Renewable Electricity Policy and Market Integration

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Abstract

I analyze renewable electricity policy in a multinational electricity market with transmission investment. If national policy makers choose support schemes to maximize domestic welfare, a trade policy motive arises operating independently of any direct benefit of renewable electricity. The model predicts electricity importing (exporting) countries to choose policies which reduce (increase) electricity prices. A narrow pursuit of domestic objectives distorts transmission investment, and thereby market integration, below the efficient level. Distortions cannot be corrected by imposing national renewable targets alone. Instead, subsidies to transmission investment and a harmonization of and reduction in the number of policy instruments can improve welfare.

Keywords: Market integration, renewable electricity, trade policy, transmission investment.

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1. INTRODUCTION

A cornerstone of energy policy in the European Union (EU) is to create a well-functioning European internal market for electricity. Another fundamental objective is to transform the EU into an economy based upon a reliable and environmentally sustainable supply of energy.

To facilitate the transformation into a greener economy, the EU has imposed national targets for the renewable share of energy consumption, but delegates to the individual member states how to fulfil them (Directive 2009/28/EC). Electricity makes up a significant share of final energy consumption; the EU average is roughly 20 per cent.[1] To achieve the renewable targets, many EU member states have thus implemented policies to promote the production of electricity from renewable energy sources, *RES-E*.

RES-E support mechanisms are now main drivers of investments in new generation capacity in many countries and thereby exercise a substantial influence over electricity wholesale prices. These price changes affect not only generation investment and consumption, but also transmission investment. Buying electricity in one country and selling it at a higher price in another allows network owners to earn a congestion rent. Support policies affect the profitability of expanding transmission capacity through the effect on electricity prices and the congestion rent. The capacity of cross-border transmission lines in turn determines the degree of market integration by limiting the volume of electricity trade between countries. Market integration, as measured by the volume of trade, and RES-E support mechanisms are therefore linked through the electricity market.[2]

The questions of how RES-E policies affect market integration and what are the outcomes of decentralized policy making have largely remained unexplored. The research on RES-E mechanisms mostly neglects transmission constraints and treats policy as given (e.g. Jensen and Skytte, 2002; Fischer and Newell, 2008; Böhringer and Rosendahl, 2010; Fischer, 2010; Fischer and Preonas, 2010), even the analyses of multinational markets (e.g. Amundsen and Mortensen, 2001; Morthorst, 2003; del Río, 2005; Unger and Ahlgren, 2005; Söderholm,

[1] See http://epp.eurostat.ec.europa.eu/portal/page/portal/energy/data/main_tables, accessed August 12, 2014.

[2] Market integration can equivalently be measured by the volume of trade or transmission capacity in the present context because international transmission is always utilized to its full capacity. ACER/CEER (2013) uses net transfer capacities and convergence of wholesale electricity prices as indicators of market integration in the EU. But small price differences are not *prima facie* evidence of market integration. In fact, market integration is insufficient here precisely because national policies drive down price differences to such an extent that socially desirable transmission investments become privately unprofitable.

2008; Amundsen and Bergman, 2012).[3] Here, I develop a theoretical model of a multinational electricity market with transmission investment to analyze the effect of RES-E policies on market integration and national policy makers' incentives for implementing such policies.[4]

A key result is that the twin goals of increased RES-E production and market integration may oppose one another when implementation is decentralized to the individual member states. Policy makers in an electricity importing country, concerned with the maximization of domestic surplus, have an incentive to implement support mechanisms such as certificates and feed-in-tariffs which reduce the import price of electricity to the benefit of domestic consumers. In an electricity exporting country, production taxes on non-renewable electricity increase the export price of electricity to the benefit of domestic producers. These national policies drive down cross-border price differences with negative consequences for congestion rent, transmission investment and market integration.[5]

Terms-of-trade effects alone are sufficient to induce policy makers to unilaterally implement RES-E policies. Ulterior motives such as trade policy can thus explain why countries, or groups of countries in a global context, would find it beneficial to implement renewable policies even in cases when these policies do not correct any obvious externality.[6] Naturally, environmental or other externalities to renewable electricity sometimes justify RES-E mechanisms.[7] Still, decentralized RES-E policies reduce overall welfare by distorting consumption, production and transmission investment.[8]

An apparent solution would be to correct distortions by imposing renewable targets on the individual member countries, as is currently done in the EU. However, binding targets are not

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[3] Traber and Kemfert (2009) consider transmission constraints, but treat them as exogenous.

[4] This is a model of market integration between jurisdictions, where each jurisdiction unilaterally decides its RES-E policy. In the present context, these jurisdictions are countries, but one could equally well assume them to be states, such as in the U.S.

[5] The EU seems to have recognized the potential for member countries to use national policies for trade policy reasons. Directive 2001/77/EC, which lays the foundation for EU RES-E policy, states that "the Commission shall evaluate … mechanisms used in Member States according to which a producer of electricity … receives direct or indirect support, and which could have the effect of restricting trade."

[6] The paper thus relates to a trade literature recognizing how governments may pursue substitute policies when trade agreements prevent governments from using tariffs and export subsidies directly; see Copeland (1990) for the seminal contribution. Market integration (transmission capacity) is here endogenous and imperfect, while the trade literature generally considers the case of perfect integration. Horn et al. (1994) develop a model of endogenous market integration, but do not consider trade policy.

[7] One such externality could be positive spill-over effects from R&D investments in renewable technologies (Fischer and Newell, 2008).

[8] In a related contribution, Ogawa and Wildasin (2009) find decentralized policy making to be efficient. Their result crucially depends on the assumption that policy makers treat prices as given. If policy makers instead take the price effect of policies into account, then decentralized policy making is generally inefficient.

enough to eliminate trade policy concerns. The electricity importing (exporting) country could still suppress import (inflate export) prices by taxing electricity consumption (non-renewable electricity production) while achieving any RES-E target, for example by means of a feed-in tariff with a cap on total revenue. Binding national targets and ulterior motives can thus explain why countries would apply multiple instruments to achieve what appears to be a single objective, RES-E production in this case.

RES-E support mechanisms, as pursued by the EU and elsewhere, largely focus on incentives to invest in renewable generation. But decentralized policies distort prices, so that price differences undervalue the marginal social benefit of additional transmission capacity. Hence, centralized subsidies to transmission investment can increase welfare under decentralized policy making. A harmonization of RES-E policies and a reduction in the set of available instruments is another way of increasing market efficiency by limiting the scope for trade policy. One possibility is to follow the example of Norway and Sweden and create an integrated certificate market. Certificate trade improves efficiency by reallocating renewable investment to its most socially beneficial location.

The remainder of this paper is organized as follows: Section 2 analyses the effects on prices, production, transmission investment and welfare of introducing certificates in a multinational electricity market. Section 3 introduces positive RES-E externalities and considers corrective policies for transmission investment and harmonization. Section 4 studies the properties of an integrated certificate market. Section 5 contains an example of the EU and discusses the robustness of the results. Section 6 concludes the paper. The analysis in the main body of the text rests on an informal graphical exposition of the model. The full model specification and mathematical proofs are relegated to the Appendix.

2. CERTIFICATES IN A MULTINATIONAL ELECTRICITY MARKET

Certificates, or renewable portfolio standards, are a common policy instrument for promoting electricity generation from renewable energy sources. Retailers are obliged to cover a share of sales by certified renewable electricity production. Certificate supply represents a source of income additional to the revenue producers earn by selling the electricity itself and creates an incentive to invest in renewable electricity production.[9]

[9] Certificates and feed-in tariffs are the two most common direct RES-E support systems (Fischer and Preonas, 2010; Schmalensee, 2012). The certificate price is market based, while the feed-in tariff is a regulated price for

Figure 1: The International Market Effects of Certificates

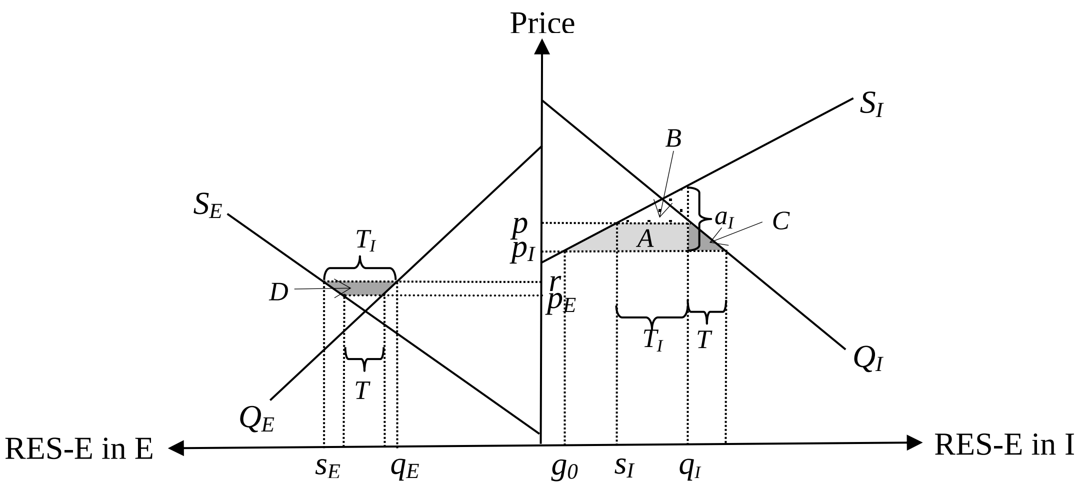

Figure 1 illustrates the effects of introducing a national market for certificates in a two-country model with electricity trade and transmission investment. The right-hand side of the figure depicts country I, which imports electricity from country E on the left-hand side. Production and consumption are on the horizontal axis. The vertical axis returns the wholesale price of electricity. Electricity is competitively supplied in both countries. Let $S_i = c_i'$ be the supply/marginal cost curve of renewable electricity in country $i = I, E$, while $Q_i = D_i - h_i'$ is the inverse residual demand for renewable electricity in country i, where total consumption D_i is constant, and h_i' is the supply/marginal cost curve of non-renewable electricity. Restricting the attention to constant total demand simplifies the graphical exposition without affecting the results in any substantial way. The Appendix presents a formal analysis of the model under the more general assumption of price elastic demand. Gains from trade render export from country E to I profitable, but bottlenecks in cross-border transmission capacity prevent full price equalization. Hence, electricity is more expensive in the import country than the export country even under full utilization of all transmission capacity.

Assume first that there are no support systems. The producers in the import country supply s_I terawatt hours (TWh) renewable electricity at equilibrium price p. Excess demand $q_I - s_I$ for renewable electricity at wholesale price p is covered by imports T_I. Producers in the export country supply s_E TWh renewable electricity at equilibrium price r, T_I of which is exported, while the remaining q_E is domestically consumed. Transmission gives rise to a congestion

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RES-E production. These two systems have qualitatively similar effects in the present deterministic framework. However, their efficiency properties may differ somewhat, an issue to which I will return.

rent $(p-r)T_I$. The socially optimal transmission capacity is found at the point at which the marginal transmission cost equals the wholesale price difference between the two countries: $c'_T(T_I)=p-r$. This is also the equilibrium if transmission is competitively supplied.[10]

Let the import country introduce a certificate system with the purpose of increasing renewable electricity production from s_I to q_I. The support system for RES-E production depresses the wholesale price of electricity in the import country from p to p_I. At the wholesale price p_I, a certificate price of a_I is required to maintain the profitability of the targeted q_I RES-E production. The congestion rent falls as the price difference between the two markets falls: $p_I-r<p-r$. Transmission becomes less profitable as a result, and capacity drops from T_I to T. Less transmission means less trade which, in turn, induces a price drop in the wholesale price from r to p_E in the export country. The introduction of a certificate system in the import country thus implies lower wholesale prices in both countries and less trade.

Introducing a certificate system in the *export* country reduces the wholesale price in that country from r to p_E which, in turn, accentuates the price differences between the two countries: $p-p_E>p-r$. An increased congestion rent renders transmission investment more profitable, resulting in increased trade between the two countries. Increased imports reduce the electricity wholesale price of electricity in the importing country from p to p_I.

Proposition 1 *A unilateral introduction of certificates for renewable electricity production (or increase in the quota obligation) in the home country*

1. *reduces the electricity wholesale price in both countries;*
2. *reduces the production of non-renewable electricity in both countries;*
3. *reduces (increases) the transmission capacity and thereby market integration if the home country is importing (exporting) electricity;*
4. *has ambiguous effects on domestic RES-E production;*
5. *reduces RES-E production abroad if the foreign country does not have any RES-E support system, but increases foreign RES-E production if that country already has a certificate system in place.*

[10] Most of transmission capacity is usually regulated in restructured electricity markets. If transmission capacity is set at the point at which the marginal transmission cost equals the price difference, then all results in this paper trivially hold even under regulation. Main predictions of the model still hold under alternative assumptions about market performance; see Section 5 for a discussion of the robustness of the results.

The negative effects on non-renewable electricity production follow straightforwardly from the decrease in electricity wholesale prices in both countries. As is well known, the effect of certificates on domestic RES-E supply is ambiguous (Amundsen and Mortensen, 2001). Total electricity demand in country i falls if certificates push up the retail price $p_i + f_i a_i$, where p_i is the wholesale price and a_i the certificate price. As RES-E is a constant share f_i of domestic consumption, the demand reduction may be sufficient to reduce RES-E production. However, domestic RES-E supply increases if the support system is modest, so that $f_i a_i$ is small or if electricity retail demand is price inelastic, as in Figure 1.

Foreign RES-E is entirely determined by the foreign price of electricity absent any RES-E support abroad. If so, foreign RES-E supply must fall because the expansion of the domestic certificate system reduces electricity wholesale prices. The situation is different if the foreign country already has a certificate system in place. The reduction in the wholesale price boosts electricity demand and curbs the supply of non-renewable electricity abroad. The price fall generates excess demand of RES-E abroad if RES-E constitutes a fixed share of consumption. This increases the certificate price and RES-E production abroad.

Consider the effect on the producer and consumer surplus of a certificate system in the import country. At the lower wholesale price p_I, it is only profitable to produce g_0 TWh RES-E in the import country absent any support system. To reach the q_I target, domestic RES-E must be subsidized by an amount equal to the sum of the light grey area *A* and the dotted triangle *B* in Figure 1 to cover the losses to RES-E production in the wholesale market. On the other hand, lower electricity wholesale prices represent a positive terms-of-trade effect on electricity imports by raising the consumer surplus by the sum of *A* and the dark grey triangle *C* in the figure. The net effect on producer and consumer surplus in the import country is *C-B*, which could be positive or negative. The price reduction causes a negative terms-of-trade effect abroad which reduces the consumer and producer surplus in the export country by an amount equal to the dark grey area *D* in Figure 1. The congestion profit also falls as a consequence of reduced electricity trade between the two countries. The loss in total surplus represents an aggregate welfare loss if all prices are at their competitive levels, production and transmission are supplied at the marginal social cost, and demand represents the marginal social valuation of electricity consumption. A certificate scheme in this situation does not only distort production and consumption, but also transmission capacity and therefore market integration below the efficient level.

Despite its adverse effects on the economy as a whole, the import country may nonetheless have a unilateral incentive to expand the certificate system. This happens if the positive terms-of-trade-effect dominates the marginal inefficiency of RES-E, so that $C>B$, and the loss in transmission profit is not too large. Introducing a certificate system is akin to policy makers in the import country exploiting trade policy to improve terms-of-trade in the international electricity market.

An electricity exporting country concerned with maximizing domestic surplus would never subsidize renewable electricity as this would not only distort domestic production, but also generate negative terms-of-trade effects. Instead, the exporting country can generate positive terms-of-trade in the electricity market by taxing the production of non-renewable electricity or by setting a carbon price floor in a market with emissions trading to drive up the electricity price. The total surplus falls also under this alternative support scheme because of distorted production and consumption. A further implication is that market integration falls below its efficient level because of insufficient transmission investments.

Proposition 2 *Countries participating in a multinational electricity market have incentives to support domestic RES-E production for trade policy reasons, even if none of them would attach any value to RES-E itself.*

1. *An electricity importing country can raise the domestic surplus by a certificate system for renewable electricity production.*
2. *An electricity exporting country can raise the domestic surplus by a tax on non-renewable electricity production.*
3. *Domestic RES-E mechanisms reduce overall surplus and distort transmission investment and thereby market integration below the efficient level if the market is otherwise well-functioning.*

Proposition 2 identifies a trade-off between support mechanisms for renewable electricity and market integration under decentralized policy making. Taxes on non-renewable electricity production and certificates are only examples of policies that countries might implement: Any RES-E policy which drives electricity prices in the desired direction would do.

The analysis has so far built on the assumption that the consumer and producer surpluses capture all costs and benefits of the electricity market. However, RES-E mechanisms are justified if there are welfare benefits to renewable electricity production that are not fully internalized in market prices. I now turn to the case of market external effects of RES-E.

3. MARKET EXTERNAL EFFECTS OF RENEWABLE ELECTRICITY

I add an aggregate benefit $B(g_E, g_I)$ of RES-E to the model in the previous section, which is not internalized by market participants through electricity wholesale prices.[11] Let (g_E^*, g_I^*) be the socially optimal production of RES-E in the two countries. The positive externality means that the marginal social cost of RES-E, $S_i^* = c_i' - \partial B(\cdot, g_j^*)/\partial g_i$, is smaller than the marginal production cost, $S_i = c_i'$. The competitive market thus delivers an insufficient RES-E supply. The socially optimal transmission capacity is found at the point at which the marginal social cost difference of renewable electricity production equals the marginal cost of transmission: $S_I^*(g_I^*) - S_E^*(g_E^*) = c_T'(T^*)$. Transmission can be over- or undersupplied at competitive equilibrium because import and export prices are distorted in the same direction.

Figure 2: A Socially Optimal RES-E Support Mechanism

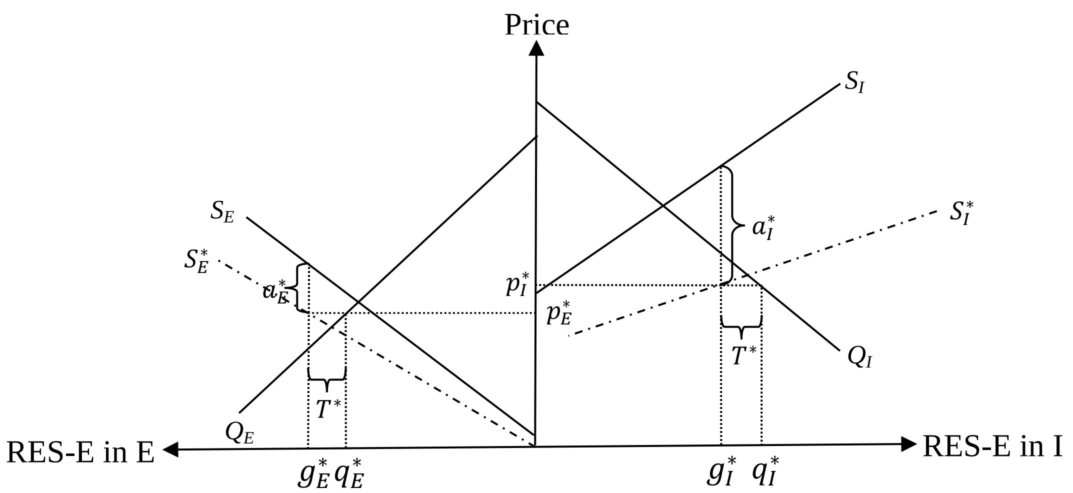

Figure 2 illustrates a socially optimal support system. A production subsidy of $a_i^* = \partial B(g_i^*, g_j^*)/\partial g_i$ in both countries financed by lump-sum transfers aligns production incentives.[12] It is not necessary to correct transmission investment because the marginal social cost of RES-E is included in the electricity wholesale price: $p_i^* = c_i'(g_i^*) - \partial B(g_i^*, g_j^*)/\partial g_i$.

[11] An alternative would be to specify a negative externality $C(b_E, b_I)$ of non-renewable production arising from greenhouse gas emissions. EU-ETS is designed with the purpose of internalizing this externality, so $C(b_E, b_I)$ is embedded in the cost functions $h_E(b_E)$ and $h_I(b_I)$ by assumption. $B(g_E, g_I)$ thus identifies a positive externality from RES-E unrelated to emissions reductions.

[12] Certificates cannot implement the social optimum unless demand is completely inelastic because they drive a wedge between consumers' marginal utility of consumption and the marginal production cost; see the Appendix for a characterization of the social optimum.

Under other support schemes, it is necessary to also correct transmission at the social optimum because investments based on congestion rent alone would be distorted. For example, a tax on non-renewable production by $\tau_i^* = \partial B(g_i^*, g_j^*)/\partial g_i$, redistributed in a lump-sum manner implements the socially optimal generation. However, the wholesale price difference $p_I^* - p_E^* = c_I'(g_I^*) - c_E'(g_E^*)$ fails to fully capture the differences in the marginal social cost of renewable electricity between countries in this case. Instead, transmission owners should receive a congestion price corrected for taxes: $p_I^* - p_E^* + \tau_E^* - \tau_I^*$.

Can decentralized policy making can implement the social optimum? The general answer is no. Increased RES-E production could have external effects abroad which the domestic policy maker fails to internalize. Let $B_i(g_i, g_j)$ be the market external effect of RES-E in country i. Cross-border externalities then arise if $\partial B_i/\partial g_j \neq 0$. But decentralized decision making is distortive even without cross-border externalities, i.e. for $B_i(g_i, g_j) = B_i(g_i)$. For trade policy reasons, the import (export) country has an incentive to deviate from the social optimum by increasing (reducing) RES-E output, causing insufficient market integration.[13]

Supranational intervention is required to improve total welfare. Ogawa and Wildasin (2009) show that it could be enough to decide on an appropriate renewable target for the economy as a whole under decentralized policy making if total renewable production is what matters to the economy, i.e. for $B(g_I^*, g_E^*) = B(g_I^* + g_E^*)$. Countries may choose policies that maximize domestic welfare, but investments flow between countries in a manner which equates the marginal social cost of RES-E across countries, thereby ensuring efficiency at equilibrium. However, this result relies on the assumption that policy makers treat prices as given in the international market. If policy makers instead take into account the effects of domestic policies on electricity prices, then decentralized decision making comes at a social cost.

Proposition 3 *If RES-E targets are fixed at the social optimum* (g_E^*, g_I^*), *but national policy makers are free to choose in a decentralized manner the policies with which to reach these targets, then resource allocation is still inefficient.*

1. *An electricity importing (exporting) country maximizing domestic welfare selects a combination of instruments which decreases (increases) electricity wholesale prices below (above) the efficient level.*

[13] Tangerås (2014) states and proves this result in the context of direct subsidies to RES-E production financed by lump-sum transfers. This result also implies that voluntary targets are unlikely to work.

2. *Domestic policies distort transmission investment and thereby market integration below the social optimum.*

Proposition 3 shows that increased market integration may stand in conflict with other energy policy goals of the EU, not least owing to the decentralized manner in which some of these goals are attained. National policy makers have access to a host of policy instruments for promoting RES-E such as certificates, feed-in tariffs and direct investment support. Taxes on consumption and production from non-renewable sources are other tools in the policy maker's toolbox. This plethora of instruments leave ample room for national policy makers to pursue objectives unrelated to the environment, RES-E or energy efficiency. An electricity importing country can suppress electricity prices and improve its terms-of-trade by taxing electricity consumption. A corresponding increase in subsidies to RES-E production allows the country to meet its national RES-E target even at lower electricity prices. An electricity exporting country can raise the electricity price and thus improve its terms-of-trade by taxing production from non-renewable sources and neutralize any incentive to overinvest in RES-E by reducing renewable subsidies. One such instrument is a feed-in tariff with a cap on total revenues which fully offsets profit increases resulting from taxes on non-renewable electricity.

Trade policy disguised as RES-E policy distorts market integration below the social optimum because inefficiently low (high) import (export) prices reduce the congestion rent and the profitabily of transmission investment. One way of offsetting the negative consequences of domestic policies would be to strengthen market integration by subsidizing transmission investment. Consider a transfer mT on top of congestion rent, financed by a lump-sum tax on electricity consumers in the two countries:

Proposition 4 *If RES-E targets are fixed at the social optimum* (g_E^*, g_I^*), *but national policy makers are free to choose in a decentralized manner the policies with which to reach these targets, then there exists a transmission subsidy* $m > 0$ *which increases the total surplus*[14]

Transmission regulation limits the distortions to transmission capacity, but does not eliminate the scope for trade policy. Policy makers can still manipulate international electricity prices to

[14] The Renewables Grid Initiative argues in a note to the DG budget that public co-funding at the EU level would facilitate investment in cross-border capacity and thereby increase market integration (http://renewables-grid.eu/documents/position-papers.html, accessed June 10, 2013). Proposition 4 shows that co-funding could be efficient.

their benefit by domestic policies.[15] An alternative to transmission regulation is to harmonize national policies and reduce the number of instruments available to national policy makers:

Proposition 5 *If RES-E targets are fixed at the social optimum* (g_E^*, g_I^*)*, and national policy makers are instructed to reach their renewable targets by means of direct subsidies to RES-E production financed by lump-sum transfers, then the socially optimal subsidy levels are the unique outcomes of decentralized policy making.*

But centralization is demanding in terms of the information needed to implement the solution. It requires that the centralized planner knows the socially optimal amount of renewables and also the correct distribution of costs and benefits of renewables throughout the economy. A more plausible assumption is that the central planner is incompletely informed about relevant aspects of the economy. Multinational support schemes can increase the efficiency in this case. The next section considers one such scheme, an integrated certificate market.

4. AN INTERGRATED CERTIFICATE MARKET

The joint Norwegian and Swedish certificate market opened in 2012 and was the first integrated certificate market in the world. In this market, a consumer fulfils the quota obligation either by purchasing Norwegian or Swedish certificates. Perfect substitutability between certificates and zero trade costs yield a uniform certificate price in the two countries.

Figure 3: Certificate Market Integration

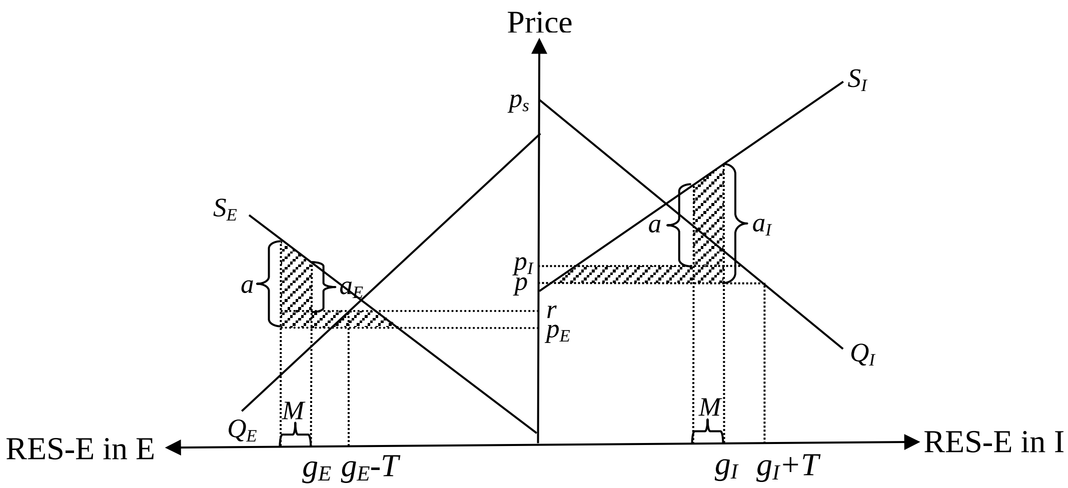

Figure 3 illustrates the effect of certificate market integration, starting from a situation with

[15] In the proof of Proposition 4, I show that domestic policy makers distort prices for any $m \geq 0$.

two autarkic certificate markets. Initially, country I produces g_I TWh renewable electricity at wholesale price p and certificate price a_I. Excess demand at price p is covered by T TWh imports from country E, which produces g_E TWh renewable electricity at wholesale price r and certificate price a_E. Transmission capacity is at the competitive level: $p - r = c'_T(T)$.

Assume that the two countries integrate their certificate markets. Certificate trade drives down the certificate price in country I and raises the certificate price in country E until the price is equalized in both countries, and the certificate market clears at a. Under the assumption of price inelastic electricity demand (this is for expositional purposes only), the relative change of certificate prices drives up renewable electricity production by M in country E with a corresponding reduction in country I. As a consequence, the wholesale price of electricity falls from r to p_E in the export country and increases from p to p_I in the import country. The increased price difference increases the congestion rent which triggers network investment. Exports now increase to T_I (not indicated in the figure), where $p_I - p_E = c'_T(T_I)$.

On the other hand, certificate market integration increases (reduces) RES-E in the import (export) country if the certificate price is initially lower in the importing country: $a_I < a_E$. This reallocation of renewable production from the exporting to the importing country reduces price differences between the two markets which, in turn, reduces trade and market integration:

Proposition 6 *Certificate market integration decreases (increases) transmission investment and thereby electricity market integration if the electricity importing (exporting) country possesses a comparative advantage in the production of renewable electricity. Certificate market integration unambiguously increases the total surplus in the electricity wholesale market.*

Certificate trade implies that the production inefficiency associated with certificates falls in country I by the scratched area on the right-hand side of Figure 3, but increases in country E by the scratched area on the left-hand side. The net effect is positive. But contrary to common belief, e.g. Söderholm (2008) and Schmalensee (2012), efficiency of an integrated certificate market does *not* imply an equalization of renewable marginal production costs across the market. Hence, one could not draw the conclusion that integrated certificate markets were inefficient based on an observation that the marginal costs of RES-E production differed across the market. In Figure 3, renewable electricity is produced at marginal cost $p_I + a$ in the import country at the social optimum, which is higher than the marginal cost $p_E + a$ of renewable electricity in the export country. Under certificate market autarky, the certificate price a_I measures the marginal deadweight loss in the electricity market associated with RES-E support in the import country because a_I is the difference between the marginal production cost $p + a_I$ of RES-E and the marginal production cost p of non-renewable electricity. Similarly, a_E represents the marginal deadweight loss of renewable electricity support in the export country. Certificate market integration increases efficiency by equating the *marginal deadweight losses* of RES-E across markets: $a_I = a_E = a$. Marginal production costs are equalized if and only if wholesale prices are the same in all markets. However, bottlenecks generally prevent the full equalization of electricity wholesale prices at the social optimum because transmission capacity is costly.

Certificate market integration induces a reallocation of renewable electricity investment to the country with the lowest certificate price in autarky. In Figure 3, RES-E production increases by M in country E and falls by the same amount in country I under integration. Total RES-E production may still decrease with certificate market integration and render it more difficult to attain an aggregate production target $g_E + g_I$. If the distribution of RES-E investments matters, i.e. $\partial B(g_I^*, g_E^*)/\partial g_I \neq \partial B(g_E^*, g_I^*)/\partial g_E$, then differentiated certificate prices are required at the social optimum. Full integration of certificate markets is suboptimal in that case. Certificate market integration may thus entail a trade-off between higher efficiency in the electricity wholesale market and the achievement of aggregate and national RES-E targets.

5. DISCUSSION

The theoretical analysis in this paper has derived a number of empirically testable predictions. Electricity importing countries have incentives to implement policies which reduce the price of electricity, such as subsidies to RES-E. Electricity exporting countries benefit from policies which raise prices, such as taxes on non-renewable electricity production.

These predictions are derived from the assumption that decentralized policies are chosen to maximize domestic welfare whereby policy makers attach equal weights both to domestic consumer and producer surplus. Energy policy is likely to depend also on the lobbying efforts of interest groups exercising political pressure to push electricity prices in their preferred direction. On the one hand, the electricity intensive industry and consumer groups lobby for policies which reduce electricity prices. On the other hand, producers benefit from higher electricity prices. Consequently, one would not be surprised to see power companies with a large portfolio of non-fossil production lobbying in favor of taxes on dirty technologies.[16] Lobbying will shift the weights in the political objective functions between consumer and producer surplus. If, for example, consumer interest groups are the most effective in their lobbying efforts, one would expect certificates or feed-in-tariffs to be more frequent than, for example, taxes on non-renewable electricity production.

Jenner et al. (2012) analyze the determinants of RES-E mechanisms (quota system or feed-in-tariff) in 27 EU member countries.[17] With regard to the importance of lobbying, they find a long presence of a national chapter of the International Solar Energy Association to increase the likelihood of early adoption of a RES-E mechanism in that country. However, Jenner et al. (2012) do not consider electricity trade flows in relation to RES-E policy. In light of the previous analysis, one might expect electricity importing countries to have been keener on quota systems or feed-in-tariffs and have introduced them at an earlier stage than electricity exporting countries. The median year of enacting a RES-E policy among the EU27 was 2002 according to Jenner et al. (2012). I henceforth define a country as an early adopter if it introduced a RES-E policy prior to 2002. A late adopter is a country which introduced RES-E policies in 2002 or later. Nine countries are identified as early adopters by this definition.

The theoretical results are derived in a two-country model with unidirectional electricity trade. In reality, electricity often flows in both directions over the course of a year to balance local demand and supply fluctuations. Countries usually have more than one trading partner, exporting electricity to one country while importing it from another. The overall incentive to subsidize renewable production or tax non-renewable production depends on net trade flows. I thus define a country as an electricity importing (exporting) country if its average annual net import (export) volume of electricity over the six year period 1990-95 was statistically significant at the 10% level. A balanced country is one with average annual net trade that is insignificant from zero. Eleven (six) of the EU27 were electricity importing (exporting) countries by this definition. All trade volumes are from Eurostat.

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[16] A case in point is the proposal by Vattenfall and other large European power companies to support renewable electricity technologies by R&D support rather than production subsidies and to strengthen the European carbon market by ambitious emissions reductions targets and expanding emissions trading to other CO_2 emitting sectors; see www.gdfsuez.com/wp-content/uploads/2013/11/12CEO_VA_v4.pdf, accessed January 13, 2014.

[17] There are now 28 countries in the EU. Croatia became a member in 2013 and is not in the sample.

Table 1: Electricity Trade and the Adoption of RES-E Policy in the EU27

	Import	Balanced	Export
Early Adopters	GR, IT, LU, PT	AT, DE, DK, ES	FR
Late Adopters	FI, GB, HU, LV, NL, RO, SK	BE, BG, CY, IE, MT, SE	CZ, EE, LT, PL, SI

The data seem consistent with the hypothesis of trade flows and early adoption. Four of the early adopters in Table 1 were net importers of electricity whereas all net exporters except one (France introduced a RES-E policy in 2001) were late adopters. Three of the balanced early adopters, Denmark, Germany and Spain, were import countries on average, but not in a statistically significant sense.

RES-E mechanisms reduce the consumption and price of all types of imported energy to the extent that energy imports and domestic electricity consumption are substitutes. The introduction of the EU Renewables Directive itself can be viewed in light of this substitution effect: “Renewable energies as indigenous sources of energy will have an important role to play in reducing the level of energy imports with positive implications for balance of trade and security of supply” (European Commission, 1997). Obviously, a desire to reduce import dependency can have spurred RES-E mechanisms also at the national level.

Table 2: Natural Gas Trade and the Adoption of RES-E Policy in the EU27

	Large Importer	Small Importer/Exporter
Early Adopters	AT, DE, ES, FR, IT	DK, GR, LU, PT
Late Adopters	BE, BG, CZ, GB, HU, PL, RO, SK	CY, EE, FI, IE, LT, LV, MT, NL, SE, SI

Table 2 relates the adoption of RES-E policies to net trade flows of natural gas in the EU. Denmark and The Netherlands were net exporters of natural gas while the 21 other countries that traded natural gas during the period 1990-95 were net importers.[18] I define a country as a large importer if and only if the country’s share of total net imports of the EU27 was above

[18] Cyprus, Greece, Malta and Portugal did not trade in natural gas during the period. The data are from Eurostat.

the median. France, Germany and Italy were responsible for three quarters of the net imports of natural gas of EU27 during the period 1990-95. The important thing to note about Table 2 is that these three countries all were early adopters of national RES-E policies.

Summarizing the two tables, we see that three of the nine early adopters of RES-E policies were net importers of electricity (Greece, Luxemburg, Portugal), four were large importers of natural gas (Austria, France, Germany, Spain) and one country (Italy) was both. Denmark is the only outlier in the sense that it was neither an importer of electricity nor a large importer of natural gas. The above results point to the importance of incorporating energy trade flows in the empirical analysis of the determinants of energy policy, but are indicative and should be interpreted with caution. I leave a rigorous analysis to future research.

The theoretical analysis rests on the assumption that generation and transmission are competitively supplied. Most electricity markets are concentrated and therefore susceptible to the exercise of market power; see Wolfram (1999) or Borenstein et al. (2002) for classical treaties. Domestic transmission networks are often owned by one or several transmission network operators (TSOs) subject to regulation. Still, main predictions of the model appear robust to changes in market performance. For example, subsidies tend to reduce electricity prices even under imperfect competition. A lower congestion rent would have a negative effect on transmission investment even under regulation.[19] A pro-competitive effect of market integration arises under imperfect competition because bottlenecks limit competition (Holmberg and Philpott, 2012). This additional externality suggests that distortions of market integration associated with domestic RES-E policies are equally and perhaps even more substantial under imperfect product market competition. Considering imperfect product market competition in a market with endogenous transmission capacity is an interesting (and difficult) problem, the solution to which is outside the scope of this paper.

6. CONCLUSION

This paper has investigated the interplay between decentralized support policies for renewable electricity production, RES-E, and market integration in a multinational electricity market. A main finding is that a trade policy motive arises if national policy makers choose support schemes to maximize domestic welfare. Electricity importing (exporting) countries have

[19]As an illustrative case in point, the Swedish TSO, Svenska Kraftnät, is under governmental instruction to invest all its congestion rent in transmission. While inducing excessive investment, this policy also has the effect that reductions in congestion rent reduce transmission investment.

incentives to implement policies which serve to reduce the import (increase the export) price of electricity. The pursuit of domestic objectives distorts transmissions investments, and thereby market integration, below the efficient level.

Distortions to production and transmission investments cannot be corrected by imposing national renewable targets alone. Instead, centralized subsidies to transmission investment and a harmonization of and reduction in the number of policy instruments can improve welfare. The analysis also reveals that certificate market integration increases the total surplus.

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APPENDIX

This Appendix formally analyses the model upon which the analysis in the main text rests. There are two countries, the export country, indexed by E, and the import country, indexed by I. The representative consumer in country $i = E, I$ purchases q TWh electricity to maximize quasi-linear utility $u_i(q) - (p_i + f_i a_i)q$, where p_i is the electricity wholesale price, f_i the quota obligation and a_i the certificate price in country i. The utility function $u_i(q)$ is twice continuously differentiable, strictly increasing and strictly concave, with $\lim_{q\to 0} u_i{}'(q) = \infty$. Indirect utility is $v_i(p_i + f_i a_i) = \max_{q\geq 0}[u_i(q) - (p_i + f_i a_i)q]$. Define electricity demand in country i by $q_i = D_i(p_i + f_i a_i)$. There are two types of electricity production in country i, renewable in amount g_i and non-renewable in amount b_i, with cost functions $c_i(g_i)$ and $h_i(b_i)$. Both cost functions are twice continuously differentiable, strictly increasing and strictly convex with $\lim_{g\to 0} c_i'(g) = 0$ and $\lim_{b\to 0} h_i'(b) = 0$. The profit of the two types of production is $(p_i + a_i)g_i - c_i(g_i)$ and $p_i b_i - h_i(b_i)$, respectively. Electricity is exported from E to I in quantity T, where T is the capacity of the cross-border interconnection between E and I. Congestion profit equals $(p_I - p_E)T - c_T(T)$, where $c_T(T)$ is the strictly increasing, twice continuously differentiable and strictly convex cost of providing transmission, with $\lim_{T\to 0} c_T'(T) = 0$. Let electricity and transmission be competitively supplied.

The set of first-order conditions ($i = I, E$):

$$p_i + a_i = c'_i(g_i), p_i = h'_i(b_i), p_I - p_E = c'_T(T) \tag{1}$$

plus the set of market-clearing conditions

$$g_i = f_i D_i(p_i + f_i a_i), b_i = (1 - f_i) D_i(p_i + f_i a_i) + (-1)^{\frac{i-E}{I-E}} T \tag{2}$$

define the unique interior equilibrium when there is no certificate trade between countries.

Proof of Proposition 1

By total differentiation of the equilibrium conditions above ($i \neq j = E, I$):

$$\frac{\partial p_i}{\partial f_i} = -\Omega h_i'' \left(K_j + \left(1 - f_j^2 c_j'' D_j'\right) \frac{h_j''}{c_T''} \right) [q_i(1 - f_i c_i'' D_i') - a_i(1 - f_i) D_i'] < 0,$$

$$\frac{\partial p_i}{\partial f_j} = -\Omega \frac{h_I'' h_E''}{c_T''} (1 - f_i^2 c_i'' D_i') \left[q_j \left(1 - f_j c_j'' D_j'\right) - a_j \left(1 - f_j\right) D_j' \right] < 0,$$

where

$$K_E = 1 - (f_E^2 c_E'' + (1 - f_E)^2 h_E'') D_E' > 1,$$

K_I is similarly defined, and

$$\Omega^{-1} = K_I K_E + \frac{h_I''}{c_T''} (1 - f_I^2 c_I'' D_I') K_E + \frac{h_E''}{c_T''} (1 - f_E^2 c_E'' D_E') K_I > 1.$$

The comparative statics above reveal that the electricity wholesale price at home is strictly decreasing in the quota obligation at home and abroad.

Bearing in mind the first-order condition $p_i = h_i'(b_i)$ and the above price effects:

$$\frac{\partial b_i}{\partial f_I} = \frac{1}{h_i''} \frac{\partial p_i}{\partial f_I} < 0, \frac{\partial b_i}{\partial f_E} = \frac{1}{h_i''} \frac{\partial p_i}{\partial f_E} < 0.$$

Hence, the supply of non-renewable electricity is decreasing in the quota obligations independently of whether the increase is at home or abroad.

Using $p_I - p_E = c_T'(T)$ and the price effects, after simplifications ($i \neq j = I, E$), I obtain:

$$\frac{\partial T}{\partial f_i} = \frac{1}{c_T''} \left(\frac{\partial p_I}{\partial f_i} - \frac{\partial p_E}{\partial f_i} \right) = (-1)^{\frac{i-E}{I-E}} \Omega \frac{h_i''}{c_T''} [q_i(1 - f_i c_i'' D_i') - a_i(1 - f_i) D_i'] K_j.$$

Transmission capacity and trade are lower (higher) if the quota obligation in the importing (exporting) country is higher ($\partial T / \partial f_I < 0$ and $\partial T / \partial f_E > 0$).

Consider next the effect on RES-E production. It is useful to study the effect on the certificate price. The effect on the domestic certificate price of an increase in the own quota obligation

$$\frac{\partial a_i}{\partial f_i} = \Omega h_i''[K_j + (1 - f_j^2 c_j'' D_j')\frac{h_j''}{c_T''}][q_i(1 - c_i'' D_i') - a_i(1 - f_i)D_i']$$

$$+\Omega c_i''[(1 + \frac{h_i''}{c_T''})K_j + \left(1 - f_j^2 c_j'' D_j'\right)\frac{h_j''}{c_T''}][q_i + a_i f_i D_i']$$

is ambiguous in general, but positive if electricity demand is inelastic or the support system is sufficiently small ($f_i a_i$ is small):

$$-\frac{(p_i + a_i f_i)D_i'}{q_i} \leq \frac{p_i + a_i f_i}{a_i f_i}.$$

However, the domestic certificate price is strictly increasing in the quota obligation abroad:

$$\frac{\partial a_i}{\partial f_j} = \Omega \frac{h_I'' h_E''}{c_T''}(1 - f_i c_i'' D_i')\left[q_j\left(1 - f_j c_j'' D_j'\right) - a_j\left(1 - f_j\right)D_j'\right] > 0.$$

Invoking the first-order condition $p_i + a_i = c'_i(g_i)$, I obtain

$$\frac{\partial g_i}{\partial f_i} = \frac{1}{c_i''}(\frac{\partial p_i}{\partial f_i} + \frac{\partial a_i}{\partial f_i}) = -\Omega h_i''(1 - f_i)[K_j + (1 - f_j^2 c_j'' D_j')\frac{h_j''}{c_T''}]q_i D_i'$$

$$+\Omega[(1 + \frac{h_i''}{c_T''})K_j + \left(1 - f_j^2 c_j'' D_j'\right)\frac{h_j''}{c_T''}][q_i + a_i f_i D_i'],$$

which is ambiguous, but strictly positive if, for example, electricity demand is inelastic or the support system is sufficiently small.

I need to consider separately the case of RES-E support systems from the case without RES-E support when analyzing the predicted effects on renewable electricity production abroad. Absent any RES-E support abroad, equilibrium renewable production is characterized by the first-order condition $p_i = c'_i(g_i)$. By necessity, $\partial g_i / \partial f_j < 0$ because $\partial p_i / \partial f_j < 0$. If there exists a certificate system abroad, then

$$\frac{\partial g_i}{\partial f_j} = f_i D_i' \frac{\partial (p_i + f_i a_i)}{\partial f_j} = -f_i D_i' \Omega \frac{h_I'' h_E''}{c_T''}(1 - f_i)\left[q_j\left(1 - f_j c_j'' D_j'\right) - a_j\left(1 - f_j\right)D_j'\right] > 0,$$

by the market clearing condition $g_i = f_i D_i(p_i + f_i a_i)$.

Finally, the domestic retail price is ambiguous to changes in the own quota obligation:

$$\frac{\partial (p_i + f_i a_i)}{\partial f_i} = \frac{\partial p_i}{\partial f_i} + f_i \frac{\partial a_i}{\partial f_i} + a_i$$

$$= \Omega \frac{h_i'' h_i''}{c_T''} K_j (1 - f_i) q_i + \Omega\left[(1 + \frac{h_i''}{c_T''})K_j + \left(1 - f_j^2 c_j'' D_j'\right)\frac{h_j''}{c_T''}\right][a_i + q_i(f_i c_i'' - (1 - f_i)h_i'')].$$

But as is also well known, the retail price is increasing in the own quota obligation if either the certificate price a_i is high, the quota obligation f_i is large, the supply of renewable electricity is inelastic (c_i'' is large) or the supply of non-renewable electricity is elastic (h_i'' is small), i.e. $a_i + q_i(f_i c_i'' - (1-f_i)h_i'') \geq 0$. ■

Proof of Proposition 2

Let all domestic electricity production be owned by domestic firms, and let country $i = I, E$ earn a share α_i of congestion profit. The surplus in country i equals the sum of the domestic consumer surplus, the domestic firm profit and the country's share of congestion profit:

$$w_i = v_i(p_i + f_i a_i) + (p_i + a_i)g_i - c_i(g_i) + p_i b_i - h_i(b_i) + \alpha_i[(p_I - p_E)T - c_T(T)].$$

By repeated use of the envelope theorem on consumer surplus, producer and transmission profits, and the market clearing conditions (2):

$$\frac{\partial w_I}{\partial f_i} = -(\alpha_E \frac{\partial p_I}{\partial f_i} + \alpha_I \frac{\partial p_E}{\partial f_i})T - X_i a_I q_I, \frac{\partial w_E}{\partial f_i} = (\alpha_E \frac{\partial p_I}{\partial f_i} + \alpha_I \frac{\partial p_E}{\partial f_i})T - (1 - X_i)a_E q_E,$$

where $X_I = 1$ and $X_E = 0$. Summing up yields

$$\frac{\partial w_I}{\partial f_i} + \frac{\partial w_E}{\partial f_i} = -X_i a_I q_I - (1 - X_i)a_E q_E < 0.$$

The total surplus falls by an increase in the quota obligation in any country.

The surplus in the import country unambiguously increases with increases in the quota obligations abroad ($\partial w_I / \partial f_E > 0$), but may increase or fall as the quota obligation at home increases. Define $f_{I0} \geq 0$ as the share of certified electricity that would prevail in in country I absent a renewable support scheme in that country, i.e. $a_I(f_{I0}, f_E) = 0$. Note that:

$$\left|\frac{\partial w_I}{\partial f_I}\right|_{f_I = f_{I0}} = -(\alpha_E \frac{\partial p_I}{\partial f_I} + \alpha_I \frac{\partial p_E}{\partial f_I})T > 0,$$

So the import country has an incentive to introduce a certificate system if the policy maker maximizes domestic surplus and places no intrinsic value on renewable electricity.

The surplus in the export country unambiguously falls with increases in the quota obligations at home and abroad ($\partial w_E / \partial f_E < 0$ and $\partial w_I / \partial f_I < 0$). So a policy maker in the export country aiming at increasing the domestic surplus would never introduce certificates. Instead, a tax on non-renewable electricity would increase the domestic surplus; see Tangerås (2014).

Subsidies to renewable electricity production in the import country and taxes on non-renewable electricity production in the export country reduce the difference $p_I - p_E$ below what maximizes the total surplus. As the transmission capacity (market integration) is monotonically increasing in $p_I - p_E$, the equilibrium market integration is inefficiently low. ■

Implementation of the social optimum under market external effects

The benevolent social planner maximizes

$$B(g_I, g_E) + \sum_{i=I,E} (u_i(q_i) - c_i(g_i) - h_i(b_i)) - c_T(T)$$

over (q_i, g_i, b_i) and T subject to the market clearing constraint $q_i + (-1)^{\frac{i-E}{I-E}} T \leq g_i + b_i$. The benefit B of RES-E is strictly increasing in both arguments, twice continuously differentiable and strictly concave. Let λ_i be the Lagrangian multiplier associated with the market clearing constraint in i. The first-order conditions ($i \neq j = I, E$):

$$\partial B(g_i^*, g_j^*)/\partial g_i + \lambda_i^* = c_i'(g_i^*),\ \lambda_i^* = h_i'(b_i^*),\ u_i'(q_i^*) = \lambda_i^*,\ \lambda_I^* - \lambda_E^* = c_T'(T^*)$$

and the complementary slackness conditions

$$\lambda_I^*(g_I^* + b_I^* + T^* - q_I^*) = 0,\ \lambda_E^*(g_E^* + b_E^* - T^* - q_E^*) = 0,\ \lambda_i^* \geq 0$$

jointly characterize the unique social optimum.

The social optimum equates the marginal social cost of production across technologies in both countries: $\lambda_i^* = c_i'(g_i^*) - \partial B(g_i^*, g_j^*)/\partial g_i = h_i'(b_i^*)$. Optimal transmission capacity is at the point at which $c_T'(T^*) = c_I'(g_I^*) - \partial B(g_I^*, g_E^*)/\partial g_I - c_E'(g_E^*) + \partial B(g_E^*, g_I^*)/\partial g_E$.

The social optimum can be implemented as a competitive equilibrium with subsidies to renewable production financed by lump-sum taxation of electricity consumers. A wholesale price of $p_i^* = \lambda_i^*$, a renewable production subsidy of $a_i^* = \partial B(g_i^*, g_j^*)/\partial g_i$ and the socially optimal allocations solve the first-order conditions for production and transmission and clear the electricity markets in both countries. With renewable production subsidies alone, competitive transmission supply is socially optimal: $c_T'(T^*) = p_I^* - p_E^*$. Given subsidies a_I^* and a_E^*, firms produce the socially optimal shares of renewable production

$$f_I^* = \frac{g_I^*}{g_I^* + b_I^* + T^*},\ f_E^* = \frac{g_E^*}{g_E^* + b_E^* - T^*}.$$

Lump-sum transfers from consumers amounting to a total of $a_I^* g_I^* + a_E^* g_E^*$ entail no welfare costs under quasi-linear preferences. However, certificates cannot implement the social optimum because they distort the marginal retail prices. At the social optimum, $u_i'(q_i^*) = h_i'(b_i^*)$. Instead, $u_i'(q_i) = p_i + a_i f_i \gtreqless p_i = h_i'(b_i)$ in a competitive electricity market with certificates, with equality if and only if $a_i f_i = 0$. Hence, certificates are efficient only if $a_I f_I = a_E f_E = 0$. But then, certificates cannot cover the losses to RES-E production.

An equivalent solution to subsidizing renewables is to tax non-renewable production by $\tau_i^* = \partial B(g_i^*, g_j^*)/\partial g_i$, let renewable production receive $p_i^* = \lambda_i^* + \partial B(g_i^*, g_j^*)/\partial g_i$ and redistribute tax revenue $\tau_I^* g_I^* + \tau_E^* b_E^*$ to consumers in a lump-sum fashion. Under this alternative support mechanism, consumers pay $p_i^* - \tau_i^*$, and the owners of transmission receive a congestion price corrected for taxes: $p_I^* - p_E^* + \tau_E^* - \tau_I^*$.

Proof of Proposition 3

Let $B_I(g_I, g_E) + B_E(g_E, g_I) = B(g_I, g_E)$. If, for example, welfare in country i equals

$$B_i(g_i^*, g_j^*) + u_i(q_i^*) - c_i(g_i^*) - h_i(b_i^*) + \lambda_i^*(g_i^* + b_i^* - q_i^*) + \alpha_i\big((\lambda_I^* - \lambda_E^*)T^* - c_T(T^*)\big)$$

at the social optimum, where $\lambda_i^* = h_i'(b_i^*)$, then the policy maker of that country is indifferent between all policies which implement the social optimum because domestic welfare then depends entirely on the allocations (g_I^*, b_I^*, q_I^*), (g_E^*, b_E^*, q_E^*) and T^*. I only need to show that national policy makers have a unilateral incentive to deviate from some socially optimal policy to establish the incentive incompatibility of decentralized decision making in this case. Let the default policy be the renewable production subsidy $a_i^* = \partial B(g_i^*, g_j^*)/\partial g_i$ with the wholesale price $p_i^* = \lambda_i^*$ financed by the lump-sum transfer $a_i^* g_i^*$.

Fix renewable production at (g_I^*, g_E^*). Assume that country E applies a combination of a non-renewable production tax $\tau_E \geq 0$ and a renewable production subsidy a_E to attain its renewable target g_E^*. Country I uses a mix of a consumption tax $\phi_I \geq 0$ and renewable production subsidy a_I to reach its target g_I^*. Both countries balance their budgets by lump-sum net transfers to electricity consumers. Let transmission investment be subsidized at the central level by mT, the cost of which is redistributed across countries in a lump-sum fashion according to the distribution of transmission ownership shares. For simplification, assume that domestic policies and m are set simultaneously.

Define electricity demand $q_I = D_I(p_I + \phi_I)$ and $q_E = D_E(p_E)$. The first-order conditions

$$p_I = h'_I(b_I),\ p_E - \tau_E = h'_E(b_E), m + p_I - p_E = c'_T(T) \qquad (3)$$

and market-clearing conditions

$$D_I(p_I + \phi_I) = g_I^* + b_I + T, D_E(p_E) = g_E^* + b_E - T \qquad (4)$$

uniquely define equilibrium wholesale prices (p_I, p_E), non-renewable production (b_I, b_E) and transmission T as functions of (ϕ_I, τ_E, m). Given the equilibrium price p_i, the policy maker in country i sets the production subsidy residually to implement the country's renewables target:

$a_i = c_i'(g_i^*) - p_i$. By uniqueness of the competitive equilibrium and the social optimum, these policies implement the social optimum if and only if $\phi_I = \tau_E = m = 0$.

By total differentiation of the equilibrium conditions:

$$dp_I = \Upsilon(\frac{1}{h_E''} + \frac{1}{c_T''} - D_E')D_I' d\phi_I + \frac{\Upsilon}{h_E'' c_T''} d\tau_E,$$

$$dp_E = \frac{\Upsilon D_I'}{c_T''} d\phi_I + \frac{\Upsilon}{h_E''}(\frac{1}{h_I''} + \frac{1}{c_T''} - D_I')d\tau_E,$$

where

$$\Upsilon^{-1} = (\frac{1}{h_I''} - D_I')(\frac{1}{h_E''} - D_E') + \frac{1}{c_T''}(\frac{1}{h_I''} - D_I' + \frac{1}{h_E''} - D_E') > 0.$$

Electricity wholesale prices are decreasing in the consumption tax ($\delta p_i/\delta \phi_I < 0$) and increasing in the production tax ($\delta p_i/\delta \tau_E > 0$) in both countries. The domestic effect is stronger than the foreign effect, so the price difference is falling in both policies:

$$dT = \frac{1}{c_T''}(dp_I - dp_E) = \frac{\Upsilon}{c_T''}(\frac{1}{h_E''} - D_E')D_I' d\phi_I - \frac{\Upsilon}{h_E'' c_T''}(\frac{1}{h_I''} - D_I')d\tau_E.$$

Thus, transmission capacity is falling in both policies: $\delta T/\delta \phi_I < 0$ and $\delta T/\delta \tau_E < 0$. Finally,

$$db_I = \frac{1}{h_I''} dp_I = \frac{\Upsilon}{h_I''}(\frac{1}{h_E''} + \frac{1}{c_T''} - D_E')D_I' d\phi_I + \frac{\Upsilon}{h_I'' h_E'' c_T''} d\tau_E,$$

$$db_E = \frac{1}{h_E''}(dp_E - d\tau_E) = \frac{\Upsilon D_I'}{h_E'' c_T''} d\phi_I - \frac{\Upsilon}{h_E''}[\frac{1}{c_T''}(\frac{1}{h_I''} - D_I' - D_E') - h_E''(\frac{1}{h_I''} - D_I')D_E']d\tau_E$$

and

$$dq_I = D_I'(dp_I + d\phi_I) = \Upsilon[(\frac{1}{h_I''} + \frac{1}{c_T''})(\frac{1}{h_E''} - D_E') + \frac{1}{c_T'' h_I''}]D_I' d\phi_I + \frac{\Upsilon D_I'}{h_E'' c_T''} d\tau_E,$$

$$dq_E = \frac{\Upsilon D_E' D_I'}{c_T''} d\phi_I + \frac{\Upsilon}{h_E''}(\frac{1}{h_I''} + \frac{1}{c_T''} - D_I')D_E' d\tau_E$$

imply that a higher consumption tax in country I leads to lower non-renewable production in both countries ($\delta b_i/\delta \phi_I < 0$) and lower (higher) consumption in the import (export) country: $\delta q_I/\delta \phi_I < 0$ ($\delta q_E/\delta \phi_I > 0$). Consumption in both countries fall with increases in the non-renewables production tax in country ($\delta q_i/\delta \tau_E < 0$), while non-renewable production increases (falls) in the import (export) country: $\delta b_I/\delta \tau_E > 0$ ($\delta b_E/\delta \tau_E < 0$).

The marginal effect on welfare

$$B_I(g_I^*, g_E^*) + u_I(q_I) - p_I T - c_I(g_I^*) - h_I(b_I) + \alpha_I\big((p_I - p_E)T - c_T(T)\big)$$

in country I of increasing the consumption tax is given by

$$\phi_I \frac{\partial q_I}{\partial \phi_I} - (\alpha_E \frac{\partial p_I}{\partial \phi_I} + \alpha_I \frac{\partial p_E}{\partial \phi_I})T - \alpha_I m \frac{\partial T}{\partial \phi_I}$$

after simplifying. It is ambiguous in general by $\delta q_I/\delta\phi_I < 0$, $\delta p_i/\delta\phi_I < 0$ and $\delta T/\delta\phi_I < 0$, but strictly positive if $m \geq 0$ and ϕ_I is small, but positive. Analogously, the marginal effect

$$\tau_E \frac{\partial b_E}{\partial \tau_E} + (\alpha_E \frac{\partial p_I}{\partial \tau_E} + \alpha_I \frac{\partial p_E}{\partial \tau_E})T - \alpha_E m \frac{\partial T}{\partial \tau_E}$$

on welfare in E of increasing the production tax on non-renewable electricity is ambiguous because $\delta b_E/\delta\tau_E < 0$, $\delta p_i/\delta\tau_E > 0$ and $\delta T/\delta\tau_E < 0$, but strictly positive for $m \geq 0$ and τ_E small, but positive. For $m = 0$, deviations from the social optimum to $\phi_I > 0$ and/or $\tau_E > 0$ imply downward distortions in transmission: $\delta T/\delta\phi_I < 0$ and $\delta T/\delta\tau_E < 0$ yield $T < T^*$. ■

Proof of Proposition 4

Summarize the domestic welfare effects to get the aggregate welfare effect

$$\phi_I \frac{\partial q_I}{\partial m} + \tau_E \frac{\partial b_E}{\partial m} - m \frac{\partial T}{\partial m}.$$

By straightforward differentiation of the first-order conditions (3) and (4):

$$\frac{\partial q_I}{\partial m} = \frac{\Upsilon D_I'}{c_T''}(D_E' - \frac{1}{h_E''}) > 0, \frac{\partial b_E}{\partial m} = \frac{\Upsilon}{h_E'' c_T''}(\frac{1}{h_I''} - D_I') > 0, \frac{\partial T}{\partial m} = -\frac{c_T'' h_E''}{\Upsilon D_I'} \frac{\partial q_I}{\partial m} \frac{\partial b_E}{\partial m} > 0.$$

Hence, it is socially optimal to raise m above zero if $\phi_I > 0$ and/or $\tau_E > 0$. ■

Proof of Proposition 5

Assume that policy makers are required to reach the renewables target by means of a subsidy to RES-E production financed by lump-sum transfers. The first-order conditions $(i = E, I)$ $p_i + a_i = c_i'(g_i)$, $p_i = h_i'(b_i)$, $p_I - p_E = c_T'(T)$ plus the market-clearing condition $D_i(p_i) = b_i + g_i + (-1)^{\frac{i-I}{E-I}}T$ define the unique equilibrium allocations as functions of (a_E, a_I).

Total differentiation of the equilibrium conditions yields

$$\frac{\partial g_i}{\partial a_i} = \frac{\frac{1}{h_i''} - D_i' + \frac{\Psi}{c_i''}(\frac{1}{h_j''} + \frac{1}{c_j''} - D_j')}{c_i''(\frac{1}{h_i''} + \frac{1}{c_i''} - D_i')}, \frac{\partial g_i}{\partial a_j} = -\frac{\Psi}{c_I'' c_E''},$$

where

$$\Psi^{-1} = c_T''(\frac{1}{h_I''} + \frac{1}{c_I''} - D_I')(\frac{1}{h_E''} + \frac{1}{c_E''} - D_E') + \frac{1}{h_I''} + \frac{1}{c_I''} - D_I' + \frac{1}{h_E''} + \frac{1}{c_E''} - D_E' > 0.$$

Define implicitly $a_i = A(a_j)$ by $g_i(A, a_j) = g_i^*$ so that for any a_j, $A(a_j)$ is the subsidy that yields the social optimum g_i^* at equilibrium, with

$$A'(a_j) = -\frac{\frac{\partial g_i}{\partial a_j}}{\frac{\partial g_i}{\partial a_i}} = \frac{\frac{\Psi}{c_j''}(\frac{1}{h_i''} + \frac{1}{c_i''} - D_i')}{\frac{1}{h_i''} - D_i' + \frac{\Psi}{c_i''}(\frac{1}{h_j''} + \frac{1}{c_j''} - D_j')} > 0.$$

Next, define $r(a_j) = g_j(a_j, A(a_j))$, where

$$r'(a_j) = \frac{\partial g_j}{\partial a_j} + \frac{\partial g_j}{\partial a_i} A'(a_j) = \frac{\frac{\partial g_i}{\partial a_i}\frac{\partial g_j}{\partial a_j} - \frac{\partial g_j}{\partial a_i}\frac{\partial g_i}{\partial a_j}}{\frac{\partial g_i}{\partial a_i}} > 0$$

because $\partial g_i / \partial a_i > 0$ and

$$\frac{\partial g_i}{\partial a_i}\frac{\partial g_j}{\partial a_j} - \frac{\partial g_j}{\partial a_i}\frac{\partial g_i}{\partial a_j} = \frac{(\frac{1}{h_I''} - D_I')(\frac{1}{h_E''} - D_E') + \sum_{i=E,I} \frac{\Psi}{c_j''}(\frac{1}{h_i''} - D_i')(\frac{1}{h_i''} + \frac{1}{c_i''} - D_i')}{c_I'' c_E''(\frac{1}{h_E''} + \frac{1}{c_E''} - D_E')(\frac{1}{h_I''} + \frac{1}{c_I''} - D_I')} > 0.$$

Hence, there exists at most one a_j satisfying $r(a_j) = g_j^*$, which by monotonicity of $A(a_j)$ implies that there exists at most one pair, (a_E^*,a_I^*), which implements (g_E^*,g_I^*). ■

Proof of Proposition 6

To analyze the effects of certificate market integration, consider the homotopy $ya + (1 - y)a_i$, where a_i is the equilibrium certificate price under autarky implicitly defined by (1) and (2), a is the equilibrium certificate price under integration defined by the first-order conditions in (1), the market clearing condition for non-renewable electricity in (2), all modified by $a_I = a_E = a$, plus the aggregate renewable electricity market clearing condition

$$g_I + g_E = f_I D_I(p_I + f_I a) + f_E D_E(p_E + f_E a).$$

The parameter $y \in [0,1]$ is a measure of certificate market integration, where $y = 1$ refers to full integration, and $y = 0$ represents autarky. In this case ($i = I, E$):

$$p_i + ya + (1 - y)a_i = c_i'(g_i), p_i = h_i'(b_i), p_I - p_E = c_T'(T)$$

plus the market-clearing condition

$$b_i + g_i = D_i(p_i + ya + (1 - y)a_i) + (-1)^{\frac{i-E}{I-E}} T$$

define the equilibrium allocations (g_I, g_E, b_I, b_E), wholesale prices (p_I, p_E) and transmission capacity T as functions of certificate market integration y. Differentiation yields

$$T'(y) = \Psi[(\tfrac{1}{c_E''} - D_E')(\tfrac{1}{h_I''} + \tfrac{1}{c_I''} - D_I')(a - a_E) + (\tfrac{1}{c_I''} - D_I')(\tfrac{1}{h_E''} + \tfrac{1}{c_E''} - D_E')(a_I - a)].$$

Certificate market integration thus reduces transmission investment ($T'(y) < 0$) if country I has a comparative advantage ($a_E > a > a_I$) in RES-E production, but increases investment ($T'(y) > 0$) if country E has the comparative advantage ($a_I > a > a_E$).

Consider the welfare effects. Define the quasi-surplus

$$\widetilde{w}_i(y) = v_i(p_i + f_i y(a - a_i) + f_i a_i) + (p_i + y(a - a_i) + a_i)g_i - c_i(g_i) + p_i b_i - h_i(b_i) + \alpha_i[(p_I - p_E)T - c_T(T)]$$

as a function of y. By utilizing the first-order and market-clearing conditions:

$$\widetilde{w}_i'(y) = (g_i - f_i q_i)(a - a_i) + (-1)^{\frac{i-E}{I-E}}(\alpha_I p_E'(y) + \alpha_E p_I'(y))T.$$

Summarizing over countries yields

$$\widetilde{w}'(y) = (g_i - f_i q_i)(a - a_i) + (g_j - f_j q_j)(a - a_j).$$

To move further, the following comparative statics result will be useful:

$$\frac{dp_i}{dy} = \Psi[(\frac{1}{c_j''} - f_j D_j')(a_j - a) - c_T''(\frac{1}{h_j''} + \frac{1}{c_j''} - D_j' + \frac{1}{c_T''})(\frac{1}{c_i''} - f_i D_i')(a - a_i)].$$

After some tedious, but straightforward arithmetic:

$$\frac{dg_i}{dy} - f_i \frac{dq_i}{dy} = (\frac{1}{c_i''} - f_i D_i')\frac{dp_i}{dy} + (\frac{1}{c_i''} - f_i^2 D_i')(a - a_i)$$

$$= \Psi(\frac{1}{c_I''} - f_I D_I')(\frac{1}{c_E''} - f_E D_E')(a_j - a) + \Psi(\frac{1}{c_i''} - f_i^2 D_i')(\frac{1}{h_j''} + \frac{1}{c_j''} - D_j')(a - a_i)$$

$$+\Psi(\frac{1}{h_i'' c_i''} - \frac{f_i^2 D_i'}{h_i''} - \frac{(1 - f_i)^2 D_i'}{c_i''})[1 + c_T''(\frac{1}{h_j''} + \frac{1}{c_j''} - D_j')](a - a_i).$$

The above expression is strictly positive by the assumption that $a_i \leq a \leq a_j$ with at least one strict inequality. Hence, $g_i(y) - f_i q_i(y) > g_i(0) - f_i q_i(0) = 0$ for all $y > 0$. By the same token, $g_j(y) - f_j q_j(y) < 0$ for all $y > 0$ owing to $g_j'(y) < f_j q_j'(y)$. Hence, $\widetilde{w}'(y) > 0$ and the surplus is therefore strictly higher under certificate market integration than autarky.■

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