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Economics of electricity grid interconnections: A heterogeneous markets' design context

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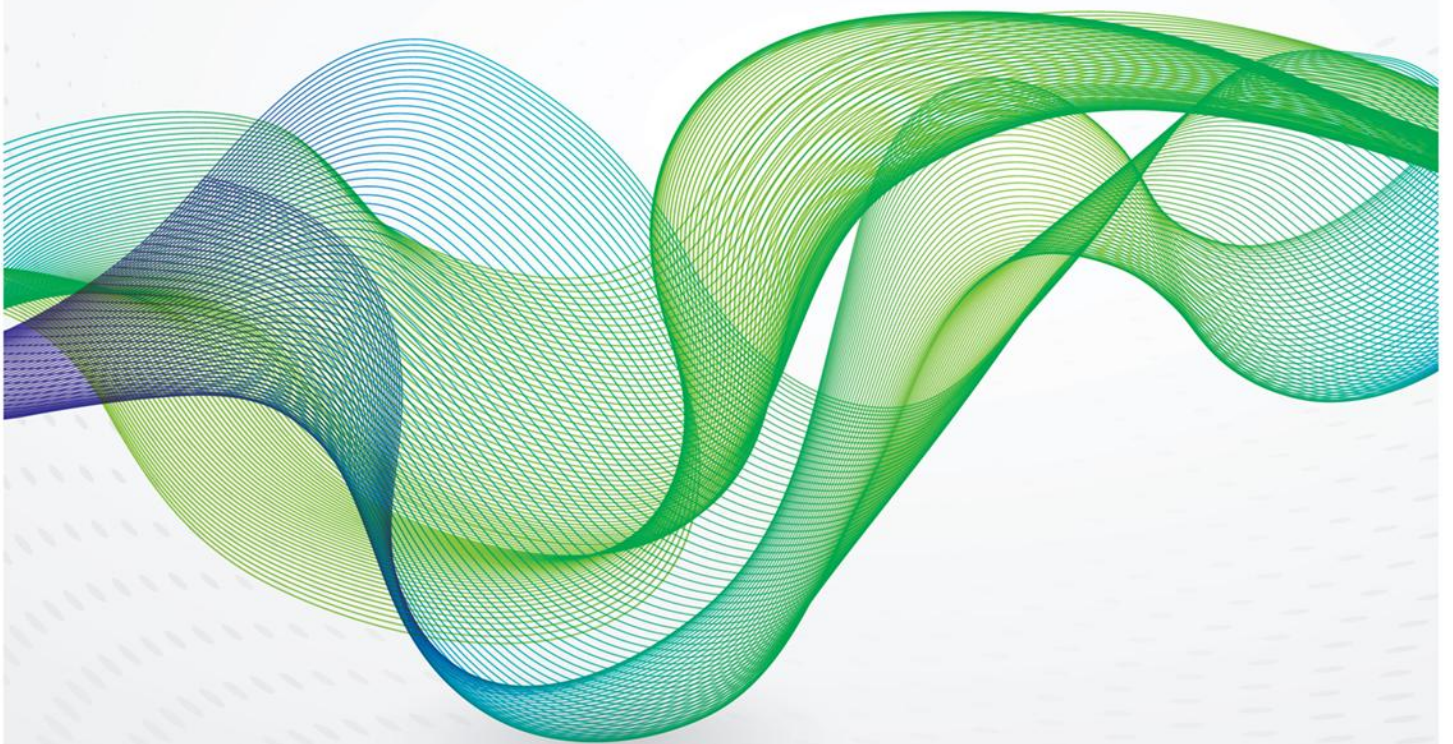
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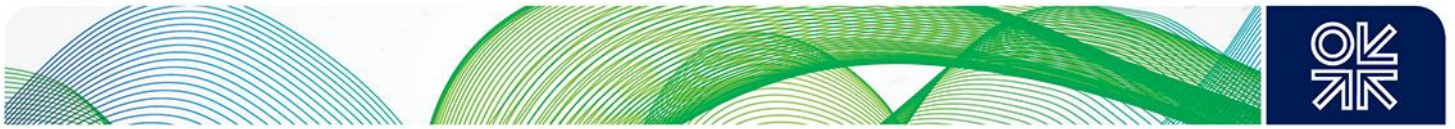
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January 2025

Economics of Electricity Grid Interconnections: A Heterogeneous Markets' Design Context





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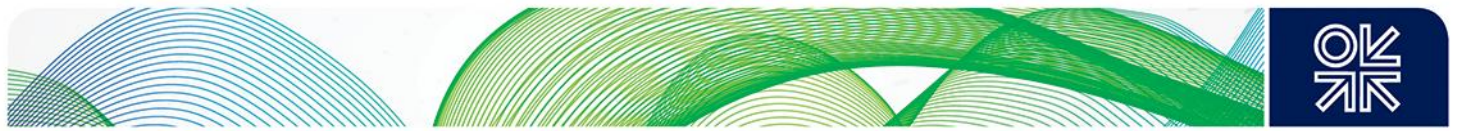
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Abstract

Heterogeneous interconnections, which link regulated electricity markets to liberalised ones, are becoming increasingly important. Several such interconnections are set to be established in the near future especially between European and North African countries (e.g., Tunisia-Italy, Egypt-Cyprus-Greece, Algeria-Italy), in addition to various already existing ones. These interconnections present unique challenges and peculiarities that are not adequately addressed in the existing literature, which often focuses on homogeneous interconnections (i.e., those linking liberalised markets). Understanding the economics of heterogeneous interconnections becomes crucial for enabling clean energy trade between markets at different development stages.

The capacity allocation mechanisms for heterogeneous interconnections often appear to be adaptations of those used in homogeneous interconnections which does not account for the unique challenges of heterogeneous contexts. In this paper we show that the regulated market has an informational advantage over the liberalised market, as it can observe both actual and historical prices in the liberalised market, as well as the aggregate supply and demand curves that determine them. It can therefore leverage its informational advantage to manipulate outcomes by misrepresenting its marginal costs and their sensitivity to cross-border exchange. As a result, heterogeneous interconnections are likely to be less efficiently utilised compared to homogeneous ones, reducing overall welfare but increasing the regulated market's individual welfare. This implies that mechanisms that decentralise exchange decisions and disregard congestion revenues (e.g., implicit auctions) are less effective in heterogeneous contexts where the regulated market's utility can monopolise arbitrage decisions. The inefficiencies in heterogeneous interconnections can be reduced by implementing appropriate allocation mechanisms and policies. For example, mechanisms that enable potential private agents in the regulated market to independently carry out cross-border operations or those that enable dispatching cross-border exchange further from delivery could be effective. Similarly, long-term cross-border contracts for energy could be negotiated to ensure a minimum utilisation level of the interconnection and reduce the manipulation margin.



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1. Introduction

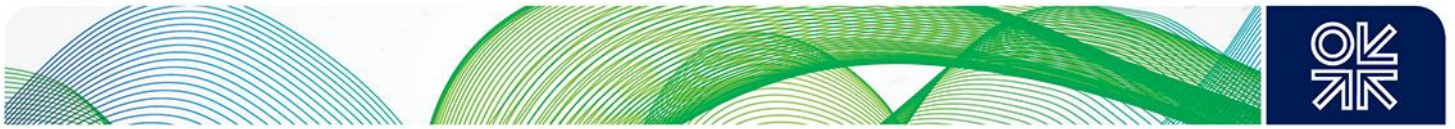
Electricity exchange across countries or jurisdictions requires interconnections between their respective grids to enable the cross-border flow of electricity. These interconnections generally allow bi-directional trade, enabling arbitrage across markets, and their transmission capacity is always limited. This grants interconnection capacity its scarce resource aspect, and as such, the efficient allocation and utilisation of this resource falls within the realm of economics, and arises as a central issue in the economics of grid interconnections.

Interconnections continue to expand globally, either by establishing completely new ones, or by increasing the transfer capacity of existing ones. This expansion is largely explained by the benefits interconnections provide to the connected markets, whether commercial (e.g. higher welfare) or technical (e.g. grid stability). The extent of these benefits is dependent on the efficient utilisation of the cross-border transmission capacity, which in turn depends on how cross-border trade is undertaken, and on how, and to whom, transmission rights are allocated (Joskow & Tirole, 2000).

The design of the linked electricity markets directly influences how a specific interconnection operates, and therefore how its capacity is utilised. From a market restructuring perspective, three possible combinations of market states arise, depending on whether or not the interconnected countries have deregulated their power industries: both countries' power markets are deregulated, neither of the power markets is deregulated, and one country's power market is deregulated while the other is not. These different states lead to different rules governing the interconnection and the allocation of its capacity to economic agents. In the first state, capacity is typically allocated to market participants through auctions, either explicit or implicit, and exchange is consequently directly or indirectly conducted between the different agents of the respective markets. In the second state, auctions are generally unfeasible due to the lack of a market. Hence, trade is carried out between the respective vertically integrated utilities of each country based on their specific arrangements or contracts. Finally, for the third state, which is less common, some forms of market mechanisms for capacity allocation and trade can be implemented in principle, or these can be exclusively governed by long-term bilateral agreements. However, the currently available literature and data on how interconnections of this type really function are scarce.

Actually, in the literature, the third state involving heterogeneous interconnections is rarely considered despite its peculiarities and its increasing importance as several links of this type are set to be established in the near future (e.g. Tunisia–Italy, Egypt–Cyprus–Greece, Algeria–Italy...), in addition to the various already existing ones. Therefore, this investigation attempts to fill this gap by reviewing how existing interconnections of this type operate, identifying the mechanisms by which their capacity is allocated, and analysing the economics of heterogeneous interconnections.

Due to the broad scope of our paper, it can be positioned within a distinct set of literature. Earlier investigations have reviewed existing interconnection capacity-allocation mechanisms, such as T. Kristiansen (2007), who focus their analysis on a specific region (South East Europe), or Turvey (2006), who largely consider a homogeneous context and do not discuss the implications of the markets' design, unlike our paper. For the economics of grid interconnections, specifically from a welfare perspective, a diverse body of literature discusses aspects of it (Antweiler, 2016; Bahar & Sauvage, 2013; Gonzales et al., 2023; M. Kristiansen et al., 2018; Turvey, 2006). Beyond the modelling approach, our paper differs in several ways: we do not limit the analysis to a specific allocation mechanism (e.g., market coupling); we identify the equilibria that arise based on the willingness of the relevant parties to exchange; we underline how the allocation of congestion rents may distort efficient outcomes; and we unveil peculiar interactions that arise specifically in the heterogeneous context. Lastly, for the literature that specifically targets heterogeneous interconnections, we are only aware of Poudineh and Rubino (2017), who look at the effects of heterogeneous market design across the Mediterranean basin on investment decisions in interconnections. In contrast, our paper focuses on the utilisation phase of heterogeneous interconnections, rather than investment.



We start by presenting an in-depth analysis of some existing heterogeneous interconnections and how they function. Then, based on this analysis, we identify and describe the currently prevailing capacity allocation mechanisms in this type of interconnections. Subsequently, we develop a conceptual framework on the economics of the utilisation of grid interconnections, highlighting the effects of cross-border exchange on aggregate social welfare, and on the markets' individual welfare, separately. Finally, based on the developed theoretical framework, we identify some inefficiencies that can plague the utilisation of grid interconnections, specifically when heterogeneous markets are involved, and we discuss some ways to limit these inefficiencies.

While our investigation focuses on heterogeneous interconnections, our results generalise to interconnections more broadly. Most of the capacity allocation mechanisms we identify are also prevalent in homogeneous interconnections. Similarly, the conceptual framework we develop models the welfare implications of cross-border exchange in general, independently of the market structures involved. Finally, although the last section of our paper highlights the peculiarities of the heterogeneous context, its conclusions apply to any interconnection setting where access to the interconnection in one market is exclusive to a single agent who also participates in the wholesale market as a buyer or seller of electricity. Especially if that agent benefits from information asymmetry.

Lastly, our investigation is solely concerned with the utilisation phase of the interconnection, and the allocation of its capacity, rather than the investment phase. While our results carry implications for investment decisions in cross-border capacity, these are beyond the scope of our paper, and are therefore not discussed. Moreover, as electricity is a homogeneous good, our conceptual results extend to arbitrage in general, beyond electricity and commodity markets.

2. Descriptive review of some existing heterogeneous interconnections

In this section, we list and thoroughly discuss a set of selected interconnections involving markets with heterogeneous designs. This is not an exhaustive review of existing interconnections of this type, rather, this is a focused analysis of some of the most interesting ones in transmission capacity, operations, and capacity allocation mechanisms. We mainly consider interconnections that allow bi-directional flows and operate distinctly from one another to ensure variety. To achieve a global and diverse perspective, we present cases from different continents. Table 1 summarises some main findings from this review, while the rest of this section goes into the details.



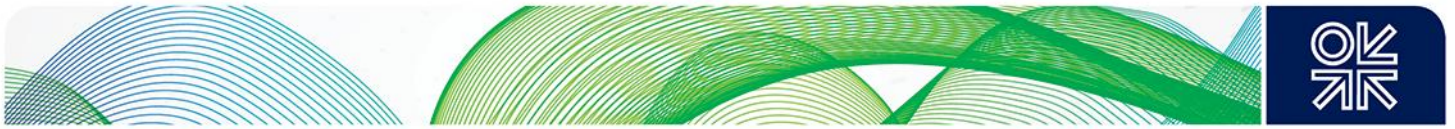
Table 1: Key operational aspects of the investigated heterogeneous interconnections

	Ontario – Quebec	Iberian Peninsula – Morocco	Turkey – Georgia
Market Design combination	Real time zonal double-sided auction – Vertically integrated utility.	Mandatory organised (double-sided auction) wholesale market – Single-buyer utility.	Non-mandatory organised wholesale market and bilateral contracts – Regulated bilateral contracts and balancing operations.
Region	North America	Western Europe and North Africa	Eastern Europe and West Asia
Bilateral flow?	Yes.	Yes.	Yes.
Capacity allocation timeframe	Very long, long, and short term.	Short term only.	Long and Short term.
Capacity allocation mechanisms	Virtual market zones, implicit auctions, arbitrageur subsidiary, bilateral contracts for energy and firm capacity.	Bilateral contracts for energy executed on the day-ahead timeframe combined with explicit auctions, implicit auctions.	Cross-border bilateral contracts, interconnection deregulation, explicit auctions.
Electricity wheel-through?	Yes.	No.	Yes.
Efficient capacity allocation and dispatch?	Yes, assuming competitive behavior.	Yes, assuming competitive behavior.	Yes, assuming competitive behavior.
Strategic actors (e.g. bidders...)	Quebec's utility.	Moroccan utility.	Turkish and Georgian eligible traders.
Existence of market power?	Yes, with Quebec's utility.	Yes, with Morocco's utility.	Limited power with Georgia's TSO due to its incomplete unbundling.
Cross-border dispatcher?	Liberalised market.	Liberalised market.	Exporting market.
Allocation of congestion rents	No established rules. Therefore, rents arising from spot market trading are fully collected by Ontario's market operator (due to the market design).	No established rules, hence: Moroccan utility collects rents from Implicit auctions, Spanish system operator collects rents from explicit auctions.	No (accessible) clause. The exporting country's system operator likely collects all the rents from the auction it implements.

2.1 Quebec and Ontario interconnection

Quebec and Ontario are two different and neighbouring provinces of Canada, due to their distinct characteristics and historical circumstances, these two jurisdictions have developed separate and significantly heterogeneous electricity markets. In Quebec, a province with a massive hydropower capacity supplying almost the totality of its demand, the power sector is still regulated, operating as a vertically integrated utility. Whereas to the west, in the province of Ontario, the electricity industry has been restructured since 2002, and a wholesale electricity market was established through which market participants can buy and sell energy, managed by the Independent Electricity System Operator (IESO).

These two Canadian provinces have long been interconnected, and as typical in North America, these cross-jurisdiction interconnections are called interties. Currently, there exists six interties linking the two provinces, and totalling a transmission capacity of about 2,775 MW, the majority of which is



bi-directional. These interties are used to either import or export electricity from the opposing market, or, as a “wheel-through” where the exchanged energy is sourced from or destined for a distinct market. That is, a trade that only involves one of these provinces, while the transmission system of its counterpart is merely used, for a charge, to transport electricity to its final destination. The available capacity of the Ontario-Quebec intertie is allocated in several ways, which can be grouped within two families: cross-jurisdiction bilateral contracts, and non-contracted spot market trade (IESO, 2023). Both these allocation methods involve Ontario’s wholesale market, so let us first describe how this quite unorthodox market currently operates, before explaining in detail how the intertie capacity is allocated. Our description is largely based on the numerous official market manuals and rules published by IESO.

Ontario’s electricity market is fairly peculiar, while it is designed as a uniform price auction and operates based on zonal-pricing (contrary to most markets in North America), it does not have a day-ahead market.¹ Rather, the province relies on a real time market based on a two schedule system, one that is domestically unconstrained (in transmission) based on which prices are determined, and the market is financially settled, followed by another that accounts for physical transmission constraints, sets the dispatch, and determines shadow prices, locational prices that only count for informational purposes.²

Both these market clearings rely on bids to buy or sell electricity submitted by market participants for each hour, and are run over two different timeframes, one that is hourly, called the “pre-dispatch scheduling”, the other is based on five-minute intervals, called the “real-time dispatch”. The latter determines dispatch instructions for every five-minute interval, and the financially binding prices for each interval, which are subsequently averaged to generate the Hourly Ontario Energy Price (HOEP). Whereas the former, the pre-dispatch schedule, is utilised to determine “advisory” prices and schedules, providing some forward information for market participants to plan their operations.³ Thus, as stated by the IESO, the real-time market is composed by both the pre-dispatch scheduling and the real-time dispatch.⁴

Non-contracted Spot Market Trade: Quasi-implicit auctions through virtual wholesale zones

The first capacity allocation arrangement utilised by this interconnection is based on non-contracted spot market trade, through “Quasi-implicit Auctions”, that is, the indirect allocation of interconnection capacity through energy dispatch.⁵ In this case, it refers to the allocation of the intertie capacity through regular bids that are submitted by market participants, domestic or foreign, in the wholesale electricity market of Ontario, the latter’s allocation approach does not distinguish between interties involving deregulated or regulated markets, nonetheless, the fact that Quebec has no established wholesale market does imply some minor peculiarities. In what follows, we provide a general description of how cross-jurisdiction trade is programmed by Ontario’s market.

IESO dispatches wholesale electricity across its interties by permitting market participants to submit export and import bids, respectively treated in the dispatch as demand and supply bids, into the market.⁶ Participants in Ontario’s wholesale market who submit foreign exchange bids have to specify exactly through which one of the interties the trade ought to be carried.

Subsequently, based on these bids, the IESO creates “virtual” zones within the market that represent each intertie. With Quebec, IESO currently has nine established zones. For each zone, the relevant bids are sorted based on merit order, exports decreasingly by price and imports increasingly, and are considered up to the transfer capacity limit. Considered bids are then combined with the bids submitted

¹ There exists a Day-Ahead Commitment Process that attempts to enhance clarity for market participants and increase reliability of the system, however, it does not determine a clearing price, nor is it financially binding.

² Note that the unconstrained schedule does account for intertie capacity constraints.

³ That is, the clearing schedules and prices from the pre-dispatch are not financially binding, with the exception of imports and exports bids, as will be detailed later on.

⁴ Note that due to several inefficiencies arising from the current market design, Ontario’s power market is set for a reform in the near future.

⁵ However, the allocation mechanism does reveal to which market participants the capacity was allocated, hence it is not a pure implicit auction.

⁶ Wheel-throughs are captured by submitting both an import and an equivalent export bid.



within Ontario zone to clear the market in Ontario and determine the dispatch, including the cross-border trade.⁷ Consequently, the transmission capacity of each intertie is implicitly allocated to importers and exporters. If the aggregate volume of economic cross-border bids in the relevant direction stands superior to its intertie capacity, transmission constraints are therefore binding, and congestion arises.⁸ Note that both export and import bids can be simultaneously dispatched in a given interval over the same intertie, and that an intertie can be import and export congested at the same time (Brown, 2024).⁹

However, there is a slight temporal difference regarding the actual dispatch of the cross-border bids, that is the binding allocation of the interconnection capacity, and energy dispatch.

First, cross-border bids are dispatched on an hourly basis, rather than five-minute intervals. Second, their dispatch is actually determined by the Pre-Dispatch Scheduling one hour prior to the dispatch hour, based on pre-dispatch prices, rather than by the Real Time Dispatch, unlike energy. In the latter, they are taken as fixed and non-dispatchable, even if prices emerge different in the real-time and it results in some otherwise dispatched (rejected) cross-border bids becoming uneconomic (economic).¹⁰

In addition to the clearing prices in Ontario, IESO likewise sets clearing prices for each intertie zone. Again, differences arise across the Pre-Dispatch Schedule and the Real-Time Dispatch. In the former, intertie zonal prices are determined as equal to the price of an incremental megawatt of electricity that would be available through the intertie if its transmission capacity was not binding. These prices can be equal (non-congested intertie), superior (export congested), or inferior (import congested) to the price within the Ontario zone, mainly decided by the intertie's transfer capacity and cross-jurisdiction price differentials, as is the case in other more conventional markets.¹¹ Subsequently, the difference between the pre-dispatch prices in each intertie zone and the price in Ontario are computed to set what is called the "Intertie Congestion Price". Conversely, in the real-time dispatch, the intertie zonal prices are defined as the sum of Ontario's real-time market clearing prices and the Intertie Congestion Price as computed in the pre-dispatch. These real-time intertie prices are the ones that are used to financially settle imports and exports through each relevant virtual zone, exporters paying, importers are paid, and as a result, IESO captures the totality of congestion rents emanating from this intertie, at least from the trade carried through Ontario's spot market (Brown, 2024).

Finally, while the intertie capacity is allocated through the liberalised market of Ontario and its market dispatch algorithms, just as all other interties involving Ontario, the fact that Quebec's market is regulated results in one principal peculiarity: the hourly bids based on which the cross-border trade is determined are all originating from within Quebec. That is because from Quebec's perspective, the cross-border exchange of electricity is managed by the vertically integrated state-owned utility Hydro-Quebec, largely through its fully owned subsidiary "HQ Energy Marketing Inc." (HQEM), acting as the sole marketer of Quebec's electricity who conducts cross-jurisdiction energy transactions with other Canadian provinces. The subsidiary is registered as a participant in Ontario's real-time market and therefore submits bids to both export and import electricity from or to Ontario. As such, HQEM is the only strategic actor in this intertie, monopolising cross-market arbitrage, at least in spot market trading.

⁷ Once the cross-border exchange is determined, the IESO confirms with the relevant jurisdictions that matching bids exist in their respective markets, or that the flow is authorised by the regulated utility.

⁸ In addition to the intertie's capacity, the IESO also sets another constraint on cross-border electricity flow, represented by an inter-hour ramp rate limit of 700 MW. More details on this constraint available at : "Quick takes: Net Interchange Scheduling Limit" document.

⁹ However, flows are netted as electricity only travels by a determined volume in a single direction. Both the direction and the volume are captured by the "Net Interchange Schedule", that is, the difference between the aggregate volumes of the dispatched import and export bids.

¹⁰ To ensure the adequacy of supply in Ontario's market, the IESO has a mechanism in place called "Intertie Offer Guarantee" to reduce price risks caused by this temporal difference in scheduling, for importers only.

¹¹ The higher the cross-jurisdiction transfer capacity, the more likely prices across Ontario and the virtual zones will converge.



Long-term bilateral contracts

The other capacity allocation method governing this interconnection is long term bilateral contracts, negotiated by the governments of the respective provinces, and involving Ontario's IESO, and Hydro-Quebec through its subsidiary HQEM. These agreements leverage the complementarity of the provinces' demand profiles, and stipulate specific terms for the cross-border trade of either firm capacity or firm energy.

Two different electricity trading agreements were negotiated between the two provinces over the last decade, while another one is currently under a memorandum of understanding. The first one, called "Capacity Sharing Agreement", specified a seasonal swap of 500 MW of firm capacity, not involving any monetary exchange, but only operated through 2015-2016, before being amended by the electricity trade agreement, effective from 2017 to 2023. Unlike its predecessor, the latter only specified a unidirectional capacity provision, from Ontario to Quebec in summer, a capacity for which Quebec had to pay on monthly basis. The electricity trade agreement included other additional terms beyond capacity: an arrangement to sell 2000 GWh of electricity every year by Quebec during specific market conditions in Ontario, destined to displace natural gas generation, to be bid within the wholesale market of Ontario at a set contracted price, and a provision for Ontario to voluntarily cycle its electricity through Quebec. Thanks to Quebec's huge hydro capacity and its storage potential, the agreement enabled IESO to "transfer" its excess capacity to Quebec, and then call on it when needed for no financial obligation whatsoever. The third agreement, currently in a memorandum of understanding phase, should cover the period ranging from November 1, 2024 to October 31, 2031. Like the initial "Capacity Sharing Agreement", this new one solely involves seasonal firm capacity swap.

All these provisions stipulated in the bilateral contracts directly (energy sales) or indirectly (capacity swap and voluntary cycling) lead to an allocation of the intertie's capacity outside of Ontario's wholesale market, even though the dispatch itself is determined through the latter. In its market rules document, the IESO states that the firm capacity provided by these agreements, once called upon, shall be provided through Ontario's market through bids to export or import electricity submitted by HQEM at any allowed price, and dispatched normally by the market's dispatch algorithm (IESO, 2023). Likewise, the energy exchanged through the cycling provision of the contracts shall similarly be offered within Ontario's wholesale market, and dispatched normally (IESO, 2017).

2.2 Morocco and the Iberian Peninsula interconnection

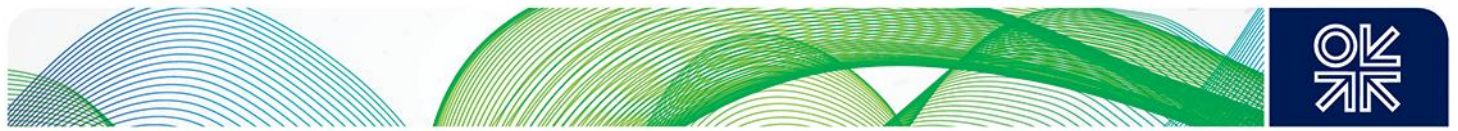
Since 1993, Morocco has undertaken significant efforts to gradually introduce private sector participation in its electricity industry, specifically in generation, and currently about 75% of its power generation is secured by private Independent Power Producers through long-term Power Purchase Agreements (PPA) with the state-owned electricity utility. However, like the rest of the African continent, Morocco's electricity market is still regulated, and no wholesale power market exists to this day (Ciarreta et al., 2024). That is unlike its northern neighbour, Spain, whose electricity industry was liberalised in 1998 through the General Electricity Law 54/1997, establishing a wholesale power market based on an hourly uniform price auction.

The heterogeneous power markets of Morocco and Spain have been interconnected since 1997, and a first expansion of the interconnection capacity was commissioned in 2006, with further expansions planned for the future.¹² In 2007, the Spanish and the Portuguese power markets were integrated into a single pool, leading to the creation of the Iberian Electricity Market (MIBEL), thus interconnecting the Moroccan electricity sector, through its interconnection with Spain, with the whole Iberian Peninsula. The current total capacity of the interconnection is 1,400 MW.¹³

The interconnection is used by both countries to import and export electricity across their shared borders, without any possibility for direct "wheel-through" to third countries. Its current capacity allocation mechanisms are largely set by the Spanish National Markets and Competition Commission (CNMC),

¹² The countries have signed a memorandum of understanding to establish a third interconnection line by 2026.

¹³ Of which 900 MW in the Spain to Morocco direction, and 600 MW in the reverse direction, are dedicated to commercial exchanges.



through its circular 3/2019.¹⁴ While some aspects governing the Moroccan side of operations are set by Morocco's laws 13-09 and 40-19. The interconnection's capacity is solely allocated over the short-term, through bilateral contracts executed in the day-ahead timeframe, non-contracted spot market trade through bids submitted in the Iberian day-ahead and intraday markets, and, exceptionally when the aggregate volume of cross-border bilateral contracts exceeds their dedicated capacity, through a daily explicit auction. Long-term allocation arrangements are currently not determined for this interconnection, nor any arrangement to trade or swap firm capacity, only energy is exchanged.

Articles 14, 15, and 16 of the CNMC 3/2019 circular outline in detail the capacity allocation procedure. In a first step, market agents eligible for cross-border electricity trading shall inform the Spanish system operator about the execution details of their physical bilateral contracts one day prior to the delivery. Subsequently, before the closure of the day-ahead market, the system operator subtracts the aggregate volume of the communicated bilateral contracts from the interconnection's capacity to determine its maximum share bound for dispatch through the Spanish wholesale market. This value shall be no less than 50% of the total capacity in the relevant direction, and is then communicated to the market operator. If any unallocated capacity remains from the day-ahead market share after its clearing, it can be added to the share assigned through bilateral contracts if their combined volume exceeds 50% of the interconnection's capacity. Note that whenever the capacity share dedicated for physical bilateral contracts is insufficient to satisfy all the demand, then the priority order by which these contracts are executed is determined by the system operator through an exceptionally conducted explicit auction for cross-border capacity. This auction is based on daily orders for capacity submitted in euros per MW by the holders of these contracts. The orders are submitted at the moment when the bilateral contracts' terms are communicated to the system operator in the first step of the procedure. The auction is competitively cleared by flow direction and hour, prioritising the highest bidders, and setting a marginal price for the interconnection capacity, defined as the order price submitted by the last executed bilateral contract. Naturally, when the combined volume of the physical bilateral contracts is inferior to their revised dedicated capacity post day-ahead market clearing, then all contracts are executed, and the capacity is allocated for free.

Lastly, in the intraday time horizon, the system operator provides the market operator with updated information regarding the residual maximum capacity available for allocation through the wholesale market. This residual capacity therefore excludes the previously allocated share through the day-ahead market and physical bilateral contracts, and is subsequently allocated, either partially or entirely, through the various sessions of the intraday market auction based on bids received by the market operator. Figure 1 presents a flowchart summarising the described capacity allocation process for this interconnection as carried by the Spanish system operator and through the Iberian market.

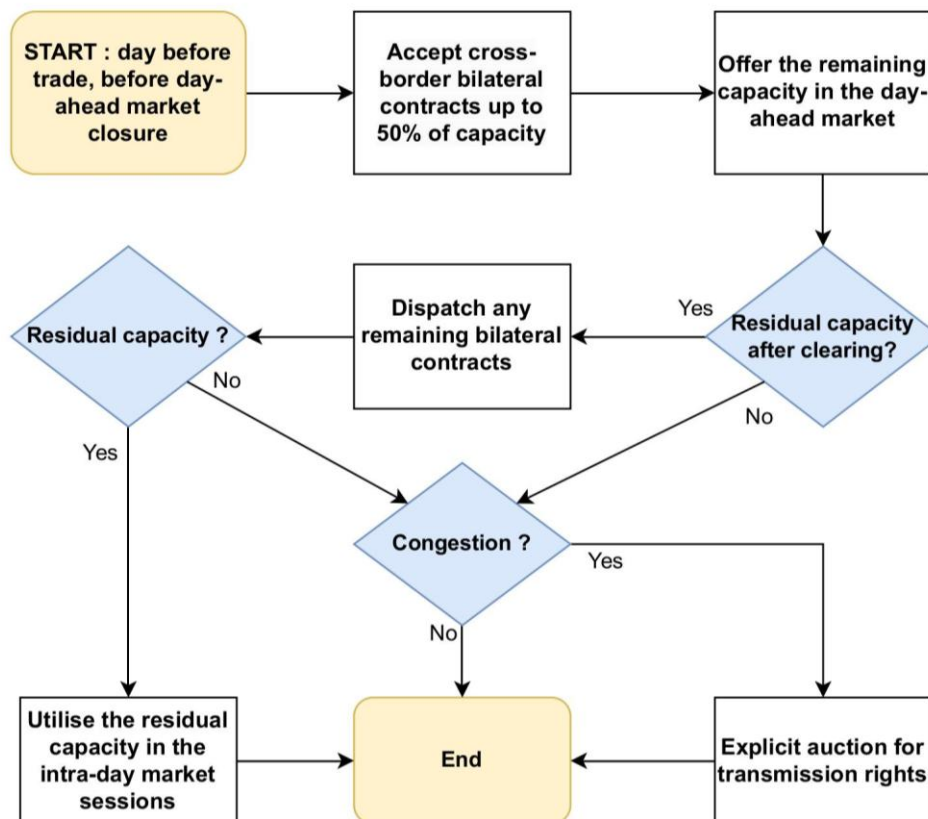
Existing market clearing algorithms of MIBEL are utilised for the cross-border capacity allocation in both the day-ahead and the intraday markets. As mentioned by the CNMC in the justification memorandum of the 3/2019 circular, Morocco is considered as a separate price zone at the border, and the interconnection capacity allocation is carried through the European market coupling mechanism. That is, the Iberian wholesale market allocates its dedicated share of interconnection capacity simultaneously with energy dispatch, on hourly basis, based on a pure implicit auction mechanism.¹⁵

¹⁴ The circular establishes the methodologies that regulate the functioning of the wholesale electricity market and the management of the system operation.

¹⁵ This is a pure explicit auction as the market coupling mechanism does not directly identify to which market agents the interconnection capacity was allocated.



Figure 1: Flowchart of the interconnection capacity allocation procedure between Morocco and the Iberian Peninsula, as implemented by the Spanish system operator



While the 3/2019 circular clearly describes the procedure by which the interconnection capacity is allocated, it does not identify the market agents eligible to participate in the cross-border trade, particularly from the Moroccan side. The Spanish market, and by extension MIBEL, does permit participation of external agents as long as they satisfy some conditions and receive the necessary authorisations, as outlined in the Order of 14 July 1998 and the Royal Decree 2019 of 26 December. For Morocco, we can get some insight on this issue by considering the regulation and structure of the Moroccan market, as well as by looking at the public data shared by the Iberian market operator and the Spanish system operator. The Moroccan market is structured as a single-buyer market where the national utility is the sole party eligible to purchase power and to whom Independent Power Producers (IPP) must sell all their electricity. However, exception is made for IPP owned renewable power plants operating within the framework of the 13-09 law, as modified by the 40-19 law.¹⁶ These generating units are allowed to sell their production to other specific parties, including exporting it to foreign markets.¹⁷

Therefore, the sole authorised importer of electricity into Morocco is the public utility, both through the Iberian wholesale market or through physical bilateral contracts. Accordingly, the public utility is the only Moroccan market agent submitting demand bids within the Iberian day-ahead and intraday markets. On the other hand, for electricity exports, both the Moroccan utility and the 13-09 renewable IPP are authorised to export. In principle, they can do so through either physical bilateral contracts or the Iberian wholesale market as none of the accessible Moroccan nor Iberian regulations forbid them from doing so. However, similarly to imports, the public utility is currently the only Moroccan market agent

¹⁶ These are mainly renewable generation units built in specific locations, not bound by any Purchasing Power Agreement with the national utility. Their developers must be subject to private laws (*personne morale de droit privé*), whether they are publicly or privately owned.

¹⁷ Exports however require receiving technical permission and setting up an agreement with the system operator on the technical and economic aspects of accessing the interconnection.



participating in the supply side of the Iberian wholesale market. The reasons for this are not clear, we assume it is largely a combination of factors, such as IPP not receiving the necessary authorisation by Morocco to directly operate within the Iberian market, a prerequisite to operate in MIBEL. In addition to inadequate regulation from the Moroccan side, or simply, Moroccan IPP ignore that they can operate within the Iberian market, or are not interested as most of their generation is tied to domestic contracts. Therefore, exports from these independent generators, if any, are limited to physical cross-border bilateral contracts. Lastly, the Moroccan regulation does not outline any specific mechanism to allocate the cross-border export capacity when demand for it exceeds the available capacity. Such a situation is therefore likely governed by the mandatory bilateral agreements signed between the system operator and each exporter prior to receiving the authorisation to export.

Lastly, regarding congestion rents and revenues, the CNMC circular does not mention any clause detailing if or how they are shared, nor does any of the previously mentioned texts of law. As such, it is safe to assume that congestion revenues from the explicit auctions established by the Spanish system operator for the execution of cross-border bilateral contracts are fully collected by the Spanish side. On the other hand, the congestion rents arising from the spot-market operations are fully captured by the Moroccan utility, as it is the sole party benefiting from cross-border price differentials.

2.3 Turkey and Georgia interconnection

The (long) process of restructuring the Turkish electricity market began in 2001 with the enactment of the first Electricity Market Law, leading to the unbundling of the Turkish Electricity Generation and Transmission Company. This process later-on led to the establishment of a wholesale power market in the country, with a design quite similar, and taken from, western European and Nordic countries.¹⁸ As a result, the Turkish wholesale electricity market is comprised of the familiar Day-ahead, Balancing, Intraday, and Ancillary services markets, introduced in their current state in 2011, 2011, 2015, and 2018, respectively. Likewise, the Turkish day-ahead market is structured as a uniform-price double sided hourly auction, unlike the intraday market which is continuous and bilateral (Şahin, 2021). However, participation in the Turkish day-ahead market is not obligatory, and the largest share of electricity trades (usually around 60%) is carried outside of it, through bilateral contracts (PwC Türkiye, 2023). The Turkish market operator, Energy Exchange Istanbul (EXIST), is in charge of operating the country's day-ahead and intraday electricity markets, whereas the Turkish transmission system operator, TEİAŞ, operates the balancing and ancillary services markets.

Bordering Turkey from the northeast lies Georgia, a small country with an equivalently small electricity market. To tackle several issues with its electricity industry, and in line with its aspirations to ascend to the European Union, Georgia has taken significant measures over the last decade towards the liberalisation of its electricity sector.¹⁹ After a set of delays, the country was expected to open its own organised wholesale power market under the European target model design in July 2023, likewise consisting of a Day-ahead, an Intraday, an Ancillary Services, and a Balancing markets. Alas, this was yet again delayed and the currently expected opening day of the market is the first of July 2024.²⁰ As a result, Georgia remains in a transitory state towards market liberalisation, there is currently no deregulated wholesale electricity market in Georgia, and the full unbundling of the country's Transmission System Operator (TSO) is yet to be completed (The Energy Community, 2023).²¹

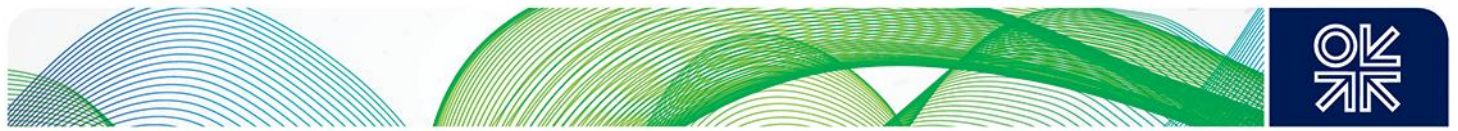
The Georgian electricity market currently operates on the basis of two distinct yet interlinked mechanisms, largely set and detailed by the two main texts of legislation still governing the market operations during its transitory period, which are the Law of Georgia on Electricity And Natural Gas (Law No.816-IIS of 1997), and the Electricity (Capacity) Market Rules (Order No.77 of the Minister of Energy,

¹⁸ Turkey is currently an observer member within the European Network of Transmission System Operators for Electricity (ENTSO-E).

¹⁹ Georgia has signed the Energy Community Treaty, whose purpose is to integrate European Union (EU) members' electricity and natural gas markets with those of some neighboring non EU states, mostly in the Balkans and Eastern Europe.

²⁰ The design and rules of the yet to be established Georgian wholesale electricity market are detailed in the Resolution 46 of August 11, 2020, adopted by the Georgian National Energy and Water Regulatory Commission (GNERC).

²¹ Georgian National Energy and Water Supply Regulatory Commission, Decision №18/5.



30 August 2006). The first mechanism, through which the majority of electricity is traded, is based on “direct contracts”, which are long or short term bilateral purchasing power agreements binding eligible sellers and buyers of electricity.²² These direct contracts do not involve Georgia’s electricity market operator, the Electricity System Commercial Operator (ESCO), unlike the other mechanism, called the “Balancing Electricity Market”.²³ This second mechanism is carried through the market operator, and its function is to balance the differences between the contracted volumes by the relevant parties in the direct contracts, and the actually delivered or consumed volumes. Simply put, the market operator buys excess electricity resulting from direct contracts’ execution imbalances, and sells it for market participants to whom the imbalances from direct contracts lead to a “shortage” of electricity.

Turkey and Georgia are interconnected by two different lines, operating in two distinct modes. The first and oldest one, the Batumi-Khopa Line, has a bidirectional capacity of 150 MW, and is solely used for emergency situations.²⁴ The second line, called the Black Sea Transmission Network, or the Borcka-Akhalsikhe Line, was commissioned in 2013, with a bidirectional capacity of 700 MW, relying on a back-to-back HVDC station technology. The interconnection is used to either directly exchange cross-border electricity across both markets, or to wheel-through electricity from Armenia, Azerbaijan, and Russia towards Turkey.

We limit our analysis to the Borcka-Akhalsikhe line as the other one is seldom used, and only when emergencies arise. The operations of this interconnection are largely governed by three bilateral agreements binding the governments of Turkey and Georgia. The first is the “Cross-Border Electricity Trade Agreement Via Borcka-Akhalsikhe Interconnection Line”, signed on 20 January 2012, and effective since June 2013, following its approval in Turkey by law 6490. The second is the “Interconnection Operation Agreement Relating to Asynchronous Operation of 400 KV Borcka-Akhalsikhe Interconnection Line” signed on 19 September 2013, whereas the last and most recent agreement is “On the Cooperation in The Field of Energy”, signed on 09 April 2015, and effective since 2016.²⁵ In summary, these agreements state that in a first step, before the 1st of August of a calendar year, the system operators of Turkey and Georgia jointly determine the Net Transfer Capacity of the interconnection line available for the next calendar year, and the electricity flow direction for each month (article 4.1, Operations Agreement). This capacity shall be allocated on a year-ahead, month-ahead, and day-ahead basis (article 9.1.c, Cooperation Agreement). Capacity allocation ought to be carried by the exporting country (article 6.1.b, Trade Agreement), prioritising electricity produced from renewable sources (articles 6.1.c and 8.4, Trade Agreement).²⁶ After the initial capacity allocation, if a share of the allocated capacity is not utilised by the transmission rights owners for a determined timeframe, it can be reassigned to different parties in the subsequent timeframe (articles 8.5 and 8.6, Trade Agreement).

As such, the currently existing capacity allocation mechanisms for this interconnection, in both Turkey and Georgia, are direct cross-border contracts, and explicit auctions for commercial transmission rights, carried over the year-ahead, month-ahead, and day-ahead time horizons. The clearing rules of the auctions are similar in both markets. When demand for interconnection capacity is less than the available capacity, then transmission rights are granted for free based on cross-border commercial contracts, and the auctions are unnecessary (article 5.4, Operations Agreement).²⁷ Whereas when demand exceeds the available capacity, auctions are conducted by the exporting country (generally Georgia), clearing based on the rules set by the same country (article 5.7, Operations Agreement), at the price of the marginal bid, by priority category.

²² The eligibility criteria are defined by the same legislation regulating the market.

²³ Note however that electricity tariffs arising from these contracts are generally regulated through a ceiling value.

²⁴ As per the Georgian system operator’s website, accessed on June 2024: <https://www.gse.com.ge/aboutus/international-affairs>.

²⁵ Henceforth, we respectively label these agreements as the Trade Agreement, Operations Agreement, and Cooperation Agreement.

²⁶ The exporting country is mostly set as Georgia.

²⁷ This is also the case when a single application for interconnection capacity has been submitted, as set by the countries’ respective auction rules.



More details can be drawn from the countries' respective regulations. For Turkey, the legislation governing cross-border electricity trade is the "Electricity Market Import And Export Regulation", published in the Gazette of 17 May 2014. It states that private licensed suppliers, licensed generators, and the government owned Electricity Generation Company (previously TETAS, now EUAS) can all engage in cross-border trade.²⁸ The law identifies four distinct methods governing Turkish cross-border exchange, for the interconnection with Georgia, two of these methods are relevant: the "Asynchronous Parallel Connection", and the "Isolated Zone". We focus on the first method as the Isolated Zone concerns the Batumi-Khopa line, solely used in emergency situation and not auctioned. For asynchronous interconnections, article 20.2 of the law states that for capacity allocations higher than six months, the transmission rights holder must utilise the interconnection above a specified threshold, otherwise, their rights can be revoked and reallocated. The assessment shall be made at the end of each month, and the threshold is set to a less than 50% utilisation factor for the last three months, or an average utilisation over the last three months below 60% of the capacity.

In Georgia, cross-border electricity trade is regulated by the same legislation governing the country's electricity market, of which the most relevant text is chapter 4 of the Electricity Market Rules, comprising articles 14.1 to 14.23. In addition to the Georgian system and market operators, any person registered as a qualified exporter or importer may engage in cross-border electricity trading, on the basis of direct contracts (article 23 of the Law on Energy and Water supply). Priority in the allocation of capacity is granted for renewable generators, in accordance with the Trade Agreement with Turkey. The first priority group are renewable plants built post-2010 and involved in long-term export agreements signed by transmission or dispatch licensees (currently the system operator), then the rest of renewable plants built post-2010 not involved in the formerly mentioned export agreements, and who started operating less than 10 years prior, and finally, the rest of eligible cross-border participants, including wheel-through (article 14.12, Market Rules). The capacity allocation auctions are governed by the "Special Auction Rules about Allocation/Reallocation Transmission Capacity of New Overhead Line for Intersystem Transit (power flow)" regulation, dated 4 March 2014.²⁹ These rules state that capacity is allocated by priority group to the highest bidders. As such, capacity is first allocated to the highest priority group, then the residual is allocated to the next lower priority group, and so on, with possibility for price discrimination by group. That is, if demand for capacity within a priority group is inferior to the remaining available capacity, then transmissions rights are granted for free. Whereas if within the same auction, demand for capacity from a lower priority group exceeds the residual available capacity, then a price is set solely for bidders from the latter group.

Lastly, for congestion rents, the three agreements signed between Turkey and Georgia governing cross-border trade do not mention any provisions regarding the sharing of congestion revenues emanating from the explicit auctions, nor do the countries' respective regulations to the best of our knowledge. We can therefore assume that congestion revenues are fully captured by the party implementing the auctions, that is, the exporting country.

3. Prevailing capacity allocation mechanisms in heterogeneous interconnections

In the previous section, we reviewed in detail how some of the main existing heterogeneous interconnections operate, and how their capacity is allocated. In this section, we rely on our results from the foregoing one, and identify the different capacity allocation mechanisms governing heterogeneous interconnections. These are not mutually exclusive, interconnections can simultaneously rely on a set of different mechanisms to allocate their capacity, or combine a set of them into a single arrangement. Table 2 classifies these mechanisms into different categories and briefly summarises how they function, the rest of the section goes into the details.

²⁸ Generators can solely export electricity, they are not eligible for imports.

²⁹ As named by the "unofficial" translation of the rules accessible on the system operator's official website.



Table 2: Classification and brief summary of the prevailing capacity-allocation mechanisms in heterogeneous interconnections

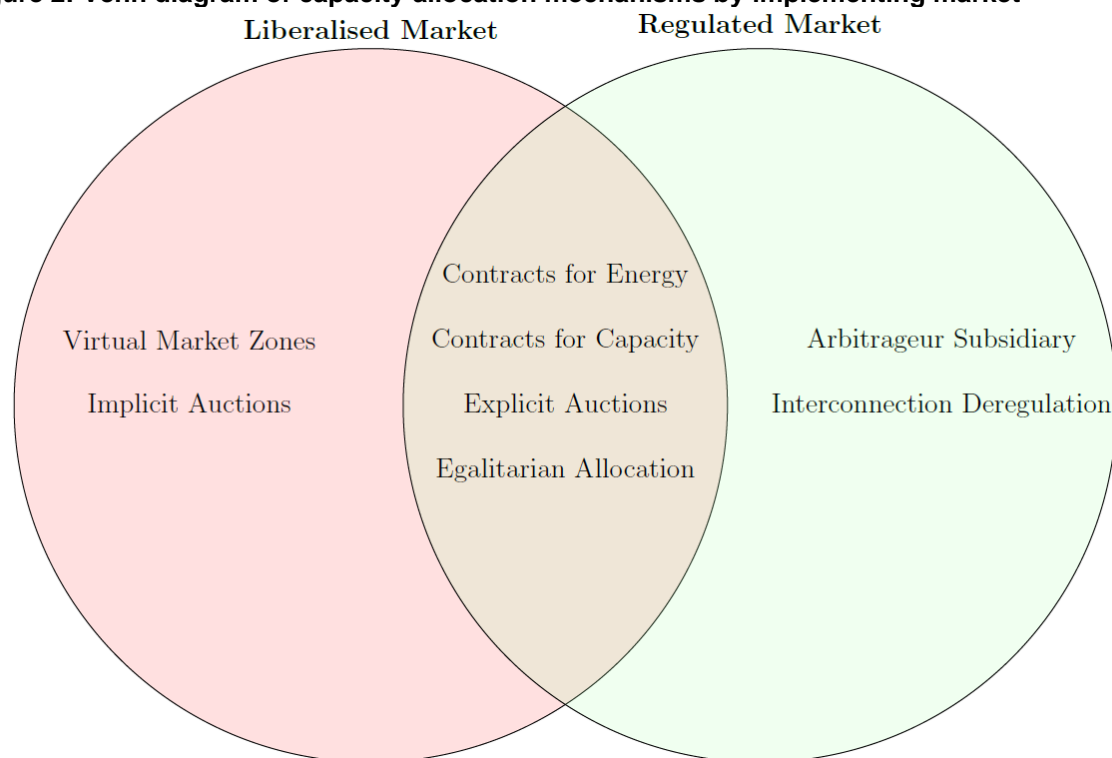
Category	Mechanism	Key Features
Auctions	Implicit Auctions	Allocates capacity through the liberalised market simultaneously with electricity dispatch, based on bids submitted by the regulated utility, maximising welfare.
	Explicit Auctions	Stand-alone auctions for physical rights utilised to manage congestion and allocate capacity by direction and timeframe.
Structural	Virtual Market Zones	The liberalised market establishes virtual zones within its wholesale market representing the regulated market. Within these zones, participants bid to import or export, and capacity is generally implicitly allocated.
	Interconnection Deregulation	The regulated market establishes liberalised access for cross-border trading. Combines with other mechanisms to manage congestion, or cedes its management to the opposing market.
	Arbitrageur Subsidiary	The regulated utility establishes a subsidiary monopolising cross-border trade. Its sole purpose is the efficient exchange of electricity across the borders.
Contracts	Contracts for Energy	Bilateral contracts for energy between market agents operating at opposing sides of the borders. Either combine with other mechanisms to manage congestion, or the contracts strike prices are utilised to set priority of access.
	Contracts for Capacity	Long-term agreements, often government-led, for firm generation capacity. It guarantees the availability of interconnection and generation capacity in the origin market.
Equity-driven	Egalitarian Allocation	Allocates capacity based on fairness criteria (e.g., first-come, proportional volume); lacks efficiency.

Note that the capacity allocation mechanisms and the broad operational aspects of interconnections are generally initially set by a bilateral agreement between the respective authorities of the interconnected markets. These interconnection operation agreements, usually signed before the commissioning of the interconnection, specify the technical aspects in the first place, before specifying some general rules and concepts on how it should operate, and how the capacity should be allocated. These rules mostly only set the general framework of capacity allocation, such as the time frame of allocation or the allocating parties, leaving out agency on the specifics to each country's respective regulation and market rules, or to future agreements. Likewise, most of the identified capacity allocation mechanisms require some degree of cooperation and coordination between the relevant system or market operators of the interconnected markets.

These mechanisms can be implemented at a single side of the border, or at both sides. Most of them can be implemented by either market, but some of them are only adapted to either the regulated or the liberalised market design. Figure 2 enumerates the identified allocation mechanisms and classifies them by implementing market in a Venn diagram. Implicit Auctions and Virtual Market Zones are exclusive to the liberalised market, whereas the Arbitrageur Subsidiary and the Interconnection Deregulation mechanisms can solely be implemented by the regulated market. The remaining mechanisms can be implemented by any of the markets. We provide a detailed description of the identified mechanisms in what follows of this section.



Figure 2: Venn diagram of capacity allocation mechanisms by implementing market



Explicit auctions: As their name suggests, these are stand-alone auctions, independent from energy dispatch, that are established by either markets, or both, to allocate the existing interconnection capacity for a determined period of time, both short and long term, and direction. Participants interested in acquiring interconnection capacity to export, import, or wheel-through electricity submit their bids, consisting of a volume-price pair, and physical transmission rights are granted to the highest paying bidders up to the existing interconnection capacity volume, based on either a pay-as-bid or a uniform-price clearing.³⁰ These auctions are generally solely implemented in a congestion context, that is when demand for interconnection capacity exceeds the available capacity, otherwise, capacity is granted for free without conducting an auction. To ensure an efficient use of the interconnection, long-term capacity allocation from these explicit auctions may be conditional on a determined minimum utilisation factor, below which capacity rights are revoked and reallocated. Likewise, capacity rights are usually granted under a “use-it-or-lose-it” clause, that is, unused capacity rights are reallocated, from the distant to the nearest timeframe.

Long-term contracts for firm capacity: These contracts, often signed by the respective governments and involving the vertically integrated utility of the regulated market and the transmission system operator of the liberalised market, are utilised to dedicate a specific amount of firm cross-border capacity to either markets. The firm cross-border capacity takes the form of guaranteed available interconnection capacity in the relevant flow direction, and generation capacity in the origin market, for a relatively extended amount of time. These contracts are mainly used to take advantage of complementarity across interconnected markets. They may specify a unidirectional firm capacity clause, often accompanied by financial compensation. Alternatively, they may dictate a bidirectional firm capacity clause, such as an inter-temporal capacity swap taking advantage of different seasonal demand peaks across the interconnected markets (e.g. Ontario - Quebec interconnection). Note that these contracts do not necessarily directly allocate cross-border capacity, rather, they may only do so once the firm capacity is called upon. However, it can be argued that this mechanism translates into an initial allocation of capacity that is subsequently reallocated if not utilised by the eligible party.

³⁰ Explicit auctions are also used to market financial transmission rights, as is done in Ontario, nonetheless, these rights do not lead to capacity allocation and are therefore disregarded in our analysis.



Long or short term contracts for energy: These contracts specify the transmission of cross-border electricity between market agents operating across different sides of the border. They can involve different market participants, whether they are public or private, such as generators, licensed traders, wholesale consumers, the system operator, or the regulated utility. This mechanism can be adopted as the sole allocation mechanism, or it can be combined with other mechanisms such as explicit auctions to allocate the capacity when congestion occurs. When contracts for energy is the only implemented mechanism, and congestion occurs, then priority in capacity allocation is determined based on the contracts' execution prices, minimising economic losses for the allocating market. As such, the cheapest importing contracts, and the highest-priced exporting ones, are prioritised. Note that these contracts can be leveraged by the regulated market's utility to indirectly participate within the wholesale market of its counterpart. The utility can achieve this by establishing a fully owned subsidiary registered within the deregulated market, and subsequently establishing contracts for energy with it. For example, the Georgian system operator GSE owns 99.4% of "Karcali Enerji JSC", a registered wholesale power trader in Turkey.³¹

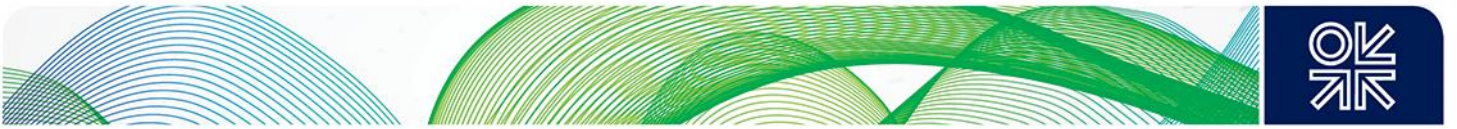
Implicit auctions: This category refers to those mechanisms that indirectly allocate the interconnection capacity simultaneously with the electricity dispatch of the liberalised market, in a way that maximises social welfare. In the context of heterogeneous interconnections, this mechanism captures the arrangements where the regulated market, either through its utility or other market agents, whether public or private, submits bids directly within the wholesale market of its counterpart. The latter subsequently determines the market's dispatch and the cross-border exchange simultaneously based on the existing market clearing algorithm. These implicit auctions can be classified into two distinct sub-categories, pure implicit auctions, and quasi-implicit auctions. In the former, the mechanism does not directly identify to which market agents the interconnection capacity was allocated (e.g. Morocco - Spain interconnection), whereas in the latter, it does reveal to whom the allocation was granted (e.g. Ontario - Quebec interconnection).

Virtual market zones or nodes: The liberalised market establishes a virtual zone or node representing the interconnection with the regulated market within which market participants, domestic and foreign, who wish to trade electricity across the border submit their bids to import or export electricity. Submitted bids are considered up to the available transmission capacity level in the clearing of the liberalised market's zone, through which capacity is implicitly allocated, import bids treated as supply bids, whereas export bids are treated as demand bids. Subsequently, a clearing price is set for the virtual zone, based on which congestion costs are determined, and rents are paid (e.g. Ontario - Quebec interconnection). Therefore, this mechanism combines with implicit auctions as capacity is simultaneously allocated with the dispatch of the liberalised market. In theory, different arrangements based on virtual zones and not involving implicit auctions could be established, however, we are not aware of a currently existing such arrangement.

Arbitrageur subsidiary: The vertically integrated utility establishes a subsidiary company whose sole purpose is to efficiently import and export wholesale electricity across the border by participating in the wholesale market of the deregulated country as an arbitrageur (e.g. British Columbia, Quebec). Naturally, this mechanism combines with other allocation arrangements, such as explicit or implicit auctions that are implemented by the liberalised market. The novelty here is from the regulated market's perspective. At first glance, it may seem that this mechanism itself does not allocate interconnection capacity, rather, allocation occurs through the auctions implemented by the liberalised market. However, note that once this mechanism is adopted, the subsidiary monopolises the interconnection capacity as it becomes the sole authorised cross-border trader by the regulated market, hence capacity is allocated. The auctions themselves only determine the volume traded in this context.

Interconnection deregulation: This arrangement concerns the regulated market. The market maintains the regulated state for its domestic operations, but establishes competitive and liberalised access to the interconnection, hence solely deregulating the cross-border activity. The regulated market therefore permits willing domestic agents who register for cross-border trading, both public and private,

³¹ GSE is supposed to give-up its ownership of said company as a result of Georgia's transition to the deregulated model.



to freely access the interconnection and either trade through bilateral contracts (e.g. Georgia), or participate in the wholesale market of its counterpart. Access is granted by direction based on some priority criteria when congestion arises, such as auctions, contract prices, a covenant with the opposing market, or by simply ceding the interconnection dispatch to the liberalised market. Therefore, except in non-congested situations, this mechanism does not directly allocate interconnection capacity by itself, it must combine with other mechanisms that sets priority access to the interconnection.

Egalitarian allocation: This allocation method comprises a set of sub-mechanisms that solely allocate the capacity to eligible traders on the basis of some fairness criteria, such as first-come first-served, or an allocation proportional to the solicited volume in case of congestion. This mechanism therefore does not account for any revealed nor stated valuation for interconnection capacity by market participants, and hence does not seek nor lead to an efficient allocation. As a result, while largely implemented during the 2000s in some regions like the Balkans, this mechanism is currently mostly obsolete, replaced by the more efficient auctions and other market mechanisms. In our analysis of a large set of heterogeneous interconnections, we have not encountered the current usage of Egalitarian allocation, nonetheless, we include it in our identification as other interconnections that we have omitted may still rely on it.

4. Efficient utilisation of grid interconnections: a conceptual framework

Having presented how selected existing heterogeneous interconnections operate, and the prevailing allocation mechanisms in them, we can now develop some theoretical concepts of their economics and discuss what a well-functioning interconnection must achieve. This will later enable us to identify some desirable criteria that capacity allocation mechanisms should satisfy to favour efficient cross-border exchange, and to highlight some special interactions that can arise when heterogeneous markets are involved. Throughout our analysis, we assume a bilateral setting, linear demand and supply functions, including both elastic and inelastic demand, no trading fees nor transmission costs, a uniform price in the liberalised market, and a competitive and rational behaviour by market agents.

Henceforth, we use “homogeneous interconnections” to refer exclusively to those connecting liberalised markets. Additionally, we use “prices” and “costs” interchangeably to denote the regulated market’s marginal costs of electricity.³²

4.1 Aggregate social welfare

Foremost, it is straightforward to highlight that as long as there is a spread in cross-border prices, the cross-border flow of electricity through arbitrage must necessarily generate a net increase in social welfare, in both or either markets, jointly with a transfer of welfare across consumers, producers, and the interconnection owner.³³ This aggregate social welfare is determined as the sum of the consumers’ surplus, producers’ surplus, and congestion rents, over both the liberalised market l , and the regulated market r :

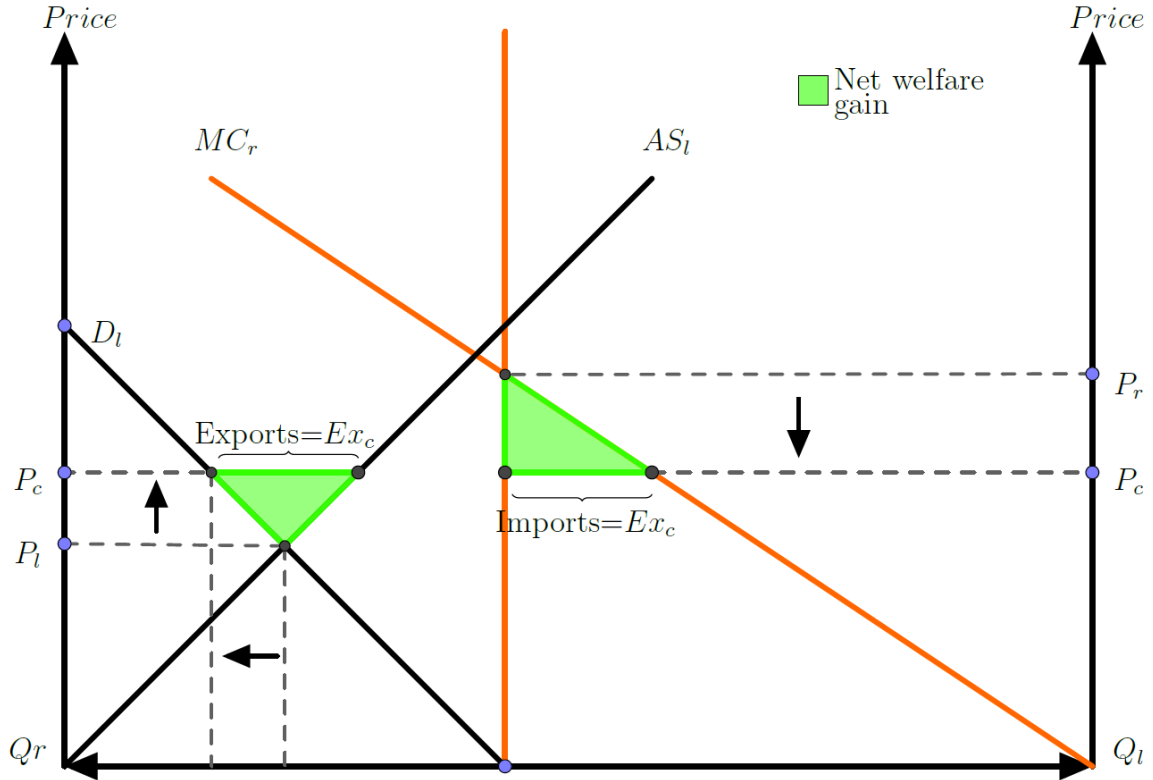
$$\text{Social welfare} = \sum_i^{i'} \text{consumers' surplus}_i + \sum_i^{i'} \text{Producers' surplus}_i + \text{Congestion rents} \quad (1)$$

where $i \in (l, r)$, and $i' \in (l, r) \neq i$. Without congestion, social welfare is affected by cross-border exchange as highlighted in Figure 3. The figure showcases a heterogeneous interconnection of a liberalised market (the Q_l axis), with aggregate demand curve D_l , and aggregate supply curve AS_l , with a vertically-integrated regulated market (the Q_r axis, right to left), with a perfectly inelastic demand $Load_r$, and a supply curve represented by the (increasing) marginal costs curve MC_r of the regulated utility.

³² As clearing prices do not exist in the regulated market, we use both “prices” and “costs” interchangeably to refer to its marginal costs to ensure clarity in the text, specifically when referring to the cross-border gap between the liberalised market’s prices and the regulated market’s costs.

³³ This holds true for heterogeneous interconnections, and whether demand is price-elastic or not as we show in this section.

Figure 3: Social welfare benefits from cross-border trade in heterogeneous interconnections



Let us first compare the two extremes: autarky state where the markets are fully isolated and exchange (Ex) is zero ($Ex = 0$), and fully integrated markets where cross-border prices converge at $Ex = Ex_c$, where Ex_c is the price-gap closing volume. If the markets were isolated, then the prevailing equilibria would lead to the autarky clearing price P_l and costs P_r , representing the intersection of the demand and supply curves in each market. Whereas assuming that the markets are interconnected, the interconnector is welfare maximising, and the transmission capacity is not binding for the period, then through arbitrage as the regulated market imports and the liberalised one exports, these values converge to P_c . This cross-border trade therefore leads to a net gain in welfare amounting to:

$$\text{Full integration welfare gain} = \frac{1}{2} \cdot Ex_c \cdot |P_l - P_r|, \quad (2)$$

represented by the green area in Figure 3, in addition to a welfare transfer between the consumers and generators in the markets, whereas no congestion rents are collected.³⁴

As a result, the welfare maximising outcome between the two extremes (and in general as we will prove shortly), leading to price convergence across the markets when transmission constraints are not binding, differs significantly from the interconnectors' profit maximising outcome through congestion rents. As rents are a direct function of the cross-border price gap, it is straightforward to deduce that when the interconnection is not congested, the efficient outcome would minimise the interconnector's profits as rents fall to zero. More formally, congestion rents are determined as follows:

$$\text{Congestion rents} = |P_l' - P_r'| \cdot Ex, \quad (3)$$

where Ex is the volume exchanged between the markets in the interval's relevant trade direction, P_l' is the market clearing price in the liberalised market l accounting for cross-border exchange, while P_r' is the marginal cost of electricity in the regulated market r accounting for cross-border exchange.

³⁴ With perfectly inelastic demand in the regulated market, the aggregate generation over both markets diminishes when the regulated market imports, and expands when it exports. In Figure 3, generation over both markets contracts from $Load_r + Q_l$ to $Load_r + Q_l'$.

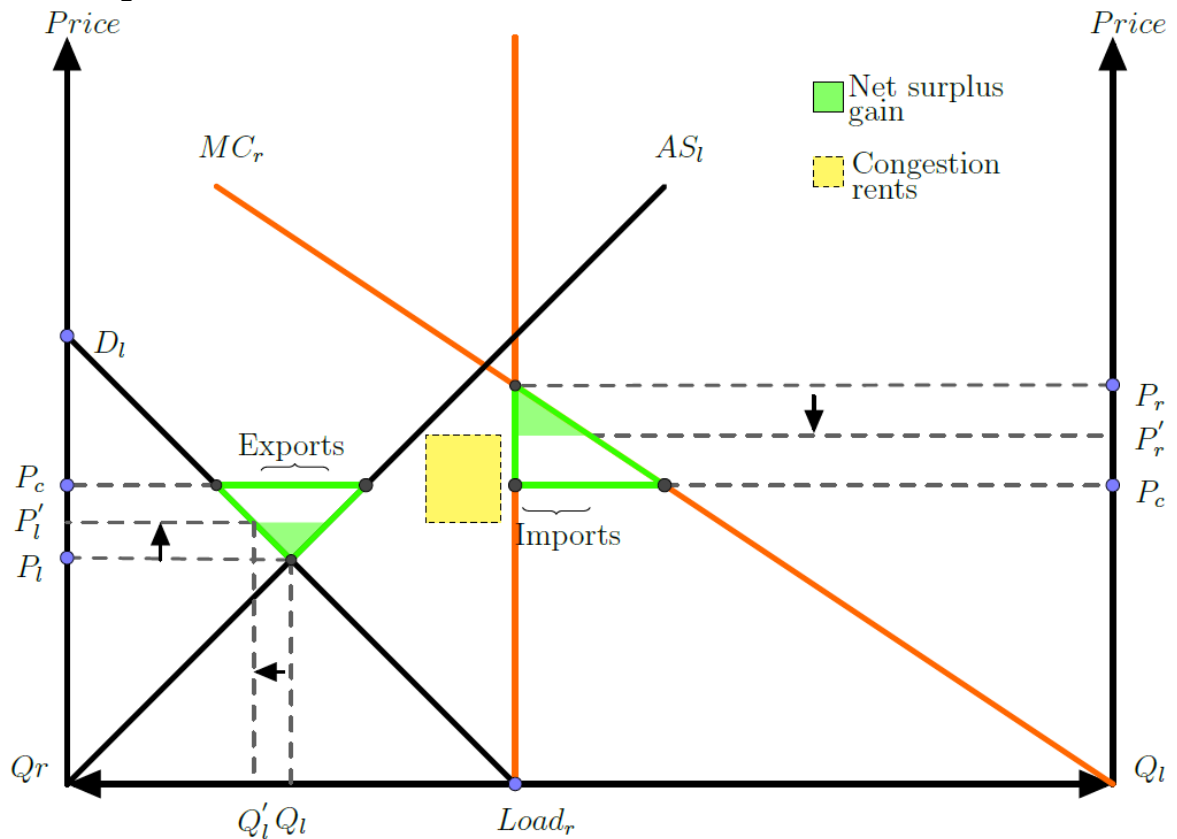
The welfare maximising outcome when transmission capacity is not binding would nullify the price gap $|P'_l - P'_r|$, thereby nullifying rents. As such, a profit maximising interconnector would have incentive to prevent cross-border price convergence.

However, when congestion arises and $0 < Ex < Ex_c$, the outcome is more nuanced, both the welfare and the congestion rents maximising volumes of exchange might coincide in some instances. More specifically, in a simple setting and without loss of generality, we know that the hourly price gap across the markets $|P'_l - P'_r|$ is itself a decreasing function (call it $g(\cdot)$) of Ex , with linear demand and supply functions, $g(Ex)$ is likewise linear, where its intercept b represents the autarky price gap, whereas its slope $a < 0$ captures the rate at which the price gap across the markets is reduced by incremental trade.³⁵ We can thus write congestion rents as a quadratic function, henceforth $cr(\cdot)$, of Ex :

$$cr(Ex) = g(Ex) \cdot Ex = (a \cdot Ex + b) \cdot Ex = a \cdot Ex^2 + b \cdot Ex; \quad 0 \leq Ex \leq Ex_c, \quad (4)$$

as both exchange and the price gap are non-negative, congestion rents are solely defined in \mathbb{R}^+ . Similarly, as the quadratic expression of congestion rents has no intercept, the following characteristics hold: congestion rents evolve as a parabola with its origin at the origin of the plane, where cross-border exchange is zero, a vertex that maximises the function at $Ex = \frac{-b}{2a}$, and a second root at $Ex_c = \frac{-b}{a}$, the price-gap closing volume at which congestion rents are once again zero.

Figure 4: Social welfare benefits from cross-border trade in heterogeneous interconnections under congestion



Representative congested equilibria of the interconnected markets are highlighted in Figure 4, which modifies Figure 3 by assuming that the cross-border flow is limited to half the volume necessary for prices to converge. In such a case, price convergence is only partial as prices increase in the liberalised market to P'_l and marginal-costs decrease in the regulated market to P'_r , rather than converging at P_c .

³⁵ Therefore, the slope a is the negative of the sum of the magnitudes of price sensitivities to exchange over both markets. Or, in our linear setting, the sum of the slopes of the markets' net-export curves.



and congestion rents are collected. Due to the reduced trade, the consumer and producer surplus generated by this lesser exchange as represented by the filled green area fall sharply compared to the non-congested situation (the whole area within the green triangles). However, part of the lost welfare is transferred to the interconnector in the form of congestion rents, represented by the yellow rectangle in the figure, due to the cross-border spread in prices.

Figure 4 therefore highlights the three different variables through which cross-border trade affects social welfare, as defined in Equation (1), revealing their dynamics. Assuming linear demand and supply functions in the interconnected markets, aggregate welfare generated by electricity exchange is equal to the sum of the areas of two triangles, representing the gains in consumers' and producers' surpluses, and a rectangle representing congestion rents. This area is defined equally no matter the direction of trade, the volume of exchange, or the elasticity of demand, and is equal to:

$$\text{Welfare gain} = |P'_l - P_l| \cdot Ex \cdot \frac{1}{2} + |P'_r - P_r| \cdot Ex \cdot \frac{1}{2} + |P'_r - P'_l| \cdot Ex, \quad (5)$$

henceforth called function $w(.)$ of Ex , which can be rewritten as:

$$w(Ex) = \frac{1}{2} \cdot Ex \cdot [|P_l - P_r| + |P'_r - P'_l|], \quad (6)$$

in which the interconnected price gap $|P'_r - P'_l|$ is the defined function $g(.)$ of exchange in Equation (4), whereas the autarky price-cost gap is the intercept b of $g(.)$.³⁶ Thus:

$$w(Ex) = \frac{1}{2} \cdot Ex \cdot b + \frac{1}{2} \cdot Ex \cdot (a \cdot Ex + b); \quad 0 \leq Ex \leq Ex_c, \quad (7)$$

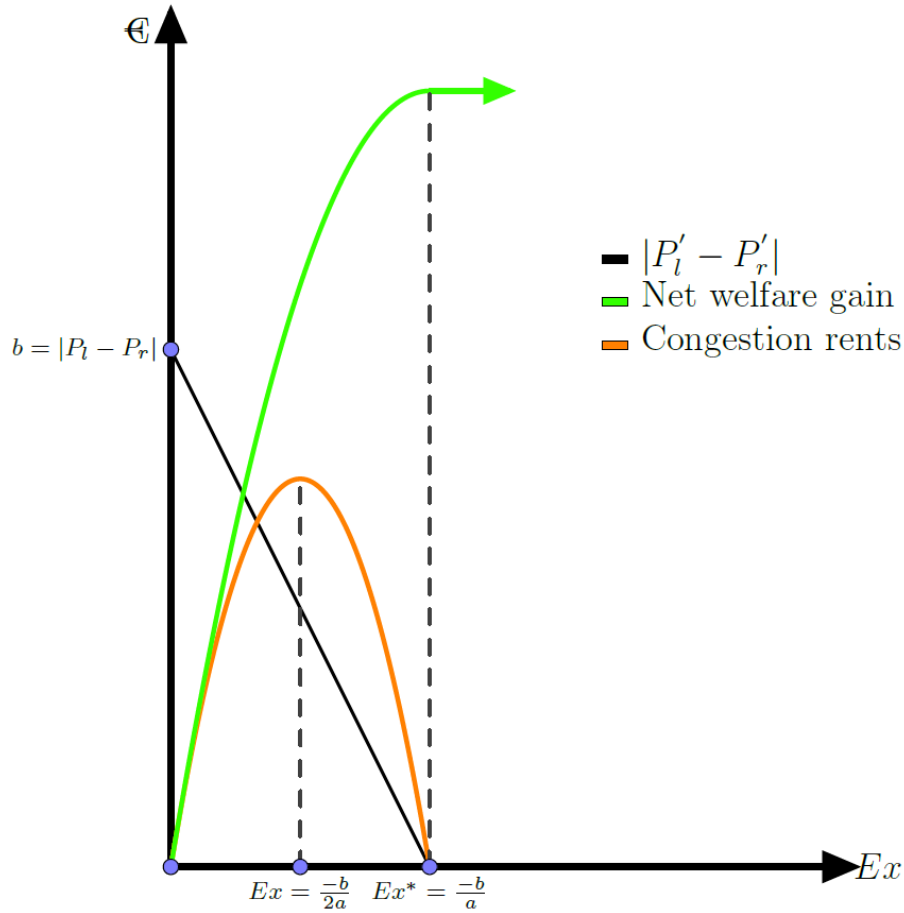
that is, welfare gains evolve in a quadratic manner as a function of exchange up to the point where the cross-border prices converge at $Ex_c = \frac{-b}{a}$, and welfare is maximised as it coincides with the parabola's vertex. Beyond this level of exchange, welfare stagnates as we assume agents are rational, and only Pareto efficient trade would take place following price convergence. Therefore, the welfare generated by cross-border electricity trade is finally represented by the following piecewise function:

$$\begin{cases} w(Ex) = Ex \cdot b + \frac{1}{2} \cdot a \cdot Ex^2; & 0 \leq Ex \leq \frac{-b}{a} \\ w(Ex) = w\left(Ex = \frac{-b}{a}\right); & Ex > \frac{-b}{a} \end{cases} \quad (8)$$

These simple models appropriately capture the behaviour of congestion rents and gains in aggregate welfare as a function of exchange. As highlighted in Figure 5, congestion rents start by increasing with exchange, all the way to their peak, beyond which they gradually decrease until reaching zero when the flow is enough for prices to converge. Indeed, incremental exchange generates both an increase in rents due to arbitraging a larger quantity, which is the volume effect, however, it also generates a negative effect by decreasing the price gap across the border, that is the price effect. At low exchange levels, the gains outweigh the losses (the derivative of (4) is positive), however, with further capacity, the gains decelerate (the second order derivative of (4) is negative) up until the reverse is valid (derivative turns negative when $Ex > \frac{-b}{2a}$). Consequently, congestion rents are maximised at the inflection point where the volume and the price effects of cross-border exchange cancel out, and the losses from further exchange equal the gains. That is, when the marginal revenues from further trade are equal to the marginal costs for the interconnector. On the other hand, the marginal welfare gains from exchange are strictly positive all the way to the point $\frac{-b}{a}$ where prices converge (the derivative of (8) is strictly positive over the arbitrage domain), any trade beyond this point does not affect aggregate welfare as it must be Pareto efficient.

³⁶ Notice that when $Ex = Ex_c$ and prices converge, the equation reduces to (2), the full integration welfare gain.

Figure 5: Illustration of the evolution of congestion rents, cross-border price gap, and net welfare gain as a function of exchange (valid for any values of the parameters a and b)

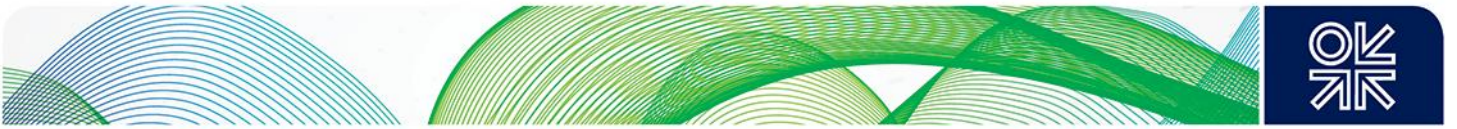


As such, the aggregate welfare maximising exchange is $Ex^* = \min\left(ATC, \frac{-b}{a}\right)$, where ATC stands for Available Transfer Capacity. The profit maximising exchange volume for the interconnector coincides with the welfare maximising volume when the Available Transfer Capacity (ATC) is inferior to $\frac{-b}{2a}$, whereas above that value, a profit-maximising interconnector would have incentive to limit the cross-border flow, hindering social welfare.

4.2 Individual market welfare

While the effect of exchange is strictly positive on aggregate social welfare, it is not necessarily the case for the individual markets' welfare as we show and model in detail in Appendix A. In summary, for each market $i \in \{l, r\}$, the welfare gained from cross-border exchange is comprised of the surplus generated for consumers (when importing) or producers (when exporting), plus its allocated share of congestion rents. As these rents significantly affect the individual markets' welfare, the share ρ of rents' allocated to the respective market is crucial for determining its optimal flow volume Ex_i^* . That is, the individual markets' gains in welfare is likewise a quadratic function of exchange, with the allocation ratio ρ affecting both of its slopes, and therefore its shape from a convex to a concave function. As a result, unlike for aggregate welfare, the function's vertex does not necessarily occur at the gap-closing volume, rather, its maximum depends on the value of the parameter ρ .

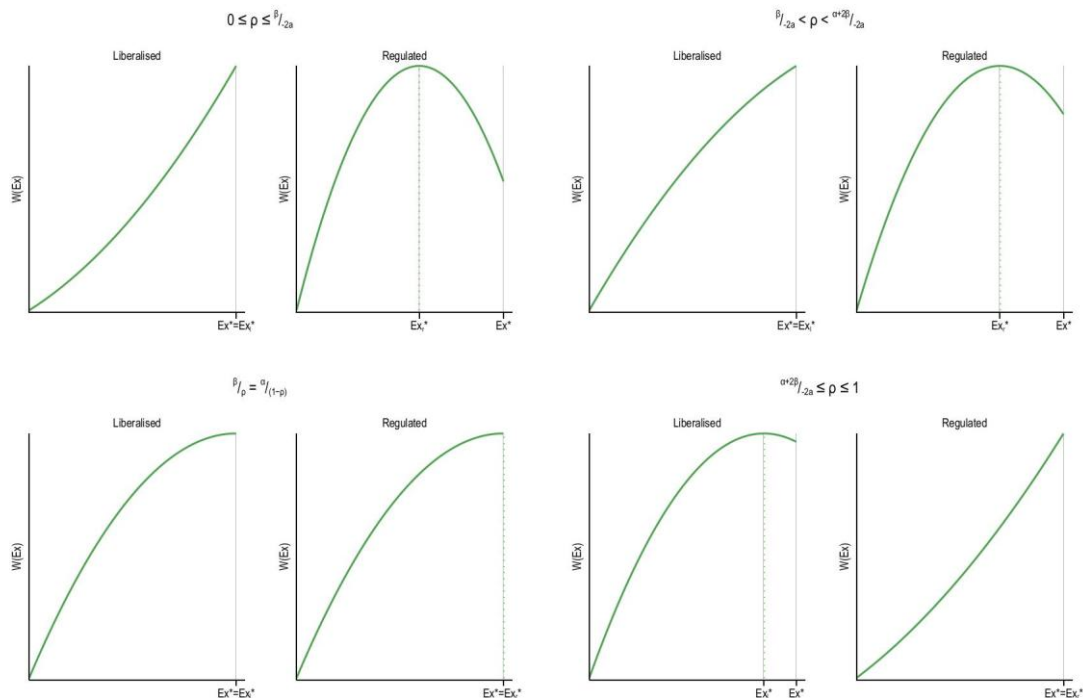
In the extreme setting where a market is not allocated any share of the rents ($\rho = 0$), incremental exchange strictly increases the market's welfare, and its optimal flow will coincide with the socially optimal outcome: $Ex_i^* = Ex^*$. On the other end, in the extreme case where a market captures the totality of the rents ($\rho = 1$), incremental exchange does not strictly increase the market's welfare over the arbitrage domain, and the latter's optimal flow will necessarily be strictly lower than the socially optimal outcome: $Ex_i^* < Ex^*$, and thus the market would not seek price convergence.



For intermediate values of allocation rate in-between the two extremes ($0 < \rho < 1$), the lower the allocation rate assigned to a market, the more likely the market's optimal exchange will coincide with the socially optimal one and the more inclined the market is toward price convergence, and vice versa. However, independently of the rents' allocation rate, both markets are better off when exchanging, and any volume of exchange would lead to higher individual market welfare compared to autarky. These results are summarised in Table A.1.

Our analysis reveals additional crucial insights by considering both interconnected markets simultaneously. Notably, outside of congestion, the optimal exchange volumes for each market will diverge: one market will aim for price convergence, while the other will hinder it, except under a unique configuration of rent allocation in which the markets' willingness to exchange coincide in a Nash equilibrium. Such configuration must ensure that the markets' ratios of price sensitivity to exchange (in magnitudes) over their respective rents' allocation rates are equal to each other. That is, $\frac{\beta}{\rho} = \frac{\alpha}{(1-\rho)}$, where β and α are respectively the magnitudes of the liberalised and the regulated markets price sensitivity to exchange, whereas ρ and $(1-\rho)$ are their respective allocation rates. That is, to attain the efficient outcome (or to approach it), the market whose prices are (relatively) more affected by cross-border exchange should receive a larger share of congestion rents. This is because said market also benefits more from trade in surpluses, and thus is less inclined to hinder trade despite a larger share of rents.³⁷ Moreover, the worse outcome from a social welfare perspective arises in the situation where one of the markets, especially the one whose prices are less sensitive to cross-border exchange, captures the totality of the rents. Which is a common occurrence in heterogeneous interconnections as we have seen in Section 2. These results are summarised in Table A.2, and are visually represented in Figure 6, displaying the different combinations of optimal cross-border flow and welfare gains function per individual market that can arise.

Figure 6: Possible combinations of the optimal cross-border flow and the welfare gains function for the individual markets based on different thresholds of the congestion rents' allocation ratio



³⁷ From an investment perspective, the market benefiting more from trade would be more willing to invest into an interconnection, and thus might indeed capture a larger share of rents relatively to its counterpart. Nonetheless, these dynamics generally vary across the hours and seasons.



Therefore, assuming the markets are maximising their individual welfare, the socially optimal exchange volume Ex^* can only be reached by setting an efficient allocation ratio ρ^* leading to the Nash equilibrium outcome, equalising the markets' willingness to exchange. However, as the allocation ratio ρ is in general set for an extended amount of time, while the ratio ρ^* will vary from one clearing period to the other as the parameters α and β fluctuate, the Nash outcome would rarely if ever occur, and the cross-border prices shall never converge under these circumstances. However, these conclusions depend on the interconnection allocation mechanism adopted by the interconnected markets, and by the parties to whom the capacity is allocated as we highlight in the next section.

5. The context of heterogeneous interconnections

In the previous section, we discussed the economics of grid interconnections from a cross-border exchange perspective, and we highlighted how the socially optimal outcome was unlikely to arise when either of the markets is maximising its own welfare. In this section, we emphasise how inefficiencies are more pronounced in the heterogeneous context compared to the homogeneous, and we highlight some ways through which the regulated market can take advantage of information asymmetry to enhance its gains to the detriment of its counterpart.

It is currently apparent that heterogeneous interconnections are largely underutilised compared to homogeneous ones. This can be observed from existing interconnections, such as that of MIBEL with Morocco, in which the interconnection was solely utilised for about 38% of the hours in 2020 and 2021, rising to respectively 63% and 73% in 2022 and 2023 with the energy crunch. Besides, when utilised, the utilisation rate was generally low, resulting in an average rate ranging from 12% to 47% between 2020 and 2024, compared to an average utilisation rate higher than 80% over the same period for MIBEL's interconnection with France.³⁸ That is despite the large disparities in cross-border prices and costs between Morocco and MIBEL due to differences in taxation, demand patterns, electricity mix, and environmental regulation. Likewise, the interconnection is seldom congested, with a congestion frequency across the same period ranging from 2 to 115 hours, over both directions, compared to several thousands of hours of congestion in MIBEL's interconnection with France. Likewise, a similar under-utilisation is observed for Ontario's interconnection with Quebec as compared to its interconnections with other neighbouring liberalised markets (Brouillette, 2017).³⁹

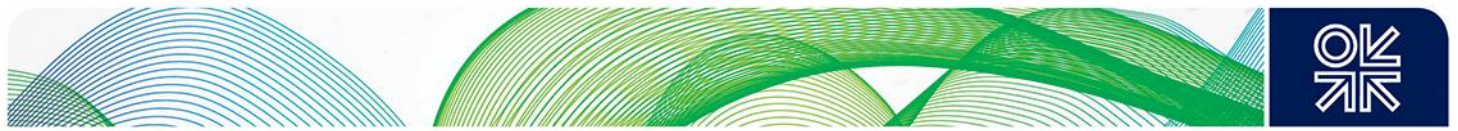
This inefficiency in the heterogeneous context can emanate from a set of factors, some of which can be deduced from our conceptual framework. First, the inefficient outcome is more likely to prevail in heterogeneous interconnections as the regulated market will most certainly maximise its own welfare. This is simply because in the regulated market, the arbitrageur (the utility or its fully owned subsidiary), usually monopolising access to the interconnection, is itself the single buyer and provider of electricity. This setup eliminates conflicts of interest between market agents with different objective functions.⁴⁰ Therefore, congestion rents always affect the regulated market's exchange decisions, and as we have seen in the previous section, if the rents captured by the market are sufficiently high, then it will constrain cross-border flow. For the same reasons, the implicit auctions that are usually utilised in homogeneous interconnections, which decentralise exchange decisions and disregard congestion revenues in the dispatch, do not achieve the same outcome in heterogeneous interconnections when implemented as the regulated arbitrageur itself submits the cross-border bids, and the implicit auction solely dispatches the liberalised market.

Second, inefficiency is exacerbated by the fact that the regulated market can leverage its favourable position due to asymmetric information to enhance its gains, particularly by capturing a larger share of congestion rents, thereby further impeding exchange and aggregate welfare. Specifically, the regulated

³⁸ The Sources for these statistics are the "Spanish Electricity System Reports" of the respective years, accessible on Red Eléctrica website.

³⁹ Unlike MIBEL, detailed publicly available data on the utilisation of Ontario's interconnections capacity across the years are scarce.

⁴⁰ It is more difficult for the market to restrict cross-border flows when other numerous market agents benefit from a full arbitrage.



market observes both actual and historical prices in the liberalised market. They can also compute or estimate the magnitude of price sensitivity to exchange (parameter β) and the autarky prices of their counterpart. Knowing their own autarky costs and the magnitude of their sensitivity to exchange (parameter α), they are thus aware of the true values of the parameters b and a in our model. In contrast, the liberalised market lacks information about the actual marginal costs of electricity in the regulated market, nor can they observe or estimate the parameter α of their counterpart. As such, the liberalised market has no precise information about the real value of the autarky price gap (parameter b), or the rate by which exchange closes the price gap (parameter a , equal to $-(\alpha + \beta)$), except for what the regulated market reveals.

With these informational advantages, the regulated market can manipulate outcomes by misrepresenting its marginal costs and their sensitivity to cross-border exchange, thereby altering the parameters a and b . This manipulation affects the volume of cross-border exchange, congestion, and collected rents. In extreme cases, the regulated market might ensure that congestion is never observed over the interconnection, even though the cross-border price gap remains. This allows the regulated market to collect all actual rents, with no congestion visible from the liberalised market's perspective, leading to the worst possible outcome efficiency wise. If such an outcome is attainable for any of the markets, then they will surely attempt to reach it as the global maximum of the individual markets' welfare function is reached when $\rho = 1$ (see Appendix A).

We illustrate the foregoing argument with a practical example. To keep results more general, we do not constrain our analysis to specific capacity allocation arrangements or market designs, rather, we raise a set of realistic conditions under which this analysis is relevant. These conditions are that the allocation mechanisms implemented permit an explicit determination of congestion rents, that these rents are shared between the interconnected markets based on determined ratios, either explicitly or implicitly, that the liberalised market clears at a uniform price, and that data on its supply and demand curves are accessible by the regulated market.⁴¹ We further assume that, from the regulated market's side, access to the interconnection is monopolised by an arbitrageur subsidiary, or the utility itself, who operates it with the objective of maximising their market's welfare. Finally, we maintain the linear demand and supply setting from which the parameters of our models emanate, but we do not go into the details of how these parameters arise as these depend on the specific market rules and allocation mechanisms. The simplest setting would be that the liberalised market constructs aggregate linear curves from bids submitted by participants, and cross-border trade is carried based on the resulting willingness to import or export electricity of the markets, as captured by the net-export curves.

Example of parameters manipulation

For simplicity, we present our example in a deterministic setting as it is sufficient to highlight our argument.⁴² Assume that autarky marginal costs in the regulated market r are $P_r = 55$, and that they are sensitive to cross-border exchange at a rate of $\alpha = 0.1$. The system operator in r is confident that autarky prices in the liberalised market l for the clearing period would stand at $P_l = 35$, and that their sensitivity to exchange is $\beta = 0.1$.⁴³ Whereas, due to asymmetric information, the liberalised market has no information on the regulated market's costs nor its parameter α , other than what is revealed by the regulated market's behaviour in the cross-border exchange or through the capacity allocation mechanisms.⁴⁴ Moreover, the interconnection capacity between the two markets is limited to 70 MW.

In the described scenario, the socially optimal trade would amount to $Ex^* = \min(ATC, \frac{-b}{a})$, that is $\min(70, \frac{-20}{-0.2})$, and as such, 70 MW of electricity should flow from l to r , and as congestion arises, prices do not converge, and the collected rents would amount to $6 \cdot 70 = 420$, these rents would have to be

⁴¹ In the case of explicit auctions, congestion rents are represented by the revenues collected from the auction.

⁴² A probabilistic setting for the regulated market's expectations about prices in the liberalised market and their sensitivity to exchange would be more realistic.

⁴³ This would be the case if the regulated market operator has access to data on the liberalised market's actual or historical supply and demand curves, as we assume and as is generally the case.

⁴⁴ Such as the bidding behavior of market r within the spot market of l in implicit auctions, signed cross-border contracts, or by the outcomes of explicit auctions...



shared between the markets depending on whichever nominal ratios are agreed upon.⁴⁵ However, the regulated market can capture all the rents, independently of the nominal rate, by revealing deceptive values of its marginal costs and thus manipulating the parameter b .

In such a case, the regulated market shall behave in a way that guarantees flows equal to its optimal exchange when it is allocated the totality of the rents (see Table A.1): $\min(ATC, \frac{-b}{\alpha+2a})$, hence in this example, the market would seek the following flow volume: $Ex^* = \min(70, 66) = 66$, that is, it should behave in a way such that the “revealed” price gap only amounts to 13.2, rather than 20. As P_l is known, then market r can achieve this by revealing autarky costs of $P_r = 48.2$, understating its real ones $P_r = 55$. Consequently, the “nominal” prices would converge, and no congestion rents would be collected from the liberalised market’s perspective, however, in reality, congestion does arise as the “real” prices do not converge across the border, and the regulated market would in fact collect the totality of the real rents resulting from this lesser trade.⁴⁶ These rents would now amount to 448.8.⁴⁷ The same outcome can be achieved by the regulated market if they manipulate the parameter α , in this case, by revealing a value of $\alpha = 0.2$, rather than 0.1. Alternatively, they can manipulate to a lesser extent both parameters simultaneously, likewise leading to the same outcome.

More generally, when importing (exporting), the regulated market can manipulate the outcome by revealing lower (higher) marginal costs and higher cost sensitivity to cross-border exchange, thus capturing higher shares of real rents, independently of the nominal rates, all the way to monopolising congestion rents over the interconnection. This is a worthwhile behaviour for the regulated market, resulting in lesser exchange and higher individual welfare, as long as the ATC is superior to the market’s optimal flow at the captured (real) share of rents. If the ATC is inferior to said value, then such manipulations should not affect cross-border flow nor aggregate welfare, but the distribution of welfare can still be altered in favour of the regulated market if the nominal rents allocate any share to the liberalised market.⁴⁸

6. Discussion and conclusions

The primary economic purpose of grid interconnections is to facilitate cross-border electricity trade. From a commercial perspective, as electricity is a homogeneous good, its trade is largely governed by arbitrage principles. Consequently, full arbitrage leading to price convergence emerges as the socially optimal outcome from our findings. Other rules governing the economics of grid interconnections and revealed by our results, such as the evolution of social welfare and arbitrageurs’ profits as a function of exchange, or the way the autarky price gap and its rate of closure through exchange directly explain welfare gains from trading, are likewise reflective of arbitrage principals (Dávila et al., 2024).⁴⁹ We also show that knowledge of the price sensitivity to exchange in each market is sufficient to determine the socially optimal allocation rate ρ^* of rents. An additional knowledge of the autarky price gap is likewise sufficient to determine the optimal exchange, in aggregate and for each market separately, for both a merchant or a regulated interconnector, the subsequent exchange equilibria, and the welfare generated by cross-border exchange, thus the interconnection’s value itself.⁵⁰

⁴⁵ You can test that as we previously determined, the ratio satisfying: $\frac{\beta}{\rho} = \frac{\alpha}{(1-\rho)}$, in this case, $\rho = 0.5$, would lead to the Nash equilibrium, coinciding with the socially optimal flow.

⁴⁶ The gains in welfare from exchange, compared to the Nash efficient outcome, would increase from 455 to 666.6 for the regulated market, whereas they fall from 455 to 217.8 in the liberalised one. Aggregate welfare falls due to lesser trade.

⁴⁷ Congestion rents increase in this case as the merchant optimal exchange amounts to 50. Thus reducing exchange towards 50 increases rents.

⁴⁸ In such a case, if the regulated market behaves as in our example, then they will not capture 100% of the real rents, but they still capture a larger share than the nominal rate. Alternatively, if they expect ATC to be binding, they can alter their behavior accordingly and still capture the totality of the rents.

⁴⁹ Many of the results from our conceptual framework are similar to those recently derived by Dávila et al. (2024), in which they quantify the social value of arbitrage in markets where friction exists.

⁵⁰ We hence confirm Dávila et al. (2024) results, in a different context, that data on the price gap and price impact is enough to measure the total social value from closing an arbitrage gap.



A well-functioning interconnection must therefore guarantee the proper utilisation (in the dispatch timeframe) of its capacity up to its limits, or up to the price-gap closing volume, representing the socially optimal outcome. In other words, what actually directly captures the welfare benefits from an interconnection is its actual utilisation, not the capacity allocation itself. Nonetheless, the allocation can either favour or hinder its proper utilisation. As such, the most important criteria the capacity allocation mechanism must satisfy are ensuring an efficient utilisation of the interconnection up to the socially optimal flow, and maximising the available interconnection capacity that can be utilised by market agents through commercially netting potential bi-directional flows arising from financial and contractual obligations.⁵¹

However, the efficient outcome will not prevail if arbitrage decisions are undertaken by the interconnection owner, collecting its subsequent rents, or if the individual markets behave strategically, and arbitrage is centralised, as is generally the case when regulated markets are involved. The main inefficiencies that arise in heterogeneous interconnections are due to the vertical integration of the regulated market's utility, its ensuing monopoly of cross-border arbitrage, and information asymmetries, granting the regulated market a dominant position. This dominance can be leveraged to maximise the market's revenues and welfare at the expense of its liberalised counterpart. These factors are inherent to this context, therefore, it should be accepted that as a general rule and all things equal, heterogeneous interconnections shall be less utilised, thus less efficient, than homogeneous ones, as observed in the real world. However, the extent of these inefficiencies is significantly influenced by the operational structure of the interconnection and the specific capacity allocation mechanisms in place.

Our review of selected existing heterogeneous interconnections revealed that the modalities by which they operate are diverse, and so are the capacity allocation mechanisms that they can implement. The selection of these operational aspects is largely defined by the underlying characteristics of the interconnected markets, and how they complement each other. However, it is apparent that existing market clearing rules of the liberalised market, and the prevailing capacity allocation mechanism governing its homogeneous interconnections, are likewise an important determinant of the heterogeneous interconnection's operational dimensions. In most cases, the capacity allocation approach with the regulated market appears to be an afterthought, an adaptation, of how the liberalised market allocates its homogeneous interconnections' capacity that does not account for the peculiarities of the heterogeneous context, thereby exacerbating its inefficiencies.

Depending on how the regulated market is structured, specifically the degree of private sector participation within it, some allocation mechanisms can in principle reduce these inefficiencies. Mechanisms such as the "Interconnection deregulation", or any arrangement that enables potential private agents in the regulated market to independently carry out cross-border operations could be effective. Similarly, long-term cross-border contracts for energy could be negotiated so as to guarantee a minimum utilisation level of the interconnection and reduce the manipulation margin. This margin could be further reduced by distancing the interconnection's scheduling from the liberalised market's clearing or dispatch. This is because guessing the parameters necessary to manipulate the exchange outcome is harder the further the exchange is determined from delivery, thus reducing the degree of informational asymmetry.⁵² Nonetheless, the vertically integrated utility would still have incentives to hinder cross-border flow, withhold transmission capacity, or manipulate the outcome to its benefit, which highlights the need for careful consideration of market structures when establishing interconnections, designing their policies, and negotiating their operational dimensions.

⁵¹ As opposite flows of electricity over the same line physically cancel each other out, commercially netting these flows maximises the interconnection capacity that system operators can offer, thereby increasing welfare through higher utilisation.

⁵² For example, information asymmetry would be less acute for cross-border exchange dispatched through the day-ahead market compared to that dispatched through the intraday or real-time markets.



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Appendix A: Analytical Derivations for the Individual Market Welfare and Strategic Equilibria

In this Appendix, we model the effects of cross-border exchange by market, to highlight some relevant dynamics affecting the interconnection utilisation and some specific interactions. We develop this theoretical analysis for the liberalised market l , however, the same results hold for the regulated market. Besides, we henceforth only consider the arbitrage domain $Ex \in \left[0, \frac{-b}{a}\right]$ beyond which gains in welfare stagnate.

Welfare generated by cross-border exchange in market l is equal to the net-surplus generated for either the consumers (importer) or the producers (exporter), in addition to its share $\rho \in [0,1]$ from congestion rents. These are equal to:

$$W_l(Ex) = |P'_l - P_l| \cdot Ex \cdot \frac{1}{2} + \rho \cdot |P'_r - P'_l| \cdot Ex. \quad (\text{A.1})$$

The difference $|P'_l - P_l|$ between the autarky clearing price P_l and the interconnected clearing price P'_l is an increasing function of exchange, and as we are in a linear demand-supply setting, the function is linear, with a positive slope equal to $\beta > 0$, representing the magnitude of the price sensitivity to exchange in the liberalised market, and no intercept. As congestion rents are as defined in (4), we have:

$$W_l(Ex) = \beta \cdot Ex^2 \cdot \frac{1}{2} + \rho \cdot [a \cdot Ex^2 + b \cdot Ex] = Ex^2 \cdot \left[\frac{\beta}{2} + \rho \cdot a \right] + Ex \cdot \rho \cdot b, \quad (\text{A.2})$$

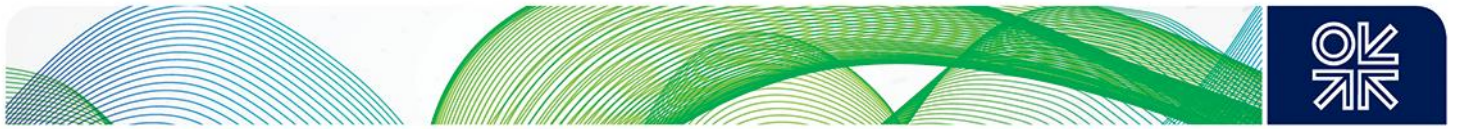
hence, the individual market's gain in welfare is likewise a quadratic function of Ex . The function is strictly positive in \mathbb{R}^+ when the coefficient $\left[\frac{\beta}{2} + \rho \cdot a \right]$ is positive or null. Whereas the function is positive when $Ex < \frac{-b}{\frac{\beta}{2\rho} + a}$ and the coefficient $\left[\frac{\beta}{2} + \rho \cdot a \right]$ is negative. As β is positive, we have $\frac{-b}{a} < \frac{-b}{\frac{\beta}{2\rho} + a}$, and as such, the function is strictly positive over the arbitrage domain, representing the possible volumes of exchange. Therefore, for each individual market, any volume of exchange is favourable over autarky, and they would prefer to be interconnected rather than isolated. On the other-hand, the welfare maximising volumes of exchange for each market may or may-not match the socially optimal one, nor each other, depending on the allocation rules of congestion rents. This is highlighted by the marginal (linear) effect of cross-border exchange on the individual market's welfare as captured by the derivative:

$$\frac{\partial W_l(Ex)}{\partial Ex} = Ex \cdot [\beta + 2 \cdot \rho \cdot a] + \rho \cdot b, \quad (\text{A.3})$$

revealing the importance played by the allocation ratio ρ of congestion rents in the utilisation of the interconnection and the individual markets' socially optimal outcomes.

Exploring the two extremes, we have that when $\rho = 0$, the marginal effect of exchange on the market's welfare is strictly positive, equal to $\beta \cdot Ex$, and the optimal flow for the market thus matches the aggregate welfare maximising one, $Ex_l^* = Ex^*$. On the other-hand, when $\rho = 1$, the marginal effect of exchange turns negative at the point where $Ex_l = \frac{-b}{\beta + 2a}$, and in this case the market's welfare maximising exchange volume is $Ex_l^* = \min\left(ATC, \frac{-b}{\beta + 2a}\right)$. Note that as $|\beta| < |a|$, and $\beta > 0$, while $a < 0$, the following holds: $\left[\frac{-b}{2a} < \frac{-b}{\beta + 2a} < \frac{-b}{a} \right]$, hence the marginal effect necessarily turns negative before the cross-border price gap is closed, and the optimal exchange volume for the market when ATC is not binding lies in between the optimal outcome for a merchant interconnector, and the aggregate social welfare maximising outcome.

Finally, for intermediate values of ρ comprised between the two extremes, different situations arise. First, for small values of ρ when the leading coefficient of $W_l(Ex)$ is positive, when $\beta + 2\rho a \geq 0$, then incremental exchange strictly increases the market's welfare, and the optimal exchange volume for the market is thus $Ex_l^* = Ex^*$. Whereas when the leading coefficient of $W_l(Ex)$ is negative, then the marginal effect of exchange is positive all the way to the volume:



$$Ex_l = \frac{-b}{\frac{\beta}{\rho} + 2a}, \quad (\text{A. 4})$$

in which the ratio ρ acts as a multiplier for the welfare maximising exchange volume, the lower ρ , the higher Ex_l^* . In this case, two situations arise and the optimal exchange for the market might or might not coincide with Ex^* . It coincides when the denominator of (A.4) is higher than a , likewise for low values of ρ when $\frac{\beta}{\rho} \geq -a$, otherwise, for higher values of ρ , the optimal exchange for the market does not close the price-gap, $Ex_l^* < Ex^*$. These results are summarised in Table A.1, and they are similar from the regulated market's perspective, replacing β with α , and the ratio ρ with $(1 - \rho)$.

Table A. 1: Allocation ratio of congestion rents and optimal flow volume by market (over arbitrage domain*)

Allocated ratio ρ	Shape of welfare gains function	Marginal effect of exchange	Market's optimal flow	Market seeks price convergence?
$\rho = 0$	Linear	Positive	$\min\left(ATC, \frac{-b}{a}\right)$	Yes
$0 < \rho < 1 \text{ \& } \beta \geq -2\rho a^{**}$	Convex	Positive	$\min\left(ATC, \frac{-b}{a}\right)$	Yes
$0 < \rho < 1 \text{ \& } \beta < -2\rho a$	Concave	$\frac{\beta}{\rho} \geq -a$: Positive $\frac{\beta}{\rho} < -a$: Switches	$\min\left(ATC, \frac{-b}{\frac{\beta}{\rho} + 2a}\right)$	$\frac{\beta}{\rho} \geq -a$: Yes $\frac{\beta}{\rho} < -a$: No
$\rho = 1$	Concave	Switches	$\left(ATC, \frac{-b}{\frac{\beta}{\rho} + 2a}\right)$	No

*Arbitrage domain includes the volumes of exchange ranging from autarky all the way to fully integrated markets: $Ex \in \left[0, \frac{-b}{a}\right]$

**The welfare function turns constant, and is strictly positive when $\beta = -2\rho a$.

That is, our results present a set of logical conclusions. The lower the allocated rents for market l , the higher its willingness to exchange electricity across the border towards price convergence, and vice versa. The market with a high allocation ratio of congestion rents will behave more similarly to a profit-maximising interconnector, whereas a market with a sufficiently low allocation ratio would behave as a welfare-maximising interconnector. A market to whom congestion rents are fully allocated ($\rho = 1$) will never seek price convergence, but would be willing to trade a larger volume than a merchant interconnector. If a market has an opportunity to capture the totality of the rents, then they will surely seize it. This is because if we consider the individual markets' welfare function $W_l(Ex)$ as expressed in Equation (A.2), but this time consider it as a function of both exchange and rent allocation rate ρ , that is $W_l(Ex, \rho)$, then the global maximum of the function over the arbitrage domain is achieved when $\rho = 1$ and $Ex_l^* = \min\left(ATC, \frac{-b}{\frac{\beta}{\rho} + 2a}\right)$. Besides, as the markets' welfare is strictly increasing with ρ , they would attempt to capture the highest possible share of rents.⁵³ Lastly, the interconnected markets are always better off with electricity exchange compared to autarky, independently of the allocation rules of congestion rents.

⁵³ The derivative of the individual market's welfare with respect to their allocated rate from rents is positive, that is, the derivative of (A.2) with respect to ρ is strictly positive over the arbitrage domain.



More conclusions can be deduced from our results by looking at both markets simultaneously and identifying the different cross-border exchange equilibria that arise based on the value ρ of rents allocation, and the possible combinations of the markets' welfare gain function shapes, as summarised in Table A.2. Outside of congestion, the optimal exchange volumes for the interconnected markets always diverge, with one market seeking price convergence while the other hindering it, except for a single combination of rents' allocation setting the efficient rate ρ^* that leads to the Nash equilibrium, coinciding with the efficient outcome. Said combination should satisfy: $\frac{\beta}{\rho^*} = \frac{\alpha}{(1-\rho^*)}$, and it leads to price convergence when ATC is not binding, resulting in $Ex^* = Ex_l^* = Ex_r^*$.⁵⁴ That is, to attain the efficient outcome, the market whose prices are (relatively) more affected by cross-border exchange should receive a larger share of congestion rents. That is because said market also benefits more from trade in surpluses, and thus is less inclined to hinder trade despite a larger share of rents.⁵⁵ Lastly, the higher the spread between the actual ratio ρ , and the efficient ratio ρ^* , the higher the divergence volume in the markets' willingness to exchange, and the most inefficient outcome arises when one market monopolises congestion rents. Table A.2 also highlights that, assuming the interconnection dispatchers maximise the individual welfare of their respective markets rather than the aggregate one, the actual prevailing exchange equilibrium would be the "Strategic" one.

Table A. 2: Exchange equilibria per congestion rents' allocation rate

Shape of welfare gains function		Occurrence conditions	Equilibrium		Price Convergence?
Market l	Market r		Nash	Strategic	
Convex	Concave	$0 \leq \rho \leq \frac{\beta}{-2a}$	Exists if $ATC \leq Ex_r^*$, equal to ATC	$\min\left(ATC, \frac{-b}{\frac{\alpha}{(1-\rho)} + 2a}\right)$	No.
Concave	Concave	$\frac{\beta}{-2a} < \rho < \frac{\alpha + 2\beta}{-2a}$	$= \min\left(ATC, \frac{-b}{a}\right)$, if $\left[\frac{\beta}{\rho} = \frac{\alpha}{(1-\rho)}\right]$. $= ATC$, if $ATC \leq \min(Ex_r^*, Ex_l^*)$	$\min\left(ATC, \frac{-b}{\frac{\beta}{\rho} + 2a}, \frac{-b}{\frac{\alpha}{(1-\rho)} + 2a}\right)$	if $\left[\frac{\beta}{\rho} = \frac{\alpha}{(1-\rho)}\right]$. No.
Concave	Convex	$\frac{\alpha + 2\beta}{-2a} \leq \rho \leq 1$	Exists if $ATC \leq Ex_l^*$, equal to ATC	$\min\left(ATC, \frac{-b}{\frac{\beta}{\rho} + 2a}\right)$	No.

⁵⁴ That is, as aggregate welfare over both markets strictly increases with exchange, a value for the allocation ratio ρ can surely be determined to guarantee the socially optimal flow of electricity for the relevant trading period.

⁵⁵ From an investment perspective, the market benefiting more from trade would be more willing to invest into an interconnection, and thus might indeed negotiate a larger share of rents relatively to its counterpart. Nonetheless, these dynamics generally change across the hours and seasons.