supply from nonrenewable energy sources causes relatively high environmental damage (e.g. because it derives from coal rather than natural gas, or because of climate conditions) should have higher national targets. In contrast countries with high cost of producing green electricity should have lower national targets.

There continue to be further avenues for research in this area. It remains, for instance, an open question whether national policy-makers under-regulate when there is interaction of the system of Tradable Green Certificates with other policy instruments and how effects are shaped by international trade in electricity. The biggest challenge to extending the research to explore endogenous policy choice with further policy interactions is the inability to derive closed form solutions. Such analysis would need to focus on calibrations, but can yield further insights. Related research questions that merit exploration are the role of international trade in electricity in containing electricity supply instability. Electricity supply that comes from renewable energy sources is inherently more uncertain than electricity production from non-renewable energy sources. Trade in electricity may serve an important role in lowering the risk of shortages when a greater share of electricity supply comes from renewable energy sources. Modelling the supply side more carefully could be of interest. Finally, capacity constraints are typically binding and meeting national targets must go hand-in-hand with infrastructural investments in renewable energy. An exploration of the interplay between national targets and national incentives for capacity expansion are also areas for fruitful further exploration.

CRediT authorship contribution statement

Ourania Karakosta: Conceptualisation, Formal analysis, Investigation, Methodology, Project administration, Validation, Visualisation, Writing – review & editing. **Dimitra Petropoulou:** Conceptualisation, Formal analysis, Investigation, Methodology, Project administration, Validation, Visualisation, Writing – original draft.

Appendix A

Externalities in the case of cross-country differences in damage functions and international trade in electricity:

We perturb W_H with a change in α_F and we get the equation given in Box III.

The term multiplied by b_H is positive (see footnote 13)

Thus $\frac{\partial W_H}{\partial a_F} > 0$ when the condition given in Box IV is satisfied.

A similar condition applies to Foreign country.

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