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Winners and losers of market coupling

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ABSTRACT

The integration of electricity markets creates new challenges to the regulators in their commitment to guarantee security of supply at affordable prices. Even at a national level, designing policies for electricity markets is an extremely complex task; but this is exacerbated in the case of market coupling, since different policies may be applied at the two ends of an interconnector. Furthermore, investors will make decisions based on their profitability, which depends among other things on the possibility of importing (exporting) from (to) neighboring countries, and will not necessarily coincide with the aims of the regulators or the consumers. We use simulation to analyze different scenarios of interconnection and capacity payments in two case studies: Colombia – Ecuador and Great Britain – France. These two cases exhibit important differences in terms of resources and complementarity between the countries, which lead to quite different outcomes for the same policies. The simulation results show that the potential benefits of market coupling are strongly related to complementarity. However, identifying the policies that should be implemented in order to achieve those benefits is far from obvious. In particular, large generation investment requirements and significant storage capacity in the region may lead to counterintuitive outcomes for certain policies.

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1. Introduction

Designing electricity markets is a very complex task. This complexity is exacerbated by the cross border effects resulting from market coupling. The lack of consensus regarding the best market design is evidenced by the variety of approaches found in different countries, and by the frequent regulatory changes.

To avoid blackouts, electricity systems require a perfect balance between supply and demand at all times. Given the low demand elasticity, it is extremely important to have ample generation and transmission capacities to be able to supply peak demand. However, too much capacity results in very high costs.

The optimal combination of transmission and generation capacities is probably impossible to determine; and even if it could be determined, the number of actors involved in the investment decisions and operation of the system, would make it impossible to implement. The fact that a grid might take around 10 years to be built does not help; it usually has to be planned under a lot of uncertainty, and some projects might not even materialize because of changes in the system during the approval phases.

Besides, investors might adopt strategic behaviors in order to maximize their own benefits. As an example, consider two countries connected by limited transmission capacity, as in Fig. 1. Assume that country A has a lack of generation capacity and country B has a surplus; however, the line is congested and prices are thus higher in A than in B.

In such a case, an investor can adopt different strategies, which may not necessarily improve social welfare. He could decide to locate a generation plant in country A – an import constrained area – rather than expand the interconnector (which would probably be more efficient for the system). The reason is that if low cost electricity cannot be imported, a generator in area A can exercise market power, increasing its offer price without risking not being dispatched. If bilateral energy trading without transmission constraint considerations is allowed, the investor might also decide to locate a generation plant in country B. In this case, the generator may schedule an "impossible" flow and will receive payment not to generate from the redispatch mechanism [1].

The transmission owner might also try to limit or delay investment in grid and/or generation capacity in order to collect higher congestion rents. Likewise, generators will make strategic decisions based on planned transmission and will try to block investments that are not in their interest [2].

These interactions between the market participants, and the long delays associated with investments in the electricity market, create significant challenges for the regulators in order to predict

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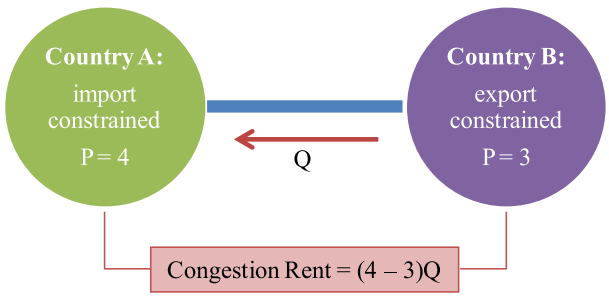

Fig. 1. Interconnector congestion.

the effects of different market designs and policies. There is no agreement on what are the right norms, policies and incentives to promote an adequate expansion of the system.

Regarding the congestion management mechanism, there is general agreement in favor of implicit auctions – or market coupling [3–5]; however, several authors have raised questions regarding the incentive problems this mechanism may cause [6], the fact that it may increase the exercise of market power under certain circumstances [7], and the potential negative effects of the interaction between countries on generation expansion [8–11]. Identifying under which conditions the potential benefits of market coupling are achievable is still an open question.

The importance of the interactions between interconnection and generation capacity has been identified in the literature; yet, most studies focus either on network investment [12–16], or on generation expansion and capacity markets [8,11,17–19] as independent problems.

There are some exceptions, such as the work of Sauma and Oren [20] and Pozo et al. [21], who apply equilibrium models to analyze the implications of network investments on social welfare, taking into account the effects of grid congestion on generators investments and production decisions. In the same line, Höffler and Wambach [22] use a two-node network model to analyze the coordination of grid and generation investments under different regulatory regimes and its implications in terms of social welfare. Nevertheless, these optimization/equilibrium models require strong assumptions that limit the analysis of systems away from equilibrium, such as the electricity markets' transition towards integration, and are conceived for national markets, where the same policies are applied at both ends of the interconnector.

Ochoa and van Ackere [10] propose a more flexible simulation model to analyze the evolution of two interconnected countries under market coupling. The model includes a short-term dispatch and investment evaluation module, with an hourly step that captures the dynamics of electricity generation and prices in each country, as well as the resulting international flows. This module is coupled to a long-term system dynamics model that simulates the expansion of generation and interconnection capacity. They use this model to analyze the impact of different policies, regarding interconnection expansion and capacity payments, on electricity prices and security of supply in the integration of Colombia and Ecuador.

This paper extends the analysis of Ochoa and van Ackere [10] using the same model. In order to identify what factors are important for the achievement of the potential benefits of integration, and how different characteristics of the countries affect the outcomes, we compare a Latin American case (Colombia – Ecuador) to a European case (Great Britain – France). In Section 2 we motivate this choice and describe the characteristics of these two regions.

2. Case studies: Latin America and Europe

Latin America and Europe differ significantly in terms of resources, technology mix and demand patterns. This may lead to different responses to the same market design and/or policies, as will be discussed below.

Table 1 shows the installed capacity and peak demand in each country. We can observe that Colombia and Ecuador are highly dependent on hydroelectricity, while Great Britain is more dependent on thermal generation and France on nuclear power.

One of the objectives of integration is to make better use of the available resources by taking advantage of the countries' complementarities. There is an important hydrological complementarity between Colombia and Ecuador, but the enormous reservoirs attenuate its usefulness in terms of generation availability. Great Britain and France also have different hydrological patterns; however, the impact in this case is less significant as hydropower represents a much smaller part of the installed capacity.

In the European case, the most important complementarity currently results from the differences in generation technology mix, France being mainly base load (Hydro and Nuclear) and Great Britain peak load (Coal and Gas). However, this complementarity tends to disappear, given the push for nuclear phase-out in France and the encouragement of renewables all around Europe.

From the demand side, in both cases there is little complementarity in terms of the daily load curves. Regarding the annual demand patterns, Europe presents stronger fluctuations due to seasonality, which does not affect electricity demand in Colombia and Ecuador. Besides, demand growth is much higher in developing countries such as Colombia and Ecuador than in Europe. This implies the necessity for larger investments in order to guarantee security of supply in the medium and long-term.

3. Methodology

Given the complexity of the electricity system, which involves a large number of interacting variables and many actors, the long-term behavior of the system is not intuitive; however, its understanding is crucial in the process of policy analysis and decision making.

Model based methodologies seem appropriate for assessing the long-term evolution of international electricity markets. Characteristics of these systems, such as the interdependencies of the elements involved, suggest an approach using behavioral simulation [23], which takes into account feedback processes, to represent and understand the behavior and evolution of the system.

We use a simulation model proposed by Ochoa and van Ackere [10], that allows us to test the long-term consequences of different policies regarding interconnection expansion and the implementation of capacity payments in two neighboring countries. The simplified structure of this model is presented in Fig. 2 (for details see Ref. [10]).

The circled components (*Investment Evaluation* and *Dispatch*) are short-term models developed in Matlab, which communicate each time step with the long-term model, developed in Vensim, via the shaded variables (*Net Present Value of Investment, Forecasted Offer Curves & Interconnector Capacity,* and *Offer Curves & Interconnector Capacity*). The same hourly *Dispatch* algorithm is used to calculate current *Generation, Flows & Prices* and *Forecasted Generation, Flows & Prices* that are used for *Investment Evaluation*. The profitability of investments is analyzed in terms of net present values, considering future (forecasted) dispatches when including the investment being evaluated. If the *NPV of Investment* is positive, the investment process will start, leading to more *Installed Capacity* in the market after a planning and construction delay.

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Table 1
Installed capacity and peak demand (2012).

	Hydro	Nuclear	Coal	Gas	Fuel oil	Wind	Interconnector	Peak demand
	GW, % of installed capacity						GW, % of peak demand	GW
Colombia	9.7	–	1.0	3.1	0.6	–	0.5	9.7
	67%	0%	7%	22%	4%	0%	5%	
Ecuador	2.2	–	0.5	1.0	1.3	–	0.5	3.5
	44%	0%	10%	20%	26%	0%	14%	
Great Britain	4.3	10.7	34.7	33.6	–	2.7	2.0	63.2
	5%	12%	40%	39%	0%	3%	3%	
France	25.2	63.1	6.9	14.7	–	6.7	2.0	102.1
	22%	54%	6%	13%	0%	6%	2%	

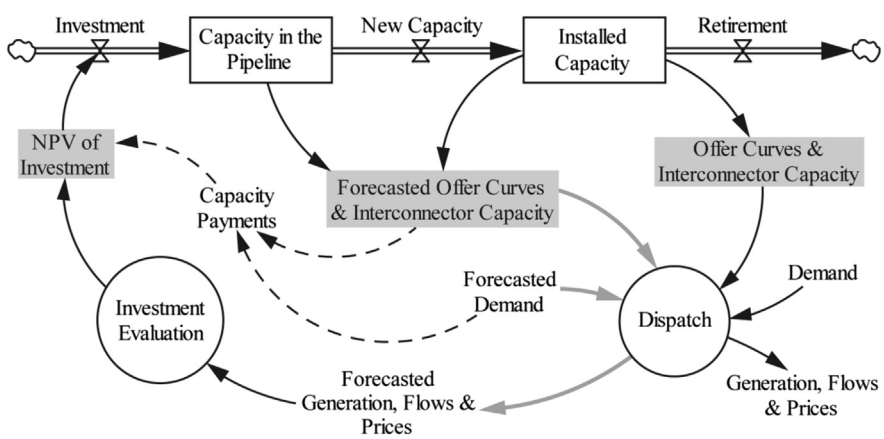

Fig. 2. Simplified model structure [10].

In the scenarios with Capacity Payments, these are calculated as a function of the expected national capacity margin, and are added to the *NPV of Investment*. We assume that capacity payments are offered as annual payments over the lifetime of the infrastructure, and do not differ across technologies. In reality, capacity payments are generally technology specific, as the regulator chooses to encourage for instance renewables or peak capacity; however, our aim is to analyze both regions under identical policies, in order to identify the initial conditions and inherent characteristics of the markets that may influence their evolution.

The results are analyzed in terms of social welfare, which allows us to compare the benefits/costs of the different scenarios for each region [24], as well as for the individual countries and market participants. The social welfare is calculated as the sum of the surpluses of consumers, generators and the interconnector, as represented in Fig. 3.

In the short term, i.e. assuming equal installed capacity and demand, an electricity trade causes a price rise in the exporting country and a decrease in the importer country. If the interconnector is not congested, prices converge; otherwise, as in Fig. 3, the interconnector collects a Congestion Rent. The price rise in the exporter country leads to a surplus transfer from consumers to producers, and also creates additional surplus collected by producers. In the importer country, the transfer of surplus is from producers to consumers, and the surplus gain is collected by consumers.

Note that in the short term (i.e. given a constant generation capacity), under Market Coupling, an international transaction

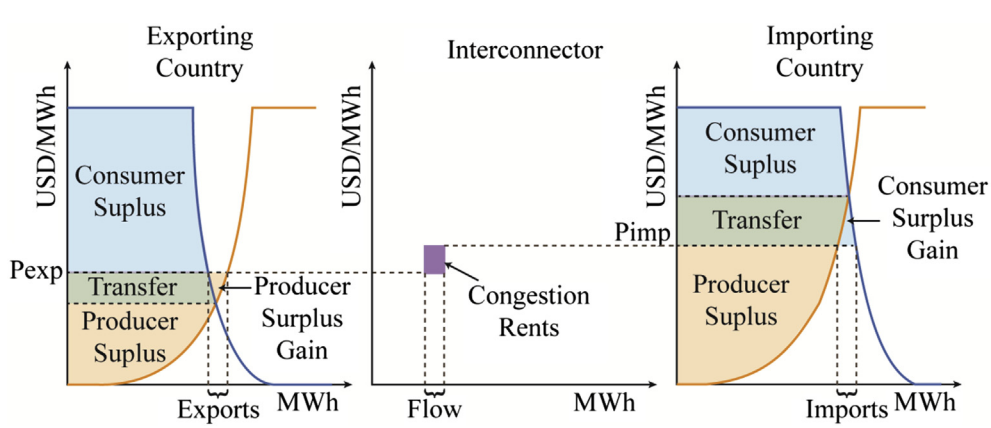

Fig. 3. Surplus of consumers, producers and the interconnector (adapted from E-Bridge, 2009).

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leads to a total social welfare gain. However, this is not necessarily the case in the long run, since the interconnection modifies the economic signals to investors, affecting the evolution of the installed capacity. This may result in higher costs, thus reducing social welfare. For this reason we also include the fixed costs of infrastructure in the welfare calculation, to account for different investment decisions. We consider four degrees of interconnection:

a) *Isolated*: no interconnection between the countries.
b) *Current Grid*: the interconnector capacity remains constant at the 2013 level during the whole simulation period.
c) *Grid Expansion*: the interconnector capacity is initialized at the 2013 level and is expanded according to its expected profitability, assuming that the grid owner can collect congestion rents.
d) *Unlimited Grid*: the interconnector is expanded "as needed" to guarantee zero congestion at all times. Investors (in generation capacity) behave as if there were no transmission constraints.

To simplify, the results are presented in terms of social welfare gain (including fixed costs) with respect to the Isolated scenario.

We also analyze the effects of capacity payments in each of these scenarios, considering implementations in one or both countries. For these scenarios, the corresponding interconnection case with no capacity payments is taken as the base case. The combination of the four degrees of interconnection considered, and the four possibilities of capacity payments yields a total of 16 scenarios.

Before turning to the analysis of the results, it is worth recalling that the System Dynamics methodology is a deterministic simulation method, aimed at understanding the behavior of a system under different policies. It is thus not intended to provide forecasts, as parameter uncertainty is not considered explicitly in a deterministic model. In order to build confidence in the model results, we have performed detailed sensitivity and extreme conditions analyses (for details and examples of the tests we performed, see Ref. [10]). These analyses allow us to conclude that, while the numerical results depend on the exact parameter values, the qualitative results we present are robust to reasonable variations in the parameter values.

4. Policy analysis

The simulation results show that the prevailing conditions in the national markets have a significant impact on the evolution of the integration. Assuming an acceptable performance of both markets at the start, there are three main factors that influence the outcome of the different scenarios: demand growth (investment requirements), complementarity between countries and storage capacity. The regions analyzed in this paper differ significantly in these aspects. In Europe, if we ignore the push for green energies and pressures to accelerate the phase out of nuclear plants,[1] little investment is required over the next 25 years since demand growth is not significant; furthermore, Great Britain and France do not exhibit significant complementarity in terms of demand patterns or energy resources. On the contrary, in Colombia and Ecuador demand grows at a significant rate, requiring important investments to guarantee security of supply. Additionally, Colombia and Ecuador are highly complementary in terms of water availability and have large reservoirs. These factors make the evolution of the generation capacity in Latin America very sensitive to policy choices. Conversely, in Europe, all scenarios lead to a similar evolution of the generation capacity.

4.1. European case: Great Britain – France

We first discuss the results for the European case without capacity payments, analyzing the pros and cons of different degrees of interconnection for the region as a whole, and for the different market participants. In Section 4.2.2 we analyze the impact of the interconnector's size on the effects of capacity payments.

4.1.1. No capacity payments

Great Britain and France do not exhibit any significant complementarity, except for France's current large share of nuclear power. Thus, in the absence of regulatory interventions both systems tend to converge to similar prices, which limits the potential benefits of integration. Therefore, the interconnector is barely expanded in the Grid Expansion scenario, yielding results almost equivalent to the Current Grid scenario; however, we retain both scenarios for the analysis in order to provide a base for comparison with the Latin American case discussed below.

As observed in Fig. 4, the Current Grid and Grid Expansion scenarios lead to a higher social welfare for the region than the Isolated case; in the Unlimited Grid scenario, though also higher in the short term, the social welfare drops abruptly as the share of nuclear power in France decreases. In fact, social welfare gains decrease over time in all scenarios, since the prices of the two countries tend to converge when their technology mixes become similar, reducing the potential benefits of integration.

However, Fig. 5 shows that, most years, both countries gain in social welfare as a result of the integration. When the interconnector is limited (Current Grid or Grid Expansion scenarios), most of the gains are in the form of congestion rents. In the Unlimited Grid scenario, the cost of "gold-plating" the grid outweighs its benefits in the long-term.

But although both countries gain in social welfare, the benefits of the interconnection are not equally distributed among all market participants. As observed in Fig. 6, the big winners of the integration are the French producers. This is logical given their large nuclear capacity that will anyway run as base load, but will obtain higher prices as a result of the increased demand created by the

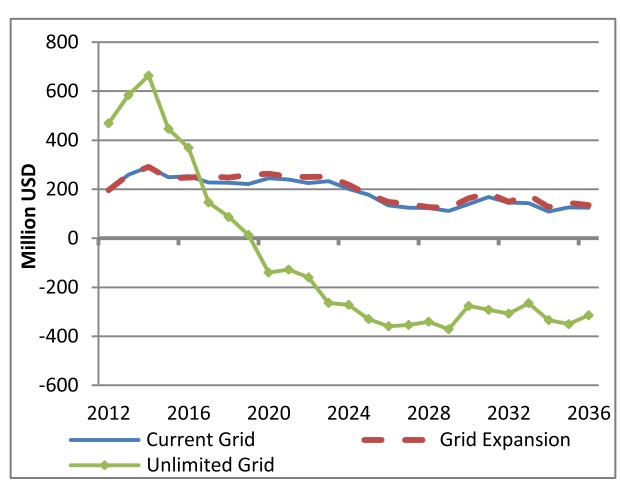

Fig. 4. Regional (Great Britain and France) Total Social Welfare Gain with respect to the Isolated case.

[1] This assumption, though not reflecting the current situation, allows us to compare the two cases: Latin America and Europe under the same policies in order to understand how the initial conditions of a market may influence the long-term outcomes of different policies.

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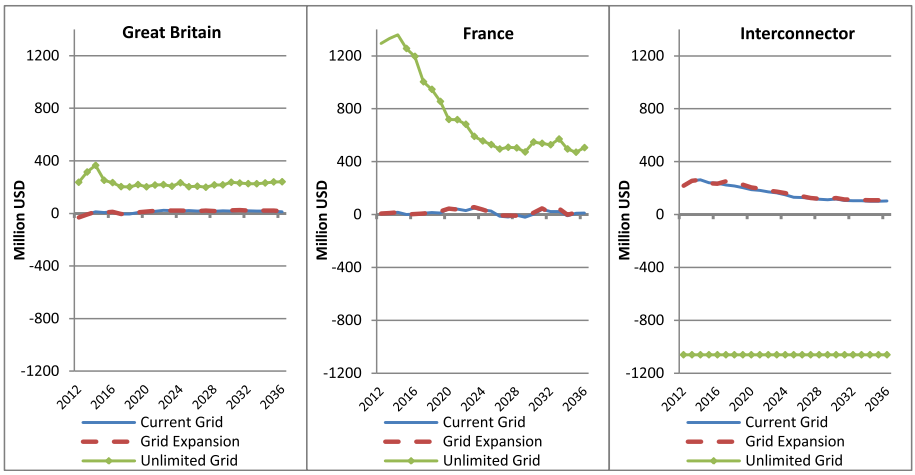

Fig. 5. Social welfare gain compared to the Isolated case for France, Great Britain and the interconnector.

interconnection with Great Britain. This situation will benefit British consumers, who will have access to cheaper electricity, at the expense of French consumers who, despite having already paid for the nuclear plants, will now have to pay the "European" price for electricity.

Still, the interconnection creates welfare. Since there is more generation than consumption in France (net exporter), the gains of producers exceed the losses of consumers. Similarly, in Great Britain (net importer) there is more consumption than generation, so once again the gains more than compensate the losses.

But, despite the welfare creation for both countries, consumers in France should object to market coupling unless a compensation mechanism is put in place. This is what France had envisioned with the TRV (*Tarif Réglementé de Vente*), which allowed consumers to choose a regulated tariff based on the historical price of electricity. However, as discussed by Percebois [25], this gives an advantage to the incumbent by preventing new entry, since prices are maintained at a low level. The design of a mechanism that allows a fair distribution of the benefits of integration, without distorting market competition is a very complex task. Furthermore, given the similarity of these countries in terms of available resources, a large interconnector capacity is not justified in the long-term, unless regulatory incentives lead the countries to develop significantly different technology mixes. Nevertheless, both countries may benefit from a limited interconnection, which will not only bring economic benefits, but also increased reliability and lower carbon emissions.

Yet, integration creates new challenges for the regulators, as national markets may be affected by the policies implemented in neighboring countries. In order to illustrate this issue, we next

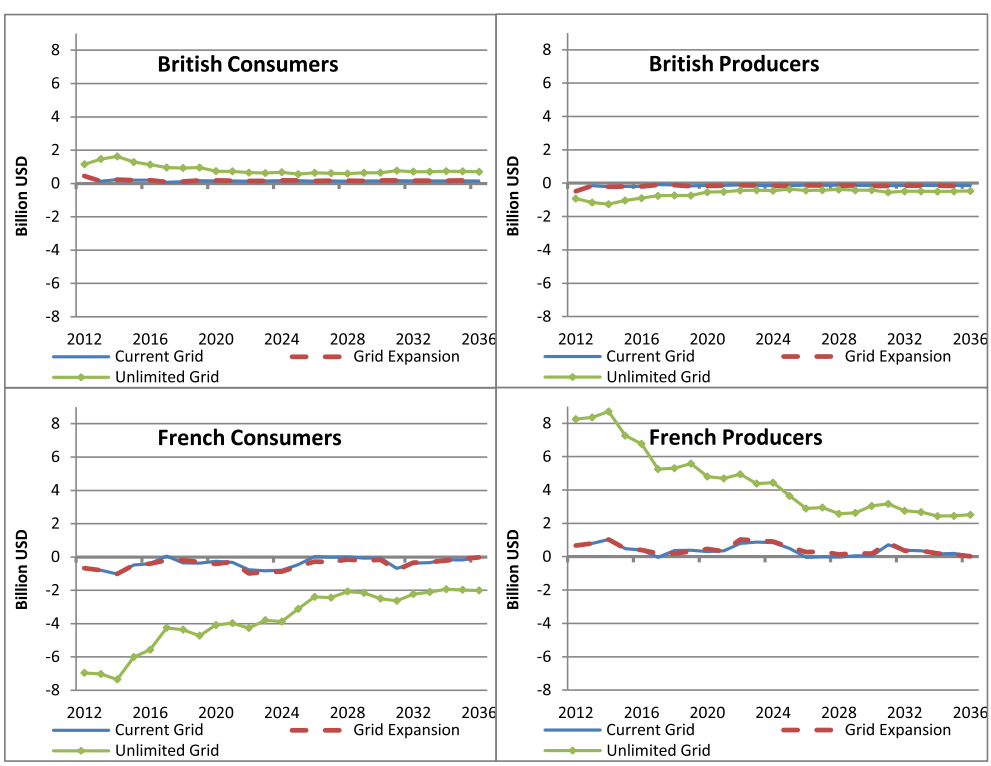

Fig. 6. Social welfare gain by agent in Europe.

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Table 2
Cumulative social welfare gain compared to the Isolated no capacity payments case (Billion USD). Shaded areas indicate Nash equilibrium. R = Region, *G* = Grid. *Consumers in parenthesis.

Isolated							
GB\FR	No CP			CP			
No CP	**GB:**	**-**	***(0.00)***	**GB:**	**-**	***(0.00)***	
	FR:	**-**	***(0.00)***	FR:	-23.45	*(-277.18)*	
	G:	**-**		**G:**	**-**		
	R:	**-**	***(0.00)***	R:	-23.45	*(-277.18)*	
CP	GB:	-7.22	*(-73.65)*	GB:	-7.22	*(-73.65)*	
	FR:	**-**	***(0.00)***	FR:	-23.45	*(-277.18)*	
	G:	**-**		**G:**	**-**		
	R:	-7.22	*(-73.65)*	R:	-30.68	*(-350.83)*	

Current Grid							
GB\FR	No CP			CP			
No CP	GB:	0.30	*(4.18)*	**GB:**	**0.35**	***(4.57)***	
	FR:	0.34	*(-9.29)*	FR:	-23.41	*(-294.73)*	
	G:	4.05		**G:**	**4.53**		
	R:	**4.69**	***(-5.11)***	R:	-18.52	*(-290.16)*	
CP	GB:	-7.44	*(-70.74)*	GB:	-7.38	*(-70.23)*	
	FR:	**0.52**	***(-6.03)***	FR:	-23.16	*(-291.50)*	
	G:	3.56		G:	4.01		
	R:	-3.36	*(-76.77)*	R:	-26.53	*(-361.73)*	

Grid Expansion							
GB\FR	No CP			CP			
No CP	GB:	0.34	*(4.56)*	**GB:**	**0.41**	***(4.99)***	
	FR:	0.42	*(-10.91)*	FR:	-23.35	*(-296.95)*	
	G:	4.26		**G:**	**4.81**		
	R:	**5.03**	***(-6.36)***	R:	-18.13	*(-291.96)*	
CP	GB:	-7.44	*(-70.34)*	GB:	-7.40	*(-69.61)*	
	FR:	**0.67**	***(-7.25)***	FR:	-23.09	*(-291.98)*	
	G:	3.67		G:	4.20		
	R:	-3.10	*(-77.59)*	R:	-26.29	*(-361.59)*	

Unlimited Grid							
GB\FR	No CP			CP			
No CP	GB:	5.78	*(21.01)*	**GB:**	**6.45**	***(25.00)***	
	FR:	**18.67**	*(-93.81)*	FR:	-3.20	*(-396.22)*	
	G:	**-26.52**		**G:**	**-26.52**		
	R:	**-2.07**	***(-72.80)***	R:	-23.27	*(-371.22)*	
CP	GB:	-4.00	*(-54.48)*	GB:	-3.39	*(-51.12)*	
	FR:	16.43	***(-69.24)***	FR:	-5.51	*(-372.52)*	
	G:	**-26.52**		**G:**	**-26.52**		
	R:	-14.09	*(-123.72)*	R:	-35.42	*(-423.63)*	

analyze the effects of capacity payments in one or both countries in the different interconnection scenarios.

4.1.2. Capacity payments

In these scenarios we assume that capacity payments are implemented for reliability reasons, without considering climate goals, which are outside the scope of this paper; thus, the payments are offered without any discrimination across technologies whenever the national capacity margin is expected to be low.

Table 2 presents the welfare gain accumulated over the simulation period for each country (GB/FR), the interconnector (G) and the region as a whole (R) for each combination of interconnection scenarios and capacity payments' implementation. The corresponding consumer surplus is presented in parentheses. The shaded areas correspond to the Nash equilibrium for each interconnection case, as each country decides whether or not to implement capacity payments. The best strategy for each agent is indicated in bold.

In all scenarios, capacity payments lead to a regional social welfare loss. This is because capacity payments create a surplus for new entrants (paid by consumers), but not for existing plants, which will see their utilization factors decrease as a consequence of the increased capacity margin. Thus, if new investments are not more efficient, and prices remain at similar levels, some existing producers lose, leading to a total social welfare loss. Note, however, that this does not consider the consumer's willingness to pay for supply reliability, which might outweigh their apparent loss.

We can observe that in all scenarios, the Nash equilibrium is not to have capacity payments at all, which is also the best strategy for the region as a whole, but not necessarily for the countries or the interconnector.

In the Grid Expansion scenario, as the interconnector capacity between Great Britain and France is barely expanded and remains small compared to national demand for both countries, the impact on the neighbor of implementing capacity payments unilaterally is minimal, though positive. The same occurs in the Current Grid scenario. This suggests a slight possibility of free riding, since the country that implements the capacity payments will assume high costs, leading to a welfare loss, while its neighbor will benefit marginally.

Additionally, the implementation of capacity payments in either country affects congestion rents, as observed in Fig. 7, since it modifies the price difference between the countries and the electricity flows. When only France implements capacity payments, the new capacity will further reduce the off-peak prices, exacerbating the price difference when France exports to Great Britain, which increases congestion rents. On the contrary, when only Great Britain implements capacity payments, congestion rents are reduced.

In summary, in the Grid Expansion scenario, there is no risk of being adversely affected by the policies implemented in the neighboring country. On the contrary, it might be seen as an opportunity of free riding. But the issue becomes more complex with large interconnection capacity, since the policies implemented in

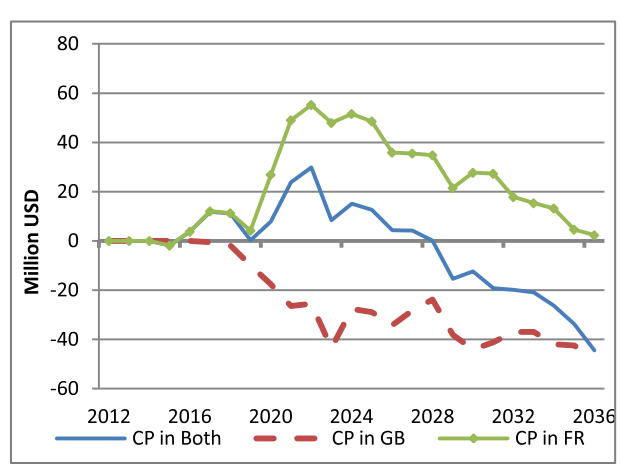

Fig. 7. Interconnector surplus gain in Europe compared to no capacity payments – grid expansion.

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one country have a stronger impact on its neighbor and may adversely affect it. As observed in Table 2, in the Unlimited Grid scenario implementing capacity payments in Great Britain has a negative impact on France's social welfare, whether France implements them as well or not. This is because, on the one hand, Great Britain will export more to France, reducing both peak prices and the French generators' utilization factors; and on the other hand, French exports will be reduced, and so will the regional off-peak prices, which results in a loss for producers that is not fully compensated by the consumers' gain.

This shows that, though market coupling may bring benefits, the risks of being adversely affected by external decisions may outweigh the potential benefits. Assuming that the Nash equilibrium can be reached, both countries should be in favor of a large interconnection capacity from a social welfare perspective, but the cost of this grid more than offsets the countries' benefit. However, for French consumers isolation is preferable, which emphasizes the need for a compensation mechanism.

4.2. Latin American case: Colombia – Ecuador

Colombia and Ecuador are considered to have a large potential for integration given their hydrological complementarity [9,26]. However, our results show that market coupling can lead to a regional social welfare loss.

4.2.1. No capacity payments

Since Colombia and Ecuador require important investments in generation capacity in order to guarantee security of supply, the system evolution is more sensitive to structural and regulatory interventions. This is reflected in the results of the different scenarios, which are much less intuitive. For instance, as observed in Fig. 8, the social welfare gain varies in a non-monotonic way with the level of interconnection.

Despite the already planned generation projects, in the medium term Colombia's capacity margin will drop, creating high price spikes in the Isolated scenario. At the same time, Ecuador will profit from a large capacity margin and inexpensive electricity as some hydropower projects, including Coca-Codo Sinclair (1.5 GW), start operations. We might think that an interconnection would yield welfare gains as Colombia imports cheap electricity from Ecuador; however, Fig. 8 shows that this is not always the case.

In the Current Grid scenario the interconnection capacity is too small to impact Colombian prices, though it allows the grid owner to collect substantial congestion rents and affects Ecuador's prices. In this scenario, Colombia is a net exporter during the first years of simulation, contributing to a price fall in Ecuador and a social welfare gain in the region. However, when Colombia's capacity margin becomes tighter and it starts importing more electricity, the regulation of the reservoirs becomes problematic in Ecuador, since Colombia will be willing to import at "any price" and can drain Ecuador's reservoirs quite fast. As a consequence, peak power plants, such as coal and fuel oil, become more profitable in Ecuador, which accelerates the expansion of peak capacity. This results in higher fixed costs and thus a lower welfare in the medium term. At the end of the simulation there is again a welfare gain compared to the Isolated case; however, the benefits are collected almost entirely in the form of congestion rents. In total, if we cumulate the welfare gain (loss) during the simulation period, there is a welfare loss compared to the Isolated scenario.

In the Grid Expansion scenario, the interconnector is expanded significantly. However, given the exploitation of the hydrological complementarity, the congestion rents are not as high as expected by the investors, and investment costs are not fully recovered. Indeed, the complementarity makes the regulation of the reservoirs, and thus the prices, quite difficult to predict.

The ample interconnector capacity makes the expansion of hydropower in Ecuador more profitable, since it will be able to export the surplus during the rainy seasons. Furthermore, Ecuador's price in this scenario exhibits a mode-locking behavior that mimics Colombian prices, which means relatively high price spikes during Ecuador's rainy seasons (quite counterintuitive at first sight) and thus a great opportunity for hydropower projects.

Colombian producers will be worse off in the medium term (Fig. 9), since they will not be able to obtain the high prices attained in the Isolated scenario once Ecuadorian hydropower is available. This will lead to lower investments in generation capacity in Colombia, resulting in slightly higher prices in the long-term. At the end of the simulation, producers in both countries win by taking advantage of the hydrological complementarity: Colombia saves in investments and Ecuador's prices rise as a result of the increased demand. But Ecuadorian consumers, though still paying reasonable prices for electricity, will obtain a lower welfare than in the Isolated scenario, as their huge hydropower capacity no longer looks huge when Colombia becomes involved.

In the Unlimited Grid scenario there is a social welfare loss at the beginning and at the end of the simulation horizon, with a significant gain in the medium term (recall Fig. 8). The reason is that the cost of interconnection capacity can only be compensated by the consumers' gain when the hydrological complementarities cause a significant price drop compared to the Isolated scenario. This is the case from around 2018 to 2028, when the hydropower share in the region peaks. The sustained low prices will however undermine the profitability of new investments in Ecuador, since the risk of large

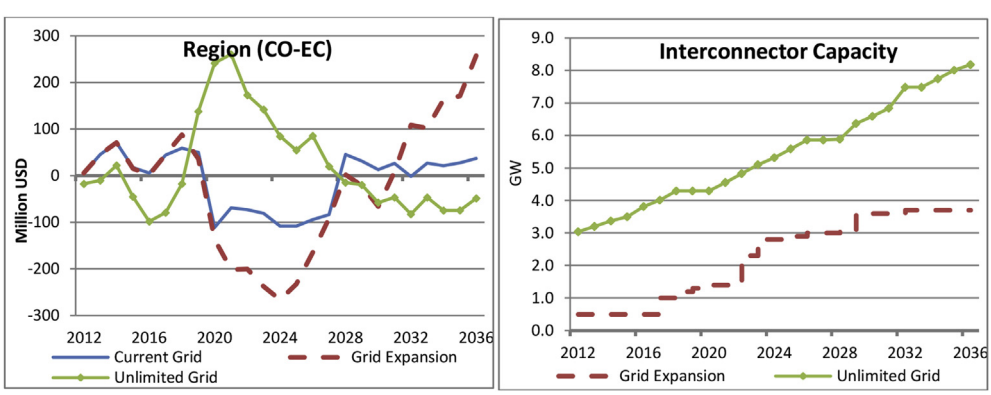

Fig. 8. Regional (Colombia and Ecuador) total social welfare gain with respect to the Isolated case (left), and interconnector capacity (right).

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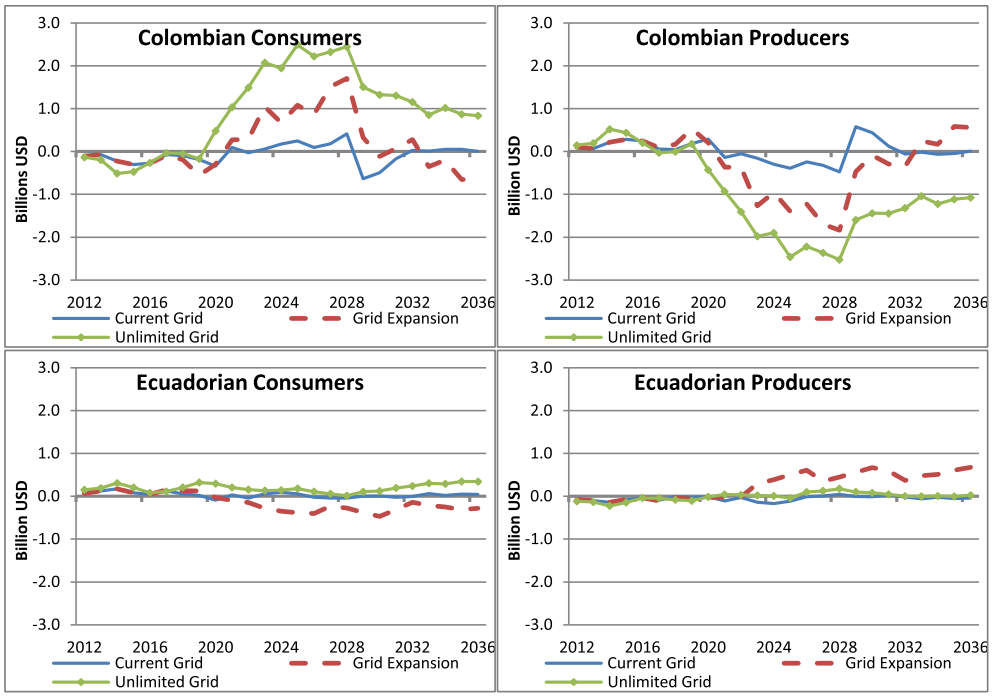

Fig. 9. Social welfare gain by agent in Latin America.

cheap electricity imports from Colombia is quite high (for details see Ref. [10]). Thus, Ecuador will halt investments, and Colombia will install peaking units to be able to supply demand during dry seasons, since Ecuador will have an extremely low capacity margin and will not be able to export.

This scenario leads to increased consumer surplus in both countries, since the interconnector size allows the full exploitation of the hydrological complementarity, inducing sustained low prices. Nevertheless, the high interconnector costs and high infrastructure costs in Colombia outweigh the gains at the end of the simulation, as observed in Fig. 10.

Fig. 8 (above) indicated the following regional ranking of scenarios according to the total social welfare accumulated during the simulation period: 1) Unlimited Grid, 2) Isolated, 3) Current Grid, 4) Grid Expansion. But the ranking looks quite different from a national perspective or when analyzed for each market participant. Fig. 10 shows, for instance, that Colombia loses in all scenarios when compared to the Isolated case; while Ecuador gains in the Grid Expansion and Unlimited Grid scenarios, but also loses in the Current Grid scenario. This is the only case in which the grid owner wins.

These differences make the conclusion of an integration agreement difficult, as each party will try to promote or block different options. The grid owner does not have an incentive to reduce congestion; Colombia should not defend integration (except for reliability reasons); and Ecuador should push towards larger integration (if energy dependence from Colombia is not a concern).

However, an interesting fact in the Latin American case is that consumers in both countries gain in the Unlimited Grid scenario compared to the Isolated case (recall Fig. 9). And though producers' welfare decreases as a result of the lower prices, especially in Colombia, this may not be a concern if we take into account that their investments may still be profitable.

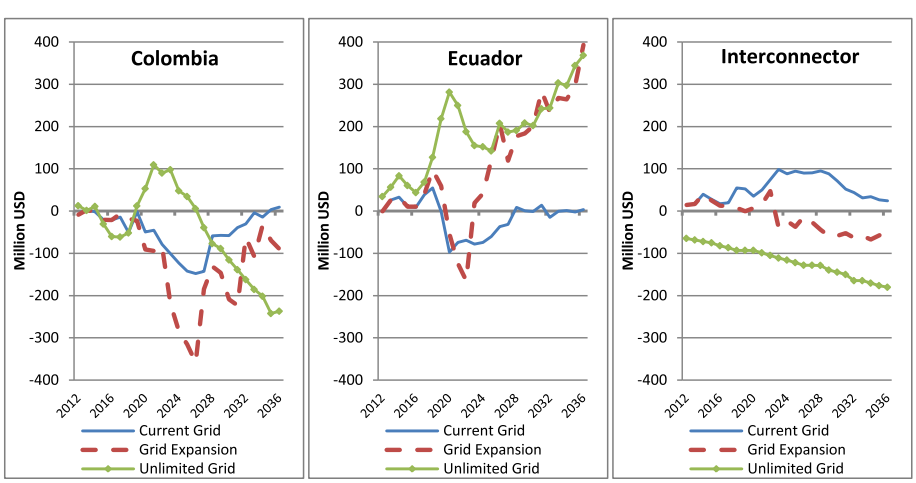

Fig. 10. Social welfare gain by country/interconnector with respect to Isolated in Latin America.

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Note that until around 2020, the behavior is similar to the European case for the three scenarios: if consumers in a country gain, producers lose; and if consumers or producers gain in one country, they lose in the other; however, the long-term behavior is modified as different investment decisions are made. For instance, in the Unlimited Grid scenario, consumers in both countries win and producers in both lose.

From the above analysis, the Unlimited Grid scenario might look like the best option, as it leads to the highest aggregated welfare as well as the highest consumer surplus in both countries. However, this welfare analysis does not take into account important factors such as the environmental impact of the technology choices; or the fact that the interconnection improves reliability; and perhaps the most important issue for this region that is not considered is the risk of import dependency.

In particular, the Unlimited Grid scenario poses significant risks for Ecuador, which would become extremely dependent on imports. Thus, the Grid Expansion scenario may be preferable from a reliability perspective, despite the welfare loss for Ecuador's consumers; furthermore, this scenario leads to a producers' welfare gain in Ecuador that largely compensates the consumers' loss and encourages investment in renewables, so it might be a desirable alternative.

In Colombia, the Grid Expansion scenario is the worst in terms of welfare, but the loss is incurred by the producers, while consumers gain. Thus, if the costs of the generation investments can still be

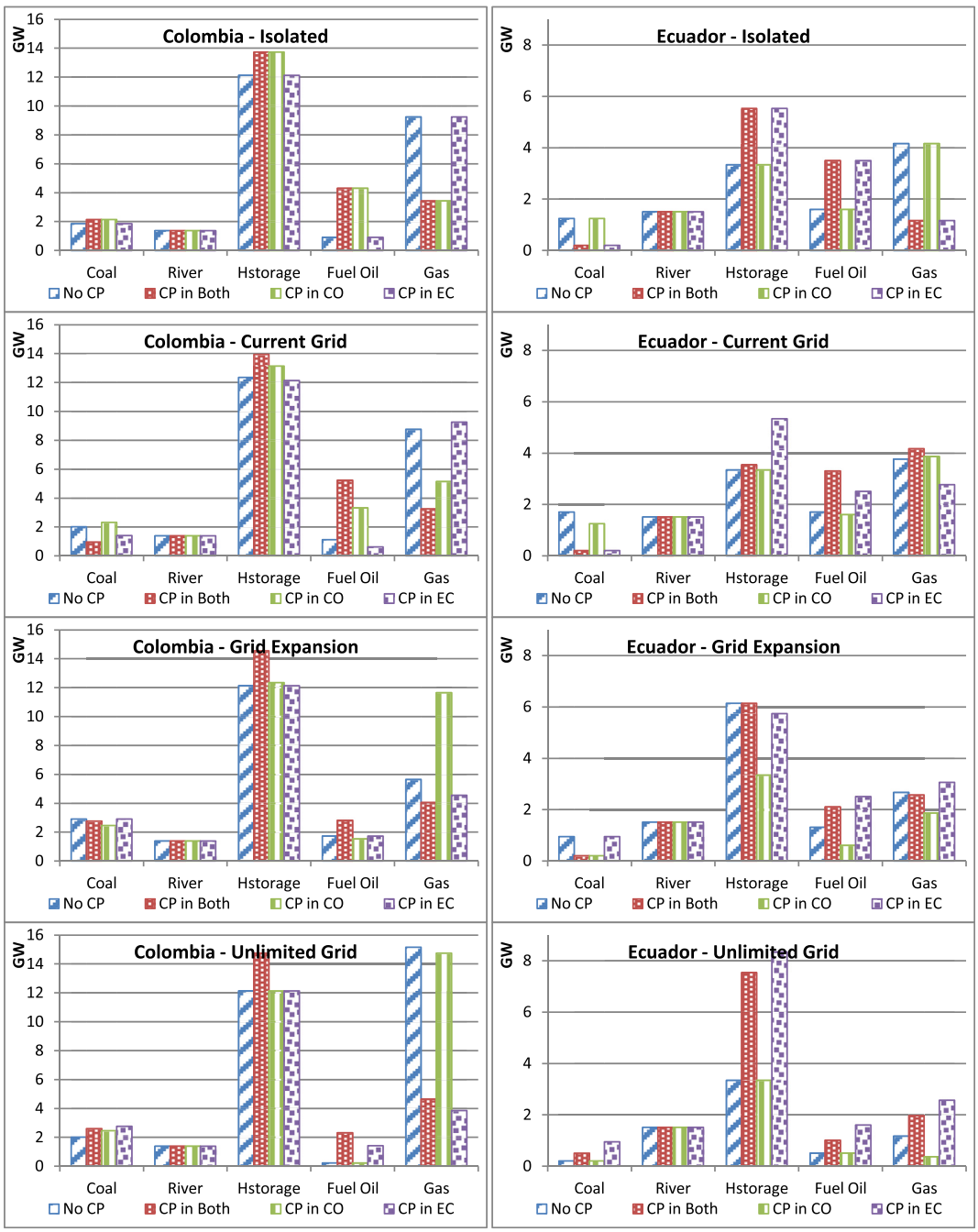

Fig. 11. Impact of capacity payments on the installed generation capacity in 2036 in different interconnection scenarios.

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recovered, the Grid Expansion scenario could be a good option for Colombia as well.

We next analyze the implementation of capacity payments in this region.

4.2.2. Capacity payments

As stated before, Ecuador's and Colombia's investments are quite sensitive to market structure. Thus, as observed in Fig. 11, different combinations of capacity payments and interconnection levels lead to different evolutions of the installed generation capacity. Note for example the Hydro-Storage capacity in Ecuador: in the Isolated case, capacity payments in Ecuador (or in Both) lead to a significant increase; in the Current Grid case, the effect of capacity payments is weakened if Colombia implements them as well, but in the Grid Expansion case, the largest expansion of Hydro-Storage is obtained when incentives are coordinated, i.e. both countries implement them or neither country does; finally, in the Unlimited Grid case, capacity payments lead again to a larger capacity, much larger indeed than in the other scenarios, and the effect is slightly reduced if Colombia implements capacity payments as well.

These different technology choices, which also involve different investment timings, create an important challenge for market regulators: anticipating the effect of policies in an integrated market is a very complex task. The implementation of capacity payments may lead to different and sometimes counterintuitive outcomes depending on the interconnector size and the characteristics of the neighboring country.

Table 3 presents the cumulative social welfare gain of different implementations of capacity payments compared to the Isolated scenario without capacity payments. We observe that when the countries are isolated, the implementation of capacity payments always results in welfare loss, while in the other scenarios some options lead to a welfare gain in one of the countries, but never in both.

However, what is the best policy in a given scenario may be the worst in another. For instance, in the Current Grid scenario Colombia has no interest in implementing capacity payments, and should also try to stop Ecuador from doing it. For Ecuador the best option is to implement them only if Colombia does not, but it can free-ride if Colombia does. On the contrary, in the Grid Expansion scenario Colombia can gain a lot of welfare by implementing capacity payments, and Ecuador should follow in order to mitigate the negative impact of Colombia's decision. In this case, both countries would prefer their neighbor not to implement incentives; nevertheless, if they cannot influence their neighbor's decisions, and each country tries to maximize its own benefit, the outcome would be the best for the region as a whole, i.e. coordinated capacity payments. This is also the case in the Unlimited Grid scenario: though Colombia would prefer not to implement capacity payments, it should follow Ecuador's decision to avoid larger losses, and this is again the best option for the region as a whole.

In conclusion, the implementation of capacity payments can be interesting from an economic perspective when there is a certain degree of integration; but it also involves higher risks, which are no longer controlled by the national regulators. The results suggest that reaching an agreement may be difficult, since both countries will sometimes have completely contradictory interests. What is interesting from a regional perspective is that for all the scenarios considered in this paper, the Nash equilibrium corresponds to the regional welfare maximizing strategy.

However, in reality, these are political decisions that do not necessarily follow the rules of economics textbooks. The regulators will probably implement capacity payments, regardless of the economic loss, as an insurance against imports dependency. Furthermore, the countries may decide to stop trading electricity if the neighbor's decision has a negative impact on their own social welfare. From a total social welfare perspective, Colombia should avoid market integration, as it always results in a loss. Nevertheless, from a consumers' point of view, ample interconnection capacity is desirable for both countries. Specifically, consumers would be willing to pay the price of eliminating grid congestion; and the region as a whole would be better off. This is possible if, despite a lower welfare for the producers, investments remain profitable.

Note that consumers will generally prefer not to implement capacity payments, except for Colombians in the Grid Expansion scenario. In this case, consumers in both countries win when

Table 3
Cumulative social welfare gain compared to the Isolated no capacity payments case (Million USD). Shaded areas indicate Nash equilibrium. R = Region, G = Grid. *Consumers in parenthesis.

Isolated						
CO\EC	No CP			CP		
No CP	**CO:**	**0.00**	***(0.00)***	**CO:**	**0.00**	***0.00***
	EC:	**0.00**	***(0.00)***	EC:	-0.18	*-18.05*
	G:	**0.00**		**G:**	**0.00**	
	R:	**0.00**	***(0.00)***	R:	-0.18	*-18.05*
CP	CO:	-0.55	*(-22.04)*	CO:	-0.55	*-22.04*
	EC:	**0.00**	***(0.00)***	EC:	-0.18	*-18.05*
	G:	**0.00**		**G:**	**0.00**	
	R:	-0.55	*(-22.04)*	R:	-0.72	*-40.10*

Current Grid						
CO\EC	No CP			CP		
No CP	**CO:**	**-1.20**	***(-1.59)***	CO:	-1.50	*(-7.21)*
	EC:	-0.34	***(0.88)***	**EC:**	**0.65**	*(-13.61)*
	G:	1.33		**G:**	**1.53**	
	R:	-0.21	***(-0.71)***	**R:**	**0.69**	*(-20.82)*
CP	CO:	-1.28	*(-4.60)*	CO:	-3.81	*(-23.56)*
	EC:	0.23	*(-0.02)*	EC:	-0.70	*(-13.80)*
	G:	0.90		G:	1.23	
	R:	-0.15	*(-4.62)*	R:	-3.28	*(-37.36)*

Grid Expansion						
CO\EC	No CP			CP		
No CP	CO:	-2.80	*(4.03)*	CO:	-4.59	*(-2.90)*
	EC:	2.74	*(-3.63)*	**EC:**	**2.82**	*(-15.48)*
	G:	-0.45		**G:**	**0.11**	
	R:	-0.50	*(0.41)*	R:	-1.67	*(-18.38)*
CP	**CO:**	**-1.36**	***(9.48)***	CO:	-1.68	*(-4.05)*
	EC:	0.94	***(1.62)***	EC:	1.98	*(-12.85)*
	G:	-0.68		G:	-0.69	
	R:	-1.10	***(11.10)***	**R:**	**-0.39**	*(-16.90)*

Unlimited Grid						
CO\EC	No CP			CP		
No CP	**CO:**	**-1.22**	***(23.58)***	CO:	-6.67	*(-5.51)*
	EC:	4.66	*(4.83)*	**EC:**	**9.10**	*(-13.63)*
	G:	-2.96		G:	-3.05	
	R:	0.48	*(28.41)*	R:	-0.62	*(-19.14)*
CP	CO:	-2.54	*(21.90)*	CO:	-1.63	*(-0.47)*
	EC:	5.11	***(6.62)***	EC:	5.41	*(-8.35)*
	G:	-3.03		**G:**	**-2.63**	
	R:	-0.45	***(28.52)***	**R:**	**1.15**	*(-8.82)*

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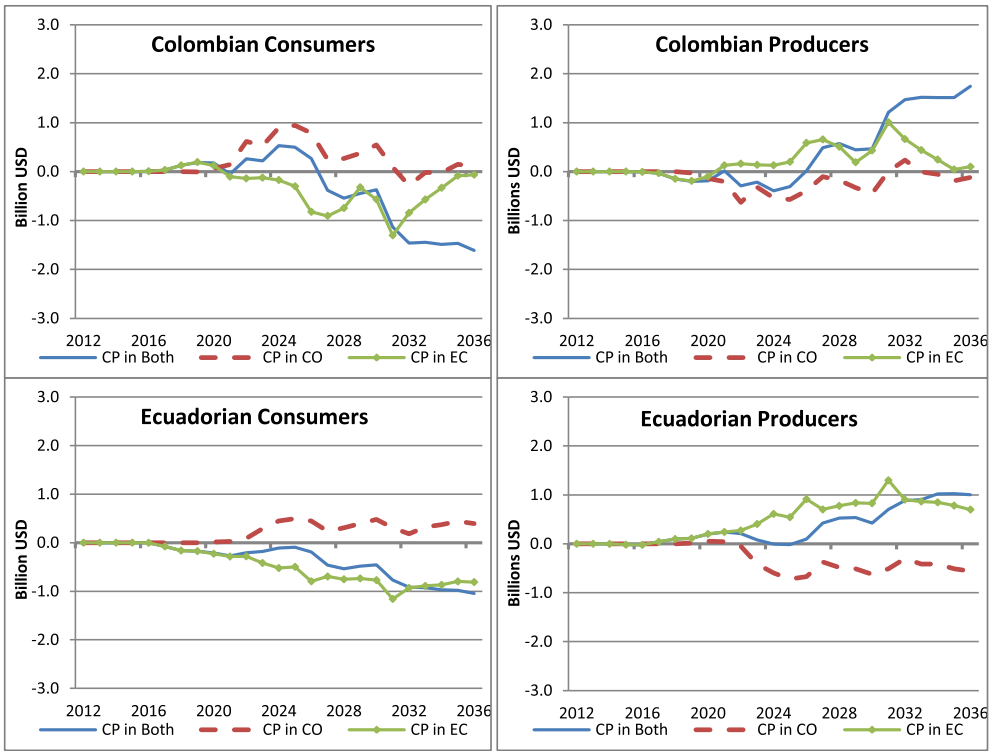

Fig. 12. Consumers and producers welfare gain of capacity payments – grid expansion.

Colombia implements capacity payments, as it results in lower prices for both countries; and for the same reason, producers lose in both countries, as observed in Fig. 12.

But the previous analysis offers a partial picture as we only consider the cumulative welfare. The results in Table 3 may hide important variations over time (see Fig. 13), which might change the regulator's decision depending on the planning horizon under consideration.

As observed in Table 4, Ecuador's best strategy in the Grid Expansion scenario changes, as well as the Nash equilibrium, if we only consider the welfare accumulated until 2024. The implementation of capacity payments, which is the best strategy for Ecuador in the long-term (recall Table 3), is the worst strategy in the mid-term. In the Current Grid and Unlimited Grid scenarios, the Nash equilibrium in the mid-term is exactly the opposite of the long-term. Thus, a decision based on a short or medium term analysis may result in really bad outcomes in the long-term. However, it may encounter less social resistance.

In the mid-term, Colombian consumers will always prefer to implement capacity payments, since the capacity margin is expected to be low and imports from Ecuador are not sufficient to guarantee affordable prices. However, this leads to investment decisions in high cost technologies, which will reduce their welfare in the long-term.

5. Discussion and policy implications

Comparing the Latin American and European cases contributes to the understanding of the market characteristics that may influence the long-term evolution of integrated electricity systems. We identify three key factors: a) complementarity, b) investment requirements, and c) storage capacity. The first determines the potential benefits of integration, the second the sensitivity to policy interventions, and the third may result in counterintuitive outcomes.

Both regions analyzed in this paper exhibit complementarity. However, between Great Britain and France the complementarity is

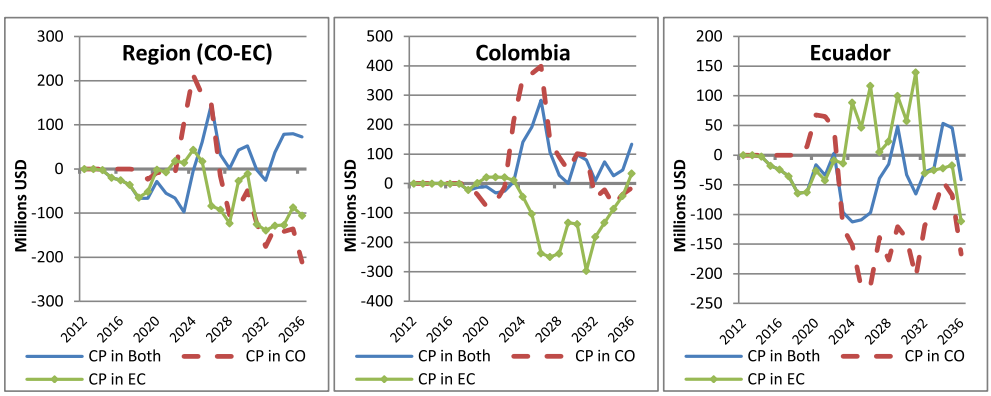

Fig. 13. Social welfare gain of capacity payments implementation in the grid expansion scenario.

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Table 4
Mid-term cumulative social welfare gain compared to the Isolated no capacity payments case (Million USD). Shaded areas indicate Nash equilibrium. R = Region, G = Grid. *Consumers in parenthesis.

Isolated							Current Grid						
CO\EC	No CP			CP			CO\EC	No CP			CP		
No CP	**CO:**	**0.00**	*(0.00)*	**CO:**	**0.00**	***(0.00)***	No CP	CO:	-0.51	*(-1.38)*	CO:	-0.50	*(-1.85)*
	EC:	**0.00**	***(0.00)***	EC:	-0.06	*(-2.38)*		EC:	-0.22	***(0.76)***	EC:	-0.47	*(-1.83)*
	G:	**0.00**		**G:**	**0.00**			G:	0.59		**G:**	**0.60**	
	R:	**0.00**	*(0.00)*	R:	-0.06	*(-2.38)*		R:	-0.15	*(-0.62)*	R:	-0.38	*(-3.68)*
CP	CO:	-0.13	***(1.56)***	CO:	-0.13	***(1.56)***	CP	**CO:**	**-0.49**	***(0.96)***	CO:	-0.67	*(0.81)*
	EC:	**0.00**	***(0.00)***	EC:	-0.06	*(-2.38)*		**EC:**	**0.02**	*(0.60)*	EC:	-0.46	*(-1.73)*
	G:	**0.00**		**G:**	**0.00**			G:	0.47		G:	0.46	
	R:	-0.13	***(1.56)***	R:	-0.18	*(-0.82)*		**R:**	**-0.01**	***(1.57)***	R:	-0.66	*(-0.92)*
Grid Expansion							**Unlimited Grid**						
CO\EC	No CP			CP			CO\EC	No CP			CP		
No CP	CO:	-0.87	*(0.17)*	CO:	-0.86	*(0.11)*	No CP	**CO:**	**0.23**	*(5.21)*	CO:	-0.93	*(0.96)*
	EC:	**-0.01**	*(0.01)*	EC:	-0.22	*(-2.14)*		**EC:**	**1.72**	*(2.51)*	EC:	1.28	*(-0.42)*
	G:	0.14		**G:**	**0.20**			G:	-1.16		G:	-1.18	
	R:	-0.74	*(0.18)*	R:	-0.87	*(-2.03)*		**R:**	**0.79**	*(7.72)*	R:	-0.82	*(0.54)*
CP	**CO:**	**-0.48**	***(2.42)***	CO:	-0.82	*(1.67)*	CP	CO:	-0.22	***(6.41)***	CO:	-0.69	*(3.07)*
	EC:	-0.09	***(0.87)***	EC:	-0.47	*(-1.39)*		EC:	1.70	***(3.34)***	EC:	1.07	*(0.85)*
	G:	0.10		G:	0.09			G:	-1.16		**G:**	**-1.15**	
	R:	**-0.47**	***(3.29)***	R:	-1.21	*(0.28)*		R:	0.32	***(9.75)***	R:	-0.76	*(3.92)*

"artificial": a result of past investment decisions which have led to a large share of base load capacity in France (Nuclear and Hydro) and peak load in Great Britain (Coal and Gas). This complementarity tends to decrease over time, since both countries have access to the same resources, so future investments lead to a more similar mix of technologies. This explains why our results show a decreasing welfare gain in all interconnection scenarios compared to the isolated case.

On the contrary, the hydrological complementarity between Colombia and Ecuador can best be exploited when both countries invest in the same technology (Hydro). This is an advantage for consumers in both countries if the interconnector is large, since demand can be met most of the time without the expensive and polluting thermal units. Comparatively, the French consumers will see the price rise significantly as result of exports; and the British, despite the lower average prices, will have to deal with the pollution resulting from an increased utilization of peak units.

Regarding investment requirements, both regions differ significantly. Great Britain and France currently have an adequate capacity margin and demand growth is slow, so in the absence of green policies little investment is needed to satisfy demand over the next two decades. This makes these markets resilient to the policy interventions tested in this paper, since the mix of generation technologies in each country is hardly modified. Thus, the undesirable long-term effects of a particular policy are minimal.

The opposite occurs in Colombia and Ecuador. Their demand grows at a significant rate, requiring large investments. Thus, any change in the market signals has a strong impact on technology choices and the amount of new generation capacity. This translates in a high risk for the regulators as well as for investors, since any decision will have a significant irreversible impact on the long-term evolution of the markets.

But probably the greatest challenge to harvesting the potential long-term benefits of integration is the existence of large storage capacity, such as in the Latin American case, where there are huge hydro reservoirs. These reservoirs where conceived to store water during the rainy seasons to generate, at higher prices, during the dry seasons. However, depending on the size of the interconnector and the hydropower capacity in each country, availability of cheap imports might keep prices down during dry seasons, as the neighbor faces a rainy season. Additionally, if there is a significant difference in size between the countries, the smaller country might find it very difficult to save water during the rainy season when the large country has a low capacity margin, since a price spike in the latter will "force" the former to empty its reservoirs. This makes the behavior of the markets difficult to predict, which may lead either to underinvestment, as in the case of Ecuador in the Unlimited Grid scenario, or to investments that cannot recover their capital costs.

From a regulatory perspective, the implementation of capacity payments may be considered as a measure to avoid dependency on imports and keep a certain control on investments. Our results suggest that, though these payments imply high costs for consumers and distort market signals, in certain cases they improve total social welfare, particularly when the resulting investments favor the complementarity (e.g. when they lead to more hydropower investments in Colombia and Ecuador). However, they may undermine the potential benefits of integration by encouraging investments without taking into account the implications for the region. Furthermore, unilateral decisions on the implementation of capacity payments may not only result in a possibility of free riding by the neighboring country, sometimes they also lead to a social welfare loss.

6. Conclusion and recommendations

According to our results, complementarity is the main factor that determines the potential benefits of market coupling. Nevertheless, the achievement of these potential benefits depends on the implemented policies. Characteristics of the countries, such as large investment requirements and significant storage capacity, make the evolution of the markets more difficult to predict, which may lead to unexpected and undesirable outcomes under certain policies, and unprofitable investments.

We recommend particular attention when assessing the effects of policies in countries with any kind of complementarity and storage facilities, since the bidding strategy of the storage units may

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distort market signals and prevent the exploitation of the complementarity. Our results show that in such a case the effect of the interconnection size on social welfare is non-monotonic, and varies significantly over time. The regulators must be aware of the fact that the interconnector size influences the effect of policies, both at home and abroad.

In addition, the interconnection causes a welfare redistribution: even when the total social welfare of the region increases, some market participants lose. This is particularly important in two cases: first, when producers lose to the point of not being able to recover their investments; and second, when consumer losses create resistance to integration. To avoid these situations, a compensation mechanism might be implemented; however, we recommend extreme caution as this may distort the market signals.

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