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On the structural design of the EU Inter-TSO Compensation mechanism

1. Introduction

Cross-border electricity flows in the European power system generate network externalities that are not fully internalized by national transmission tariffs or market prices. Power flows follow physical laws rather than commercial schedules, and in meshed transmission networks, they frequently traverse control areas that are neither the origin nor the destination of the underlying transaction. In the European Union, where system operation remains institutionally fragmented across several dozen transmission system operators (TSOs), these externalities have been addressed through the Inter-TSO Compensation (ITC) mechanism.

The ITC system provides a multilateral settlement framework intended to remunerate TSOs that host cross-border flows and incur associated losses, while charging those deemed responsible for generating them. Its legal basis was initially established through ETSO agreements and later codified in Commission Regulation (EU) No. 838/2010, with the current framework anchored in Regulation (EU) 2019/943 (ETSO 2007; European Commission 2010; EU 2019). Implementation and transparency are supported by ENTSO-E's methodological reporting and ACER's (The EU Agency for Cooperation of Energy Regulators) annual monitoring (ENTSO-E 2023; ENTSO-E 2024; ACER 2024; ACER 2025).

From an economic perspective, the design problem faced by the ITC mechanism is nontrivial. The system seeks to allocate costs that arise from complex network interactions using a limited set of observable quantities, primarily boundary power flows sampled at standardized snapshots. In meshed networks with internal congestion and loop flows, such observables provide only indirect and potentially ambiguous signals of underlying physical causation.

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Early analytical work by Daxhelet and Smeers (Daxhelet, Smeers 2005) demonstrated that, under realistic conditions, the ITC rules can generate paradoxical or indeterminate outcomes, while subsequent equilibrium-based analyses embedded the mechanism within a broader market-design context and highlighted interactions with congestion management and trade (Daxhelet, Smeers 2007).

A parallel strand of the literature examined alternative compensation approaches and their properties. Comparative analyses assessed different Inter-TSO Compensation schemes against criteria such as cost causation, neutrality, and implementability, concluding that no method simultaneously satisfies all desirable properties in a meshed transmission network (Olmos, Pérez-Arriaga 2007b; Olmos and Pérez-Arriaga 2007a).

Further work explored refinements and hybrid designs, emphasizing the inherent trade-off between theoretical consistency and practical feasibility (Stoilov et al. 2011; Stoilov, Stoilov 2013). Collectively, these contributions underscore that boundary-based allocation rules necessarily rely on proxies that may only imperfectly reflect the physical drivers of network usage and losses.

A number of additional contributions have approached the ITC problem from complementary perspectives. Early work by Glavitsch and colleagues (Glavitsch et al. 2004) proposed a flow-based methodology for allocating cross-border network usage, highlighting the inherent difficulty of linking physical flows to economic responsibility. From a regulatory standpoint, CEER (the Council of European Energy Regulators; CEER 2004) emphasized the long-term design challenges of the ITC mechanism, including the trade-off between cost causation, neutrality, and practical implementability.

Somewhat more recent modeling efforts have explored the optimization of cost and benefit allocation within the ITC framework under alternative assumptions and system conditions (Andročec et al. 2011). These contributions reinforce the view that the allocation of cross-border network costs remains a structurally complex problem for which no fully satisfactory solution exists.

A more conceptual critique was advanced in Sabolić's work (Sabolić 2017), which showed that even in a simple two-zone setting, internal congestion within one area can induce physical power detours through neighboring networks in the absence of commercial exports. In such cases, the ITC mechanism records symmetric inflows and outflows and assigns transit to both zones, despite the fact that only one zone causally generates the detour. The argument is structural rather than statistical: increasing measurement precision or temporal granularity refines the proxy but does not alter its informational content. As a result, the mechanism may fail to distinguish between zones that induce network stress and zones that merely host it.

More recent work has revisited the ITC mechanism from an institutional and descriptive empirical perspective. Using party-level data published by ACER and

ENTSO-E, a legal–economic reappraisal documented that aggregate ITC outcomes often display a high degree of internal consistency by construction, while material deviations persist at the level of individual parties (Sabolić 2025). That analysis also highlighted the continued reliance on the with/without-transit (WWT) approach for loss attribution and on standardized snapshots, despite ongoing discussions about higher temporal granularity (ACER 2023; ENTSO-E 2024). These findings suggest that procedural evolution and improved transparency have not fundamentally altered the informational basis of the mechanism.

At the operational level, both the literature and public documentation indicate that TSOs have actively responded to unscheduled and loop flows by investing in controllability measures, most notably phase-shifting transformers (PSTs). Case studies involving the German–Polish border and other highly interconnected interfaces illustrate how such investments can materially alter physical flow patterns (PSE 2014; ENTSO-E 2016; Opala, Ogryczak 2017). While these measures are primarily justified on operational grounds, they also affect the incidence of measured transit and losses and, indirectly, ITC settlements, reinforcing the importance of understanding what the mechanism does and does not capture.

Against this background, the present paper offers an additional analytical contribution by developing a new stylized three-zone counterexample that builds on, but goes beyond, earlier constructions. The example considers a configuration in which internal congestion in one control area induces a physical flow detour through another, non-causal area, leading to compensation outcomes that are difficult to reconcile with the physical origin of the burden.

Unlike the two-zone case, the presence of a third control area allows a clearer separation between the zone that induces network stress and the zone that passively accommodates it. The purpose of the exercise is not to claim empirical prevalence or to derive welfare rankings, but to show how, under admissible and transparent network conditions, the ITC settlement rules can map identical observable inputs into paradoxical compensation outcomes that are inconsistent with the intended redistribution goals of the mechanism.

2. Methodology

The analysis in this paper is analytical and relies on a stylized thought experiment. The approach follows the tradition of earlier paradox-based analyses of the Inter-TSO Compensation (ITC) mechanism, such as those developed by Daxhelet and Smeers (Daxhelet, Smeers 2005) and by Sabolić (Sabolić 2017). As in those articles, the purpose is to examine how the ITC settlement rules operate under transparent and economically meaningful network configurations, rather than to assess their empirical frequency or statistical relevance.

The thought experiment considers a simplified three-zone transmission system in which physical power flows differ from commercial schedules due to internal network physics. The construction focuses on how such configurations are recorded by the boundary-flow observables used in the ITC mechanism and how these observables translate into compensation outcomes. The emphasis is on the logical mapping from physical flows to ITC-relevant quantities, not on equilibrium behavior, welfare comparisons, or parameter calibration.

The present work extends this line of analysis by introducing a new configuration that complements previously identified paradoxes and sheds additional light on the interpretation and incentive properties of the mechanism.

An analytical approach is particularly appropriate in this context, as the objective is to identify structural properties of the ITC mechanism that arise from its very design and are not contingent on specific empirical configurations.

3. EU Inter-TSO Compensation mechanism

A brief description of the ITC mechanism and its underlying data architecture (European Commission 2010) is provided in Sabolić's works (Sabolić 2017, 2025). Nevertheless, we shall reproduce it here for the reader's convenience.

ITC settlement is carried out on a monthly basis and is constructed from a predefined set of standardized system states, commonly referred to as *snapshots*. Let $t = 1, \ldots, N$ index these snapshots, where N is determined by the prevailing methodology. Each snapshot is intended to represent a class of hourly operating conditions, and monthly quantities are obtained by aggregating across the N snapshots.

For a given control area i and snapshot t, let $U_i(t)$ denote the total physical outflow to neighboring areas, and $I_i(t)$ the total physical inflow. Let $G_i(t)$ and $K_i(t)$ denote total internal generation and consumption, respectively. A boundary-based proxy for transit through area i is defined as:

$$T_i(t) = \min\{U_i(t), I_i(t)\} \tag{1}$$

Aggregation over the accounting month is performed across snapshots using the weights specified by the ITC methodology, reflecting the representativeness of the snapshots (ENTSO-E 2024). For expositional convenience, without affecting the analytical argument and in line with earlier analytical formulations, the scaling ratio is written as an unweighted average:

$$\rho_i = \frac{1}{N}\sum_{t=1}^{N} \frac{T_i(t)}{T_i(t) + \max\{G_i(t), K_i(t)\}} \tag{2}$$

which relates measured transit to total activity in the area.

Infrastructure component. The entitlement of area i to infrastructure compensation is computed as:

$$R_i = \rho_i \cdot LRAIC_i \tag{3}$$

where $LRAIC_i$ denotes the calibrated long-run average incremental cost of the extra-high voltage network. Summing across all participating TSOs yields the total infrastructure fund:

$$F = \sum_i R_i \tag{4}$$

Financing of this fund is based on a measure of the so-called absolute accumulated cross-border flow:

$$A_i = \sum_{t=1}^{N} \left| U_i(t) - I_i(t) \right| \tag{5}$$

so that the contribution of area i is given by:

$$D_i = F \cdot \frac{A}{\sum_j A_j} \tag{6}$$

where the index j runs over all TSOs participating in the ITC mechanism. The resulting net position in the infrastructure component is:

$$Net_i^{infra} = R_i - D_i \tag{7}$$

Following the entry into force of Commission Regulation (EU) No. 838/2010, the infrastructure component was partially modified. While 75% of the infrastructure fund continues to be allocated according to the above rules, the remaining 25% is redistributed using a consumption-related adjustment factor defined as:

$$f_{K,i}(t) = \frac{T_i(t)}{\sum_j T_j(t)} \cdot \frac{T_i(t)}{T_i(t) + K_i(t)} \tag{8}$$

This factor moderates pure transit-based allocation by incorporating the ratio of transit to internal consumption. At the system level, its quantitative impact on redistribution has been reported to be limited (ACER 2014).

Losses component. Compensation for transmission losses is based on a with/without transit (WWT) approach, which estimates the reduction in network losses under a counterfactual state without transit relative to the observed state

(ACER 2023). Let δP_i denote this loss difference in energy units. Valuing losses at the prior-year average procurement cost C_i yields:

$$L_i = \delta P_i \cdot C_i \tag{9}$$

and the corresponding losses fund is:

$$F_L = \sum\nolimits_i L_i \tag{10}$$

Contributions to the losses fund are allocated using the snapshot-level factor:

$$f_{L,i} = \frac{T_i(t)}{T_i(t) + K_i(t)} \tag{11}$$

which is aggregated across the month using snapshot weights. In current practice, ITC settlement relies on $N = 6$ standardized snapshots per month (3:30 a.m., 11:30 a.m., and 7:30 p.m. CET/CEST on the third Wednesday and the preceding Sunday). Each hour of the month is mapped to one of these snapshot types, and the corresponding hour shares are used as weights w_t (ENTSO-E 2024; ACER 2025).

Formally, letting $\sum\nolimits_{t=1}^{N} w_t = 1$, we can define the monthly transit-loss weighted average as:

$$\bar{f}_{L,i} = \sum\nolimits_{t=1}^{N} w_t \frac{T_i(t)}{T_i(t) + K_i(t)} \tag{12}$$

so that the contribution of area i to the losses fund is:

$$D_{L,i} = F_L \cdot \frac{\bar{f}_{L,i}}{\sum\nolimits_j \bar{f}_{L,j}} \tag{13}$$

The construction is intentionally based on quantities that can be measured consistently across all participating control areas using boundary metering and a limited number of standardized system states. As a result, the mechanism abstracts from internal network topology and does not attempt to identify the physical origin of individual power flows. This reliance on perimeter-based observables ensures implementability but also constrains the informational content available for settlement. The implications of this feature are central to the analytical discussion that follows.

Firm-level implications for TSOs

From the perspective of an individual transmission system operator, the ITC mechanism operates as a largely ex post and non-strategic clearing arrangement.

Monthly settlement outcomes are effectively price-taking: the methodology, the mapping of hours to standardized snapshots, and the valuation of losses under the with/without-transit framework are determined outside the control of individual firms. Day-to-day operational decisions – such as unit commitment, remedial actions, and redispatch – affect ITC outcomes only indirectly, through their influence on boundary-measured physical flows.

In a coupled zonal market design without nodal (LMP) signals, TSOs face limited scope to manage network externalities through prices. This institutional setting is consistent with broader assessments of European pricing-rule alternatives, which emphasize the weak signaling properties of zonal pricing for internal congestion management (Weißensteiner 2023). As a result, managerial discretion shifts away from short-run operational adjustments toward slower-moving and capital-intensive instruments. These include investments in network controllability (most notably phase-shifting transformers), engagement in cross-border capacity governance and coordinated operational arrangements, and internal policies for procuring and valuing technical losses.

The experience on the Poland–Germany border illustrates this pattern. Persistent unscheduled flows associated with northern German wind generation led to coordinated investments in phase-shifting transformers, formalized in the 2014 agreement between PSE and 50Hertz and followed by concrete steps to regulate flows on the Poland–Germany interface (PSE 2014; ENTSO-E 2016). Engineering studies document how automatic PST adjustment can be used to steer active power flows on international lines (Opala, Ogryczak 2017). These interventions are structural rather than transactional: they reshape physical flow patterns and thereby modify exposure to ITC allocations indirectly.

Related evidence from the Germany–Netherlands–Belgium–France interface highlights a complementary issue. Boundary-based proxies may allocate compensation in ways that diverge from cost causation, so that a system inducing large internal transfers can appear as a beneficiary, while neighboring systems that physically host the resulting loop flows bear a disproportionate burden (Daxhelet, Smeers 2005). Such outcomes reinforce the incentives for TSOs to invest in controllability and to advocate institutional changes that reduce unwanted transits.

The managerial implications are therefore twofold. In the short run, ITC outcomes should be regarded as largely exogenous realizations of a proxy-based settlement rule. In the medium run, however, exposure management is closely tied to structural decisions – network investments, topology choices, and governance arrangements – rather than to tactical operational behavior. While firm-level challenges in this environment are substantial, a detailed managerial analysis lies beyond the scope of this paper. For the purposes of the present study, the key observation is that the ITC mechanism leaves relatively little room for active short-term management within its existing institutional framework.

4. A three-zone thought experiment

This section develops a stylized three-zone thought experiment that illustrates how the ITC infrastructure settlement responds to changes in commercial exchange patterns when the underlying physical configuration of the transmission system remains unchanged. In this example, the loss component of the ITC compensation will not be analyzed.

The intuition behind the example is as follows. Internal congestion in one control area may induce physical loop flows through neighboring systems without any corresponding commercial transaction. If compensation is based solely on boundary-measured flows, the mechanism may attribute responsibility symmetrically across affected areas, even when the underlying physical causation is asymmetric. The construction below isolates this effect and examines how such situations are reflected in ITC settlement outcomes.

The construction is deliberately simple and should be read jointly with Figure 1, Table 1, and the defining equations in Section 3. Its purpose is to make the mapping from physical flows to ITC compensation transparent and to examine the incentive properties implied by that mapping.

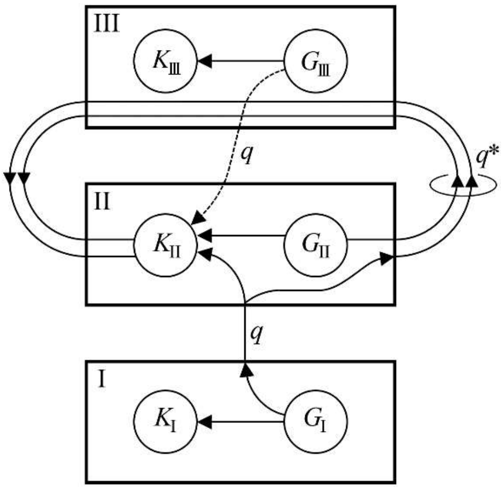

Figure 1. Stylized three-zone transmission system used in the thought experiment

Figure 1 illustrates the structure of the example. Area I exports power to Area II under a commercial schedule that corresponds exactly to the cross-border flow q. However, due to internal constraints within Area II, part of the power destined for its consumers is physically rerouted through Area III, giving rise to an unscheduled loop flow q^*. Importantly, this transit through Area III is not associated with any commercial transaction involving Area III, but is instead caused by internal network conditions in Area II. In Model 2, an additional commercial export of magnitude q from Area III to Area II (dashed arrow) is added relative to Model 1, without altering the underlying physical configuration of the system.

In Table 1, variables are indexed by Roman numerals corresponding to the control areas I, II, and III from Figure 1. It applies: $F = \rho_{II} + \rho_{III}$, where $\rho_{II} = q^*/(q^* + K_{II})$ and $\rho_{III} = q^*/(q^* + G_{III})$. Δ denotes the change in net financial position between Model 2 and Model 1. All variables T, ρ, R, F, A, D, and Net are defined as in the corresponding equations in Section 3. For simplicity, the *LRAIC* parameter from (3) is normalized to unity for all three areas, and all snapshot observations are assumed to be identical.

Table 1

Infrastructure component of ITC compensation in the three-zone thought experiment

Model	Parameter	I	II	III
Model 1	T	0	q^*	q^*
	ρ	0	$q^*/(q^* + K_{II})$	$q^*/(q^* + G_{III})$
	R	0	$q^*/(q^* + K_{II})$	$q^*/(q^* + G_{III})$
	A	q	q	0
	D	$F/2$	$F/2$	0
	Net	$-(\rho_{II} + \rho_{III})/2$	$(\rho_{II} - \rho_{III})/2$	ρ_{III}
Model 2	T	0	q^*	q^*
	ρ	0	$q^*/(q^* + K_{II})$	$q^*/(q^* + G_{III})$
	R	0	$q^*/(q^* + K_{II})$	$q^*/(q^* + G_{III})$
	A	q	$2q$	q
	D	$F/4$	$F/2$	$F/4$
	Net	$-(\rho_{II} + \rho_{III})/4$	$(\rho_{II} - \rho_{III})/2$	$(3\rho_{III} - \rho_{II})/4$
	Δ	$+(\rho_{II} + \rho_{III})/4$	0	$-(\rho_{II} + \rho_{III})/4$

Consider three control areas, denoted I, II, and III. Each area contains internal generation G and consumption K, connected by an internal network. Area II is internally constrained: its transmission system cannot accommodate the full transfer required to supply internal demand using internal generation and imports alone. As a consequence, part of the power destined for consumers in Area II flows physically through Area III, giving rise to a loop flow of magnitude q^* that is caused by internal physical conditions in the grid of Area II; Area III merely hosts the resulting unintentional and commercially unscheduled transit.

We now consider two configurations, referred to as Model 1 and Model 2. In both cases, the internal topology, the magnitude of the loop flow q^*, and the physical burden borne by Area III are identical. The only difference lies in the pattern of commercial exchanges.

In Model 1, Area I exports a quantity q to Area II. Area II imports q and, due to its internal bottleneck, induces a loop flow q^* through Area III. Area III is commercially neutral. The resulting ITC-relevant quantities are reported in the upper panel of Table 1. Area III is entitled to infrastructure compensation through ρ_{III}, while Areas I and II finance the infrastructure fund equally.

By construction, the variables ρ take values in the range [0, 1]. With this in mind, the net financial position of Area II depends on the relative magnitudes of ρ_{II} and ρ_{III}. When Area III is electrically significantly larger than Area II (as, for example, Germany compared to Austria), ρ_{II} may exceed ρ_{III}, and Area II receives a positive net payment, even though it is the only one of the three zones that actually causes the loop flows.

The resulting outcome can be interpreted as a situational form of free-riding: Area II benefits not from its behavior within the system, but from its relative electrical size compared to the hosting area. This advantage is merely a coincidence – a fact of life that has nothing to do with the behavior of Area II in the system composed of the three areas. Note, however, that in the present model setting, where transit is caused solely by loop flows originating in Area II, the coefficient ρ_{II} cannot in principle be much larger than 1/2. A higher value would imply that Area II has virtually no internal transmission grid, forcing almost the entire flow $K_{II} + q$ to be routed through Area III. Therefore, Area II can be net-positive only if the coefficient ρ_{III} is smaller than approximately 1/2.

Model 2 introduces an additional commercial exchange without altering the physical structure of the system. Area III now exports a quantity q to Area II, so that Area II imports $2q$ in total. Internal congestion and the resulting loop flow q^* remain unchanged.

The lower panel of Table 1 reports the corresponding ITC outcomes. Although Area II increases its reliance on external supply and remains the exclusive cause of the loop flow, its net infrastructure position is unchanged relative to Model 1, as indicated by $\Delta_{II} = 0$. The comparison across models highlights a structural feature of the ITC design.

Because settlement is driven by boundary-based transit proxies rather than by physical causation, changes in commercial behavior that increase dependence on external networks need not translate into higher compensation payments by the importing area.

In the present construction, the area responsible for the loop flow is not penalized for worsening the behavior of the system, even though it increases its import by q, while the additional financial burden is shifted to another party that increases its export by exactly the same amount q. Under the logic of the ITC mechanism – specifically, the notion of absolute accumulated flow – both actions are meant to be treated equally, yet only one of them – the "less guilty" party in this example – bears the entire additional cost. This outcome follows mechanically from the settlement rules summarized in Section 3. It does not rely on special parameter choices, nor does it require extreme assumptions about system configuration or size.

5. Conclusions and further research

This paper has examined the structural properties of the EU Inter-TSO Compensation (ITC) mechanism using a stylized three-zone thought experiment. Building on earlier analytical critiques, the construction isolates a configuration in which internal congestion in one control area induces physical loop flows through another area that is not causally responsible for the network stress. By varying commercial exchange patterns while holding the physical configuration constant, the analysis highlights how boundary-based transit proxies map identical physical outcomes into compensation results that differ in their economic interpretation.

The central finding is not merely that the ITC mechanism can misattribute costs in the presence of loop flows – an issue already documented in the literature – but that it may fail to penalize worsening behavior by the area that causes those flows. In the example developed here, an importing area can increase its reliance on external networks without facing a corresponding deterioration in its net ITC position, while another area undertaking an exactly symmetric action bears the entire additional financial burden. This outcome follows directly from the design of the infrastructure component and, in particular, from the use of absolute accumulated flow and boundary-based transit ratios as proxies for responsibility.

The analysis does not rely on extreme assumptions or parameter choices. All variables take admissible values, and the configurations considered are consistent with transparent and economically meaningful network conditions. The results therefore point to a structural feature of the ITC design rather than to a pathological special case. While the mechanism ensures implementability and administrative simplicity, it does so by abstracting from internal network topology and physical causation in a way that constrains the economic interpretation of its outputs.

These observations have implications for how ITC outcomes should be understood in practice. Party-level net positions should not be interpreted mechanically as indicators of responsibility or burden, especially in systems characterized by internal congestion and loop flows. More broadly, the findings suggest that the ITC mechanism, in its current form, provides weak incentives to internalize the network externalities associated with increased cross-border dependence.

A final point concerns the interpretation of ITC outcomes in relation to the stated economic objective of the mechanism. The ITC framework is commonly understood as an attempt to approximate cost causation in a system where direct attribution is infeasible. The present analysis shows that, even under transparent and internally consistent conditions, the mapping from physical flows to financial outcomes may systematically diverge from this objective. In particular, identical physical configurations can give rise to different allocations solely due to changes in commercial exchange patterns, without any corresponding change in the underlying network burden. This suggests that the mechanism should be interpreted primarily as a pragmatic settlement rule based on observable proxies, rather than as a reliable indicator of economic responsibility within the system.

Several directions for further research follow naturally. One avenue is to explore whether alternative proxy designs – still implementable with limited and standardized data – could better align compensation with physical causation without sacrificing administrative feasibility. Another is to examine how ITC settlements interact with investment incentives in network controllability and grid reinforcement, particularly in systems where loop flows are persistent. Finally, integrating the present analytical insights with descriptive empirical evidence may help clarify under which conditions the structural features identified here are likely to be most relevant in real-world operation.

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Summary

This paper examines the structural design of the EU Inter-TSO Compensation (ITC) mechanism, which aims to remunerate transmission system operators for the costs associated with cross-border electricity flows. Building on the established legal and institutional framework and earlier analytical critiques, the paper develops a new stylized three-zone counterexample to assess how the mechanism allocates costs under realistic network interactions. The analysis shows that settlement rules based on boundary-flow proxies can assign compensation in ways that diverge from the physical origin of network burdens and may fail to penalize behavior that increases reliance on external networks. This finding complements existing paradoxes in the literature and highlights how proxy-based clearing can mute or distort operational and investment incentives, particularly in meshed networks with internal congestion. The contribution is analytical rather than empirical and is intended to clarify the scope and limitations of what the ITC mechanism can reasonably be expected to achieve, given its current design and informational basis.

JEL codes: L94, D47, Q48, L51

Keywords: *Inter-TSO Compensation, cross-border electricity flows, transmission networks, zonal market design, network externalities*