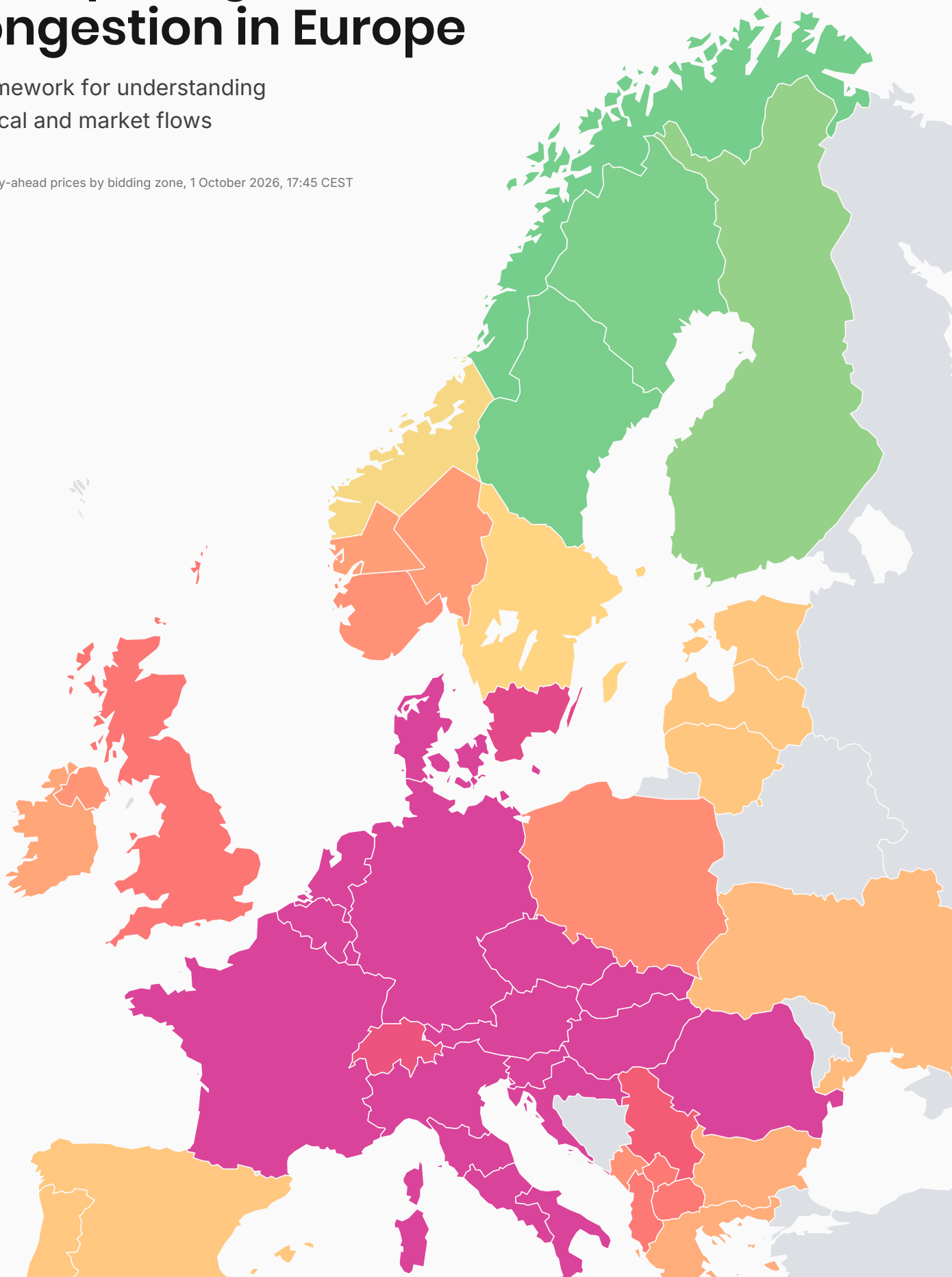


WHITEPAPER · OCTOBER 2026

# Anticipating interconnector congestion in Europe

A framework for understanding  
physical and market flows

Cover: day-ahead prices by bidding zone, 1 October 2026, 17:45 CEST



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## ABOUT THIS PAPER

A framework for reading interconnector signals across European borders, built from what we learned developing our interconnector data offering.

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## ABOUT ELECTRICITY MAPS

Electricity Maps provides global access to electricity mix, prices, load and carbon intensity: real-time, historical and forecasted.

## PUBLISHED

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# Executive summary

Interconnector congestion is the point at which a border reaches its limit and prices on either side diverge. Anticipating it matters to anyone trading or analysing cross-border spreads, yet the signals available are easy to misread. This paper shares what Electricity Maps learned while building interconnector signals for European borders.

The central finding: comparing a flow to a capacity is not enough. The power grid and the power market are two different realities, and the rules that translate constraints from one to the other change from border to border.

## 1 Physical and market flows are different realities.

On the France–Germany border in 2026, the physical net flow and the total scheduled commercial flow differed by more than 1 GW in 46% of hours, and pointed in opposite directions in 12% of hours.

## 2 Physical capacity is only clear-cut for HVDC links.

For AC borders, how much power can cross depends on the state of the surrounding grids, so a single physical capacity figure rarely exists.

## 3 Market capacity depends on the methodology.

Under CNTC, each border has a defined market capacity (NTC, then ATC). Under flow-based, capacity becomes a set of network constraints (CNEC, PTDF and RAM), that cannot be approximated by a single number.

## 4 Congestion means different things on each side.

Physical congestion occurs when the physical flow reaches the physical capacity. Market congestion occurs when the market flow reaches the market capacity. One can happen without the other, so signals should never be compared across realities.

## 5 Every border needs its own reading.

Methodologies vary by capacity calculation region and interconnection type. We introduce a framework that sorts each signal by reality (physical or market) and measure (capacity or flow), and apply it border by border.

### GLOSSARY

#### AAC

Already Allocated Capacity

#### AC

Alternating current

#### ATC

Available Transfer Capacity

#### CCR

Capacity calculation region

#### CNE

Critical Network Element

#### CNEC

Critical Network Element and Contingency

#### CNTC

Coordinated Net Transfer Capacity

#### HVDC

High-voltage direct current

#### MaxBex

Maximum Bilateral Exchange

#### NTC

Net Transfer Capacity

#### PTDF

Power Transfer Distribution Factor

#### RAM

Remaining Available Margin

#### SDAC

Single Day-Ahead Coupling

#### SIDC

Single Intraday Coupling

#### TRM

Transmission Reliability Margin

#### TSO

Transmission System Operator

#### TTC

Total Transfer Capacity

# Introduction

Interconnectors are the cables and lines that link electricity grids, allowing power to flow across borders. In theory, understanding them is straightforward: how much electricity can flow (capacity) and how much actually flows (net flow). In practice, once you add power markets to the picture and specificities from one border to the next, the complexity rises.

In this report we share what we learned at Electricity Maps as we built out our interconnector data offering. We started with our existing net flow data, which underpins our flow-tracing methodology, and set out to enrich it with signals to help anticipate congestion in power markets: the point at which a border reaches its limits and prices diverge.

What we found is that this limit can mean different things depending on the border in question. It is not as easy as simply comparing a flow to a capacity. The power market and the power grid are two different worlds, and they each operate based on entirely different mechanisms. The methodology used to translate constraints from one to another varies from one border to the next, and from one power market to another, even for grids within the same bidding zone.

# From the physical grid to power markets

Electricity Maps was built to show where electricity comes from and how carbon-intensive it is. The methodology that makes this possible is called flow-tracing. Rather than only looking at what each country generates locally, flow-tracing follows electricity as it crosses borders and attributes consumption correctly to its actual sources. This means that if Germany is importing French nuclear power, the carbon intensity for German consumers reflects that import, not just Germany's domestic generation mix.

For ten years, this meant working primarily with physical grid data: real-time and historical net flows across interconnectors, generation by source, and consumption by zone. As we began building forecasts of the grid state up to 72 hours ahead, we needed to forecast those net flows too, rather than just observe them.

The question we kept running into was: Can these forecasts help predict congestion? Congestion is a central concern for market participants, and it creates challenges for grid operators that have to keep the grids balanced. Answering that question reliably required us to understand both the physical and the market dimensions of interconnectors and how they interact.

## Determining an interconnection's physical capacity

Our starting point was physical net flow data. Hence, the data we first thought we needed was the cross-border 'physical' capacity in order to calculate whether a line is operating at full capacity. That is, what is the capacity of cables linking France and Great Britain? And the capacity of cables linking France and Germany?

### 4 GW

combined capacity of the three HVDC links between France and Great Britain

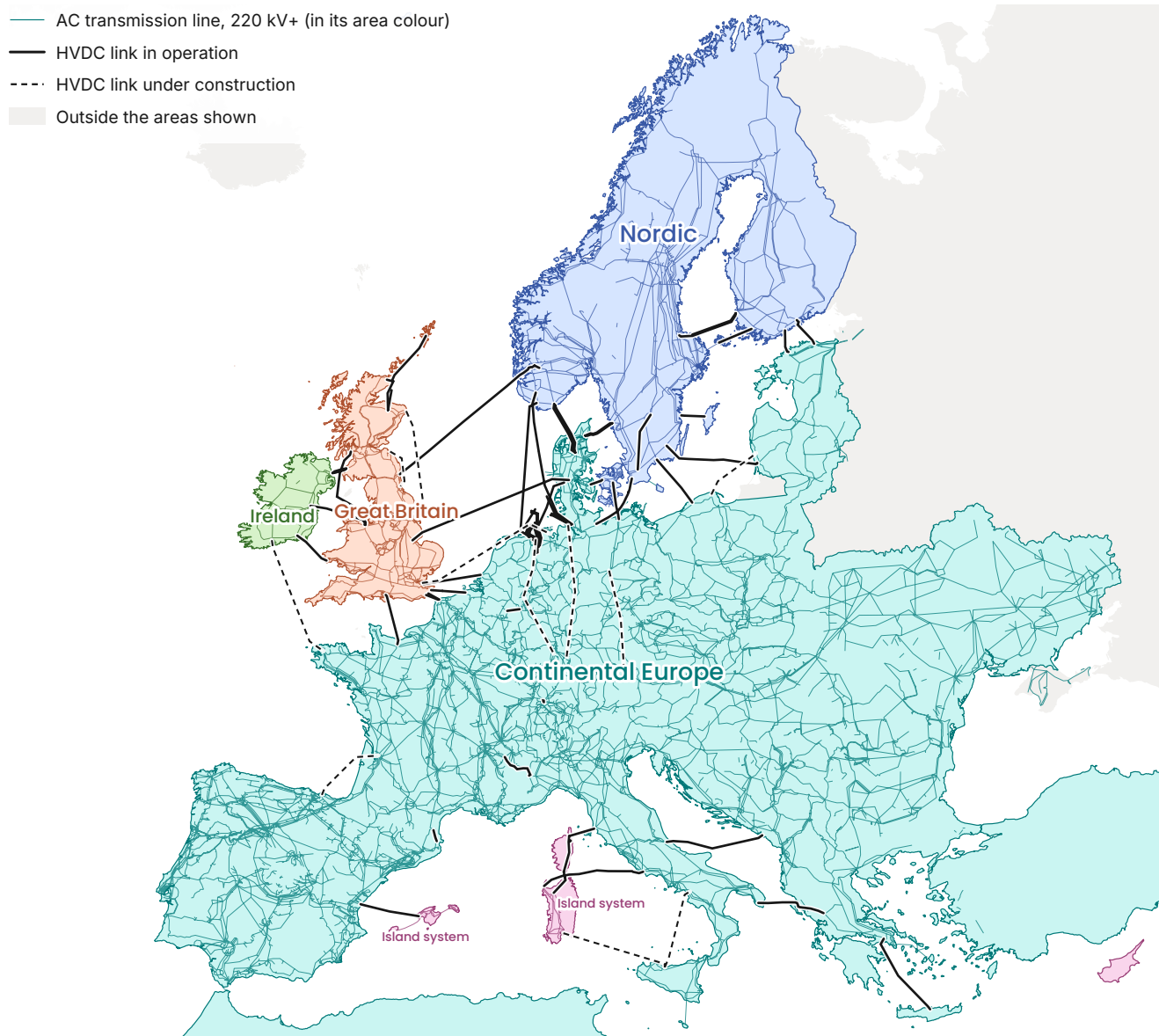
The cross-border capacity between France and Great Britain is straightforward. The two grids are not synchronized; they operate in isolation. They are connected by three High-Voltage Direct Current (HVDC) links that together have a capacity of 4 GW. An HVDC cable is controllable point-to-point, and it has a well-defined capacity.

But France and Germany are part of the Continental Europe Synchronous Area, which means they are tied and operated together. There is no set of cables connecting the two grids; they are part of a meshed network of connections. The capacity of the French-German border, that is, the flow limit between the two grids, is a vague concept. The physical components on the grid have limits, which means unlimited electricity cannot flow from France to Germany. But the limit can't be easily translated into a single figure. It depends on the state of all surrounding grids. As an example, the French TSO provides a single number for combined flows with Germany and Belgium rather than two separate figures, since these are intricate.

Anticipating congestion in the physical reality is already challenging for most European borders. Understanding and anticipating congestion in power markets is an even bigger challenge.

## Exhibit 1: Europe's power system runs as several separate synchronous areas

Synchronous areas of the European power system, connected to each other by HVDC links



Approximate rendering of the synchronous areas, drawn at country level. Not an accurate depiction of their boundaries.  
Links under construction drawn schematically.

**Source:** ENTSO-E grid maps (2022 data via PyPSA-Eur, checked against 2024 editions); Electricity Maps analysis.

# Market coupling: Incorporating cross-border capacity in European power markets

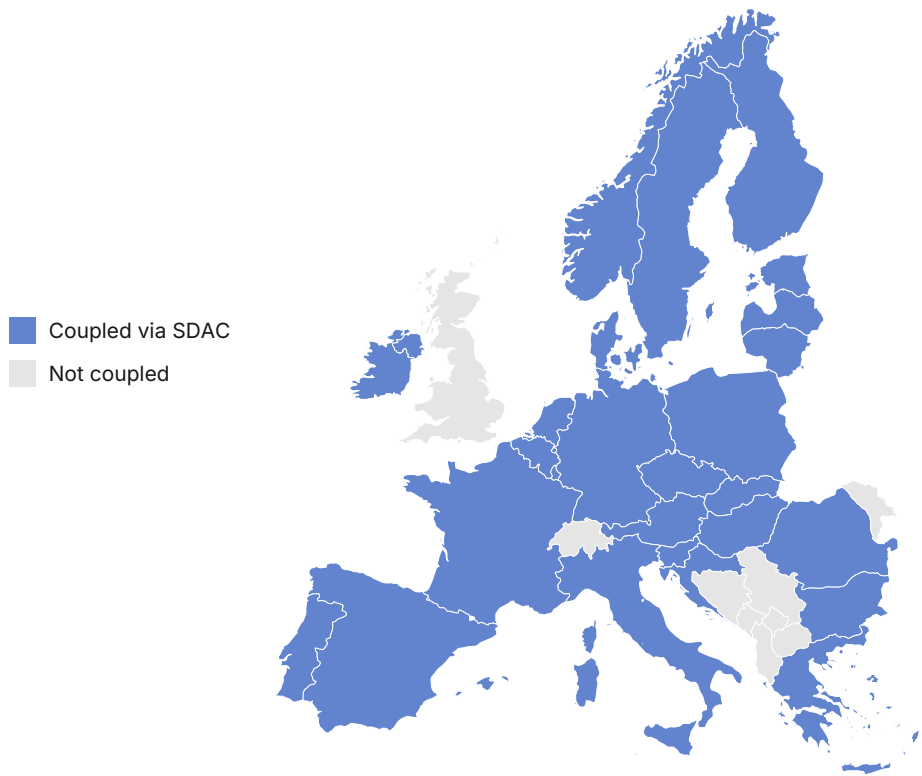
In Europe, the day-ahead market is the primary venue for buying and selling electricity for the following day. In 2025, 84% of volumes traded on Nordpool were in the day-ahead market (against 15% in the intraday continuous and 1% in intraday auctions). It is also the most tightly coupled market: 26 countries participate in the Single Day-Ahead Coupling (SDAC), a single auction that simultaneously determines clearing prices for ~40 zones. The auction is resolved by an algorithm called Euphemia, which finds the set of trades that maximizes overall economic welfare across all coupled zones.

The map below shows which countries currently participate in the SDAC. Most of Europe is included, with a small number of markets still operating outside the coupled system.

**84%**  
of Nordpool volumes were traded in the day-ahead market in 2025

## Exhibit 2: Most of Europe clears its day-ahead market in a single auction

Countries participating in the Single Day-Ahead Coupling (SDAC)

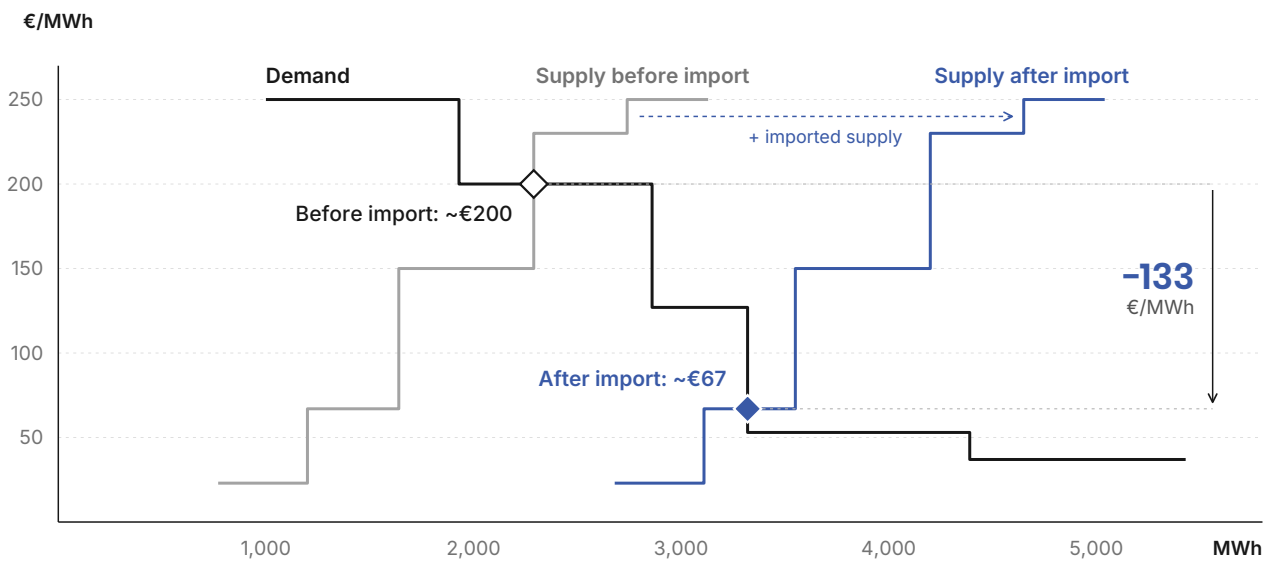


Source: ENTSO-E; Electricity Maps analysis.

Under SDAC coupling, cross-border transmission capacity is integrated directly into the market-clearing process as predefined constraints. According to the merit-order principle, sell orders from neighbouring grids will be ranked alongside domestic orders, allowing the market-clearing algorithm to use cross-border capacity up to its maximum limit to optimize the overall economic surplus. This means a French generator will be prioritized over more expensive German generators to match German demand as long as there is available cross-border capacity.

### Exhibit 3: Cheaper imports shift supply to the right and lower the clearing price

Day-ahead supply and demand curves in one bidding zone, before and after import



Source: Illustrative example by Electricity Maps.

The outcome of this auction has a simple but important implication for interconnectors. When the cross-border capacity between two bidding zones is not reached, they clear at the same price. Electricity produced in one zone can be matched with consumption in the other, and the market treats them as a single zone. When cross-border capacity is reached, prices diverge. This is a congestion event in the market. The spread size indicates the value of extra transmission capacity.

#### DEFINITION

**Market congestion:** cross-border capacity is reached and prices on either side of the border diverge.

Market coupling is not limited to the day-ahead market. Intraday markets are getting increasingly coupled through the Single Intraday Coupling (SIDC). Balancing markets are also moving in this direction, with platforms such as PICASSO and MARI handling the automatic and manual frequency restoration reserve energy markets, respectively. The principle is the same: interconnectors are valuable for grid balancing and for increased welfare. Markets are being designed to use them more efficiently.

## Market flows are not physical flows

When a power market matches a seller in France with a buyer in Germany, a commercial flow is scheduled across the French-German border. And the cross-border capacity available to the market is updated accordingly. But that scheduled flow will not translate into a physical flow on the grid. Power won't flow from the French generator all the way to the German consumer across the respective grids and the border.

### DEFINITION

**Transit flow:** power that physically passes through a third zone that neither scheduled nor requested it.

Electricity does not follow instructions. It follows the path of least resistance. It distributes itself across all available conductors according to the laws of physics, between ingestions (generation) and extractions (consumption) of power. This means that a commercial flow scheduled between two zones can physically materialize through a third zone entirely, as a transit flow that neither market participants nor grid operators explicitly requested.

The figure below illustrates this with a concrete example. Imagine a generator in France bidding a sell order on the market for 100 MW that is matched with a buy order of a German consumer. The scheduled commercial flow will be 100 MW from France to Germany. But in reality, the majority of that electricity might actually flow through Belgium and the Netherlands despite these grids not having scheduled flows. Physics distributes the flow across all available paths regardless of what the market has scheduled.

This distinction has a direct consequence for anyone trying to anticipate congestion: a border can be congested on the market while the physical line is running below its limit, and vice versa.

## 46%

of hours, physical and scheduled flows were more than 1 GW apart

## 12%

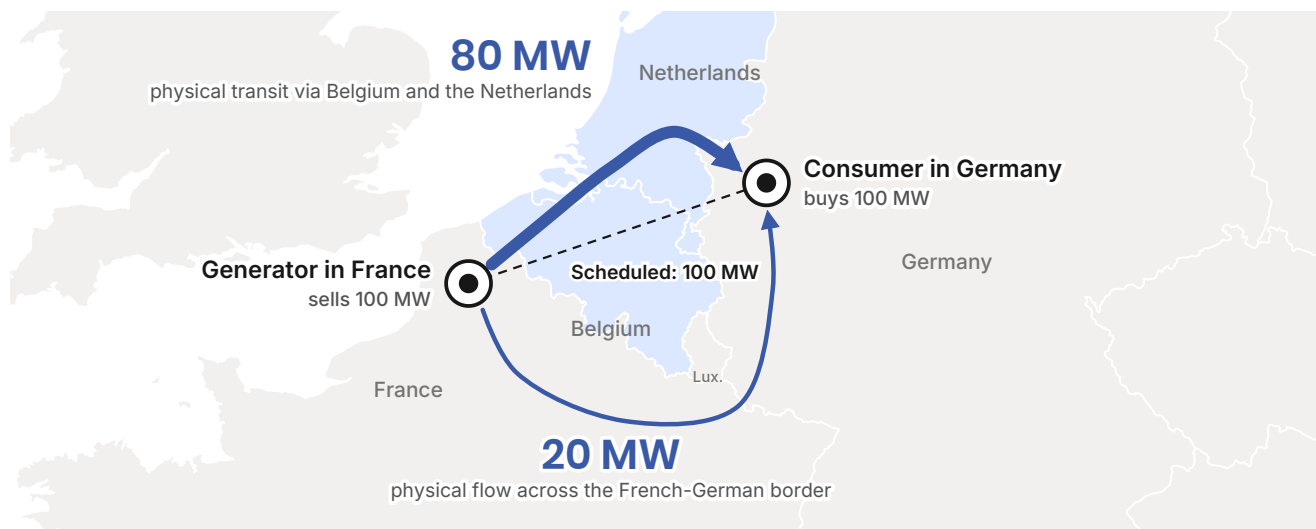
of hours, they pointed in opposite directions

On the border between France and Germany, the physical net flow and the total scheduled commercial flow, as an outcome of the day-ahead and intraday markets, have differed considerably in 2026. The absolute difference between the net flow and the total scheduled commercial flow has exceeded 1 GW 46% of the time. This represents roughly a third of the interconnector capacity. The differences not only apply to the magnitude but also to the direction of these flows. Physical net flows have had the opposite direction of scheduled commercial flows 12% of hours so far in 2026.

It can be tempting to compare a physical flow with either a market capacity or a physical limit, to anticipate congestion risk on the market. But it produces misleading conclusions. The signals belong to different realities and need to be interpreted separately, according to the specificities of each border. Next, we introduce a framework for doing exactly that.

## Exhibit 4: A trade scheduled from France to Germany mostly flows through Belgium and the Netherlands

Scheduled commercial flow vs physical flow for a 100 MW trade



----- Scheduled by the market: 100 MW France → Germany

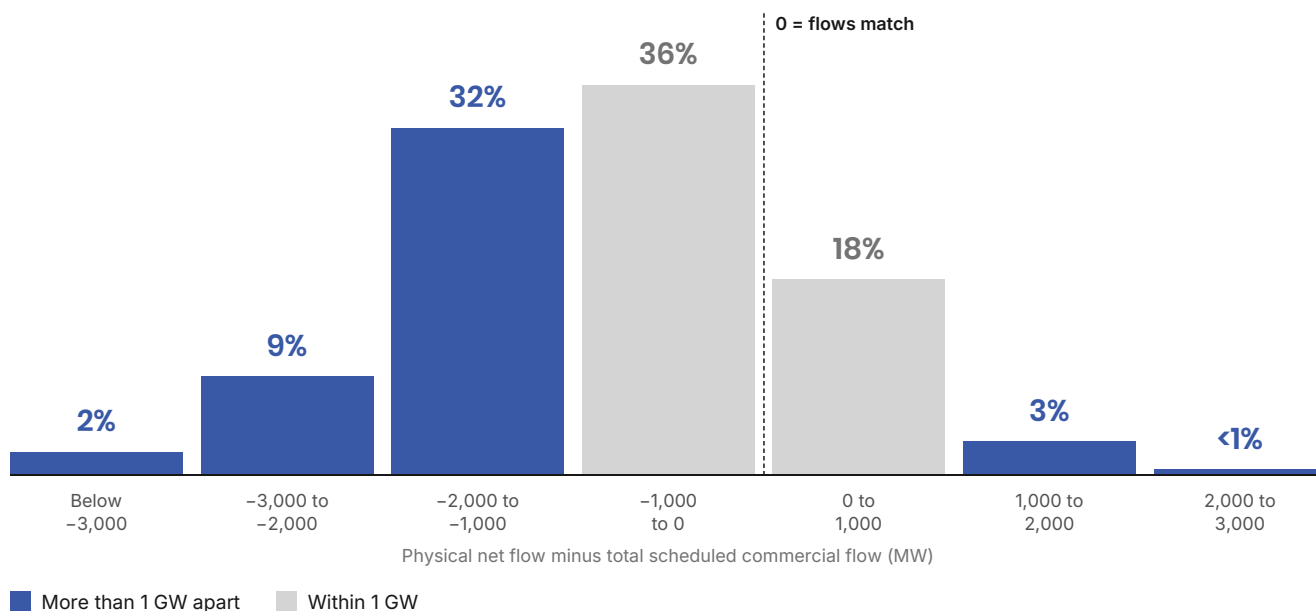
— Physical flow: follows every available path

Light blue Transit zones with no scheduled flow

Source: Illustrative example by Electricity Maps.

## Exhibit 5: Physical and scheduled flows differed by more than 1 GW in 46% of hours

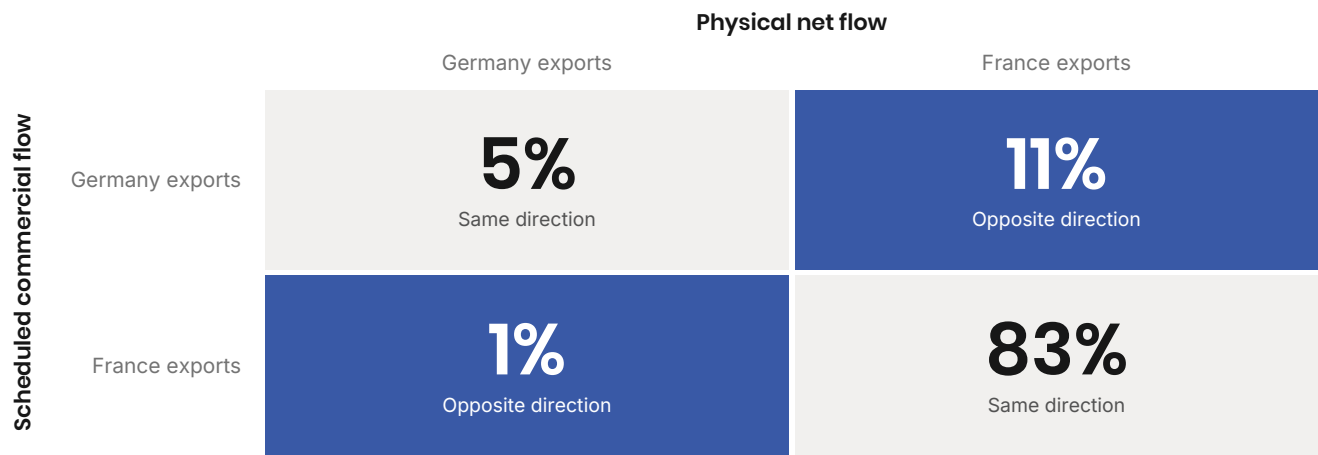
France–Germany border, May 2026. Share of hours by difference between physical and scheduled flow



Source: Electricity Maps analysis.

**Exhibit 6: Physical and scheduled flows pointed in opposite directions in 12% of hours**

France–Germany border, 2026. Direction of physical net flow vs total scheduled commercial flow, share of hours



Source: Electricity Maps analysis.

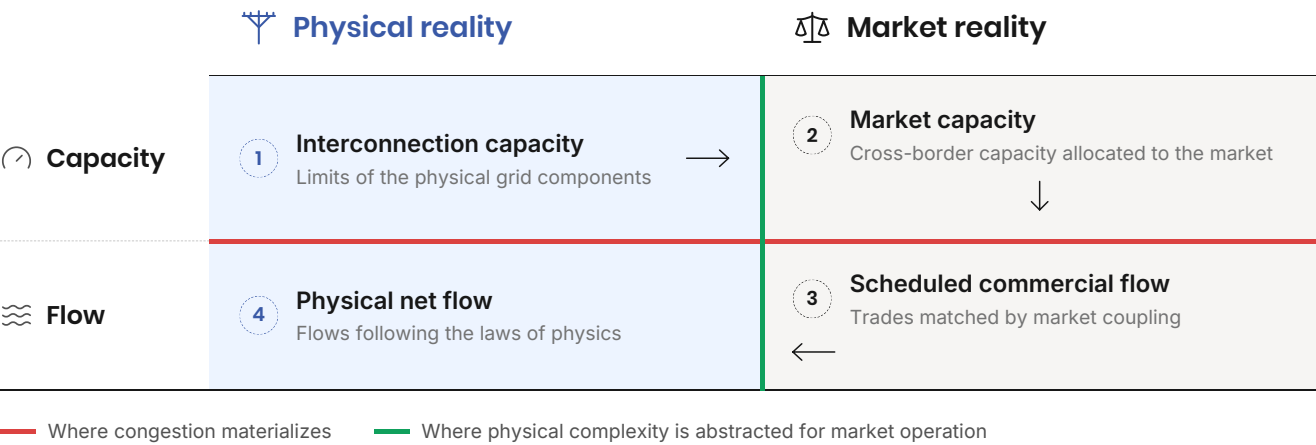
# Framework for interpreting interconnector signals

Two dimensions matter for any interconnector signal. The first is which reality it belongs to: market or physical. The second is what it measures: capacity or flow. Capacity describes how much electricity can move through the interconnector. Flow describes how much electricity is actually moving through it.

These two dimensions give us a matrix with four quadrants, each containing a distinct category of signal.

## Exhibit 7: Every interconnector signal sits in one of four quadrants

Signals by reality (physical or market) and by what they measure (capacity or flow)



Source: Electricity Maps analysis.

At the start of everything, there is a capacity linked to the limitations of physical components on the grid. This is a physical capacity. To operate markets at maximum efficiency, cross-border capacity is allocated to markets as part of market coupling. This is a market capacity. The market is solved, incorporating cross-border capacity constraints. It matches generators and consumers from different grids producing scheduled commercial flows. These are market flows. Ultimately, injections and withdrawals occur on the grid, creating flows according to the laws of physics. These flows are physical flows.

The framework makes two things immediately clear. First, congestion means different things depending on which side you are working on. Physical congestion occurs when the physical flow reaches the interconnector's physical capacity. Market congestion occurs when the market flow reaches the market capacity. These are separate events, and one can happen without the other.

Second, and more practically, comparing signals across diagonals will not give you a reliable understanding of any congestion risk. A physical flow compared against a market capacity is not a meaningful ratio. The signals need to be interpreted within their own reality.

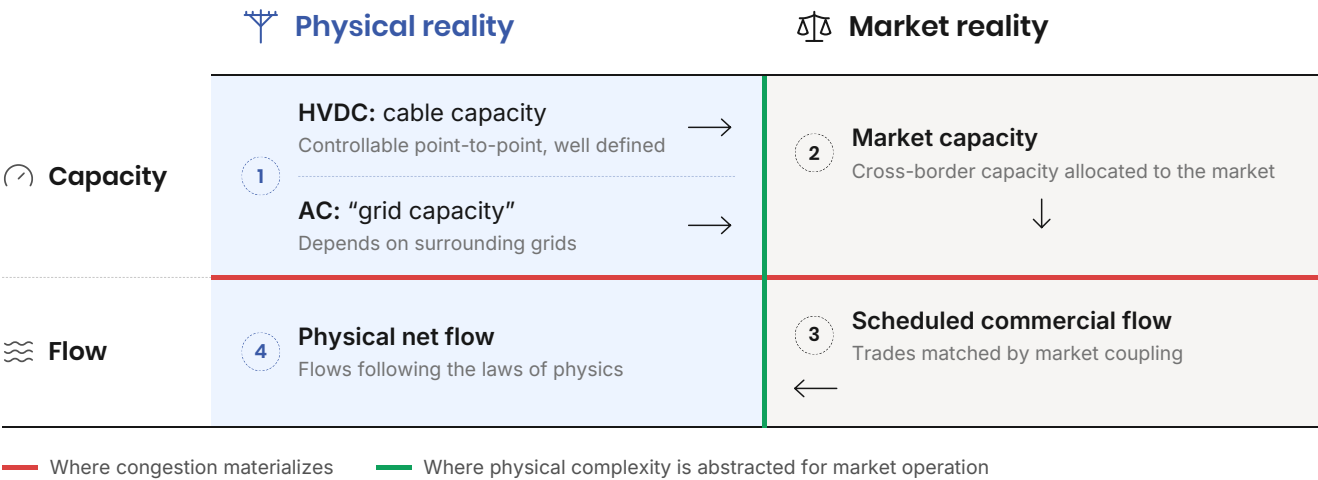
As introduced earlier, though, physical capacity means different things for different borders, and can be a challenging concept for most European borders. Thus, the framework becomes:

DEFINITION

**Physical vs market congestion:** physical flow reaching physical capacity, versus market flow reaching market capacity. Separate events.

### Exhibit 8: Physical capacity depends on the type of interconnection

Well defined for HVDC links, but not for borders within a meshed AC grid



Source: Electricity Maps analysis.

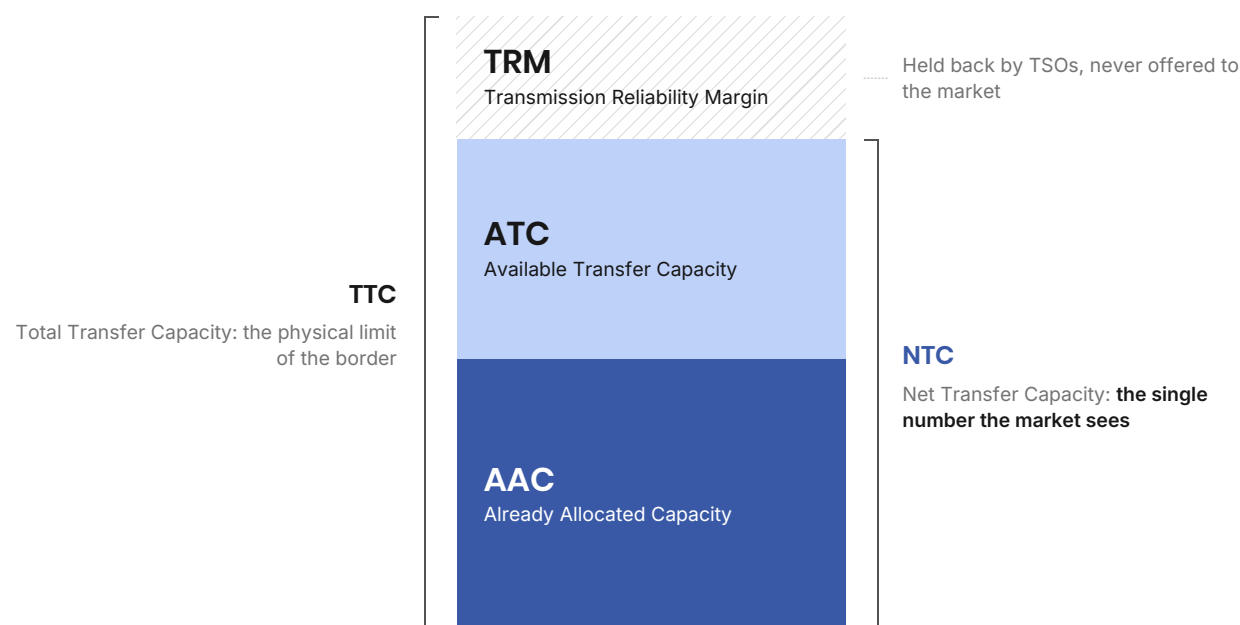
The complexity of defining a physical capacity for most European borders also translates into how capacity is allocated to markets. The next section works through that complexity.

# The flow-based methodology

The easiest methodology (from an external perspective) to manage cross-border capacity allocation for power markets is Coordinated Net Transfer Capacity (CNTC). Each border is assigned a single number: the maximum amount of electricity that can be traded across that border without pushing the physical grid beyond safe operating limits. It is called the Net Transfer Capacity (NTC). Transmission System Operators (TSOs) calculate these numbers conservatively to ensure that whatever market outcome verifies this NTC constraint, the physical grid remains within safe operating limits. Several markets exist, and the cross-border capacity already used by other markets defines the Available Transfer Capacity (ATC) that remains.

## Exhibit 9: Under CNTC, each border gets a single capacity number

How the capacity of one border is split under coordinated net transfer capacity



$$TTC - TRM = NTC \quad NTC - AAC = ATC$$

Source: Illustrative proportions, Electricity Maps.

TTC = Total Transfer Capacity, TRM = Transmission Reliability Margin, NTC = Net Transfer Capacity, AAC = Already Allocated Capacity, ATC = Available Transfer Capacity.

But this methodology actually hides how complex the physical grid is. It overlooks the fact that some borders can't be assigned a single capacity figure. Managing cross-border capacity with CNTC offloads the management of this complexity to TSOs rather than the markets. But it also forces an underutilization of interconnectors, as the calculation must remain conservative.

The flow-based methodology does just that: it exposes more of the grid's complexity to the market coupling, to enable better utilization of interconnections. The diagram below illustrates this progression: from a full, detailed grid model on one end, through flow-based, to the simplified CNTC representation on the other. Flow-based sits between the two, more accurate than using NTC figures and more tractable than modelling every line in the grid. The practical result is that more combinations of cross-border trades become possible because the market is working with a richer picture of what the grid can actually handle.

### Exhibit 10: Capacity calculation simplifies the physical grid for the market

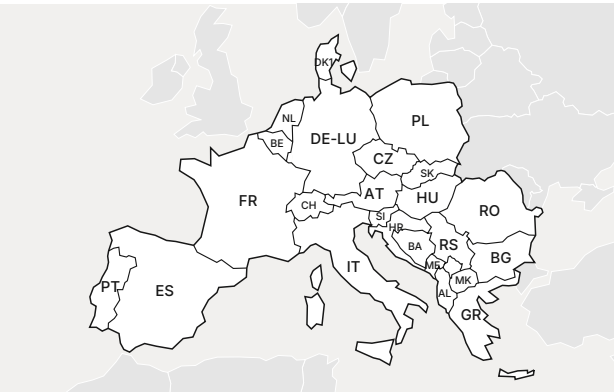
Methodologies range from a detailed grid model to a single capacity number per border

 **The physical world**



Thousands of lines and substations

 **The commercial world**



Bidding zones and cross-border capacities



Source: ENTSO-E grid map of Continental Europe (2024); Electricity Maps analysis. Bidding zones simplified to national borders.

Today, flow-based methodology is used for a large and growing share of European borders for capacity allocation on the day-ahead market. For intraday markets, this is also becoming a reality, with a phased roll-out for borders of the Core region (introduced below) from 2024. For market participants, this matters because intraday trading will increasingly be governed by the same capacity constraints as the day-ahead market, rather than a separate and simpler system. The signals introduced in the next section will become relevant across more trading timeframes as that rollout progresses.

# Market capacity under a flow-based methodology

With the CNTC, anticipating market congestion is quite straightforward. Each border is assigned an NTC, of which a certain ATC is left after already committed trades. As trades are made and scheduled commercial flows reach the NTC (and ATC falls to zero), the border becomes congested (on the market), and prices on either side of the border diverge. One number, one threshold.

With the flow-based methodology, that single NTC is replaced by a set of network constraints directly translated into constraints for the market solving algorithm. Instead of asking "is the scheduled flow exceeding the ATC?", the market coupling algorithm asks "does this combination of cross-border trades keep every critical network element within its safe operating limit?" This is more representative of the grid reality, though anticipating congestion becomes more complex.

The constraints the algorithm works with combine:

- **Critical Network Elements (CNE):** grid elements (power lines or transformers) that are most sensitive to cross-border flows. When a CNE reaches its limit, it constrains the trades that the market can schedule across borders. A CNE is monitored under the assumption that a different element has failed (called N-1 contingency) to ensure the grid remains secure and resilient. In that framing, it is called a Critical Network Element and Contingency (CNEC).
- **Power Transfer Distribution Factors (PTDF):** a set of coefficients that describe how much a given cross-border trade affects the physical flow on each CNE. PTDFs are what link commercial trading decisions to physical grid behaviour.
- **Remaining Available Margin (RAM):** the capacity left on a CNE after accounting for existing flows and security margins. RAM is what the market has left to work with on each critical element.

Together, CNECs, PTDFs, and RAMs define the feasible space of cross-border trades. The market coupling algorithm searches for the most efficient outcome that respects constraints defined by RAM and PTDF on each CNE.

There is no single ATC in a flow-based system: capacity is defined as a set of network constraints. Some proxy signals express border capacity as a single figure, but they remain imperfect approximations in a flow-based context:

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## DEFINITION

**N-1 contingency:** a grid element is monitored assuming another element has already failed.

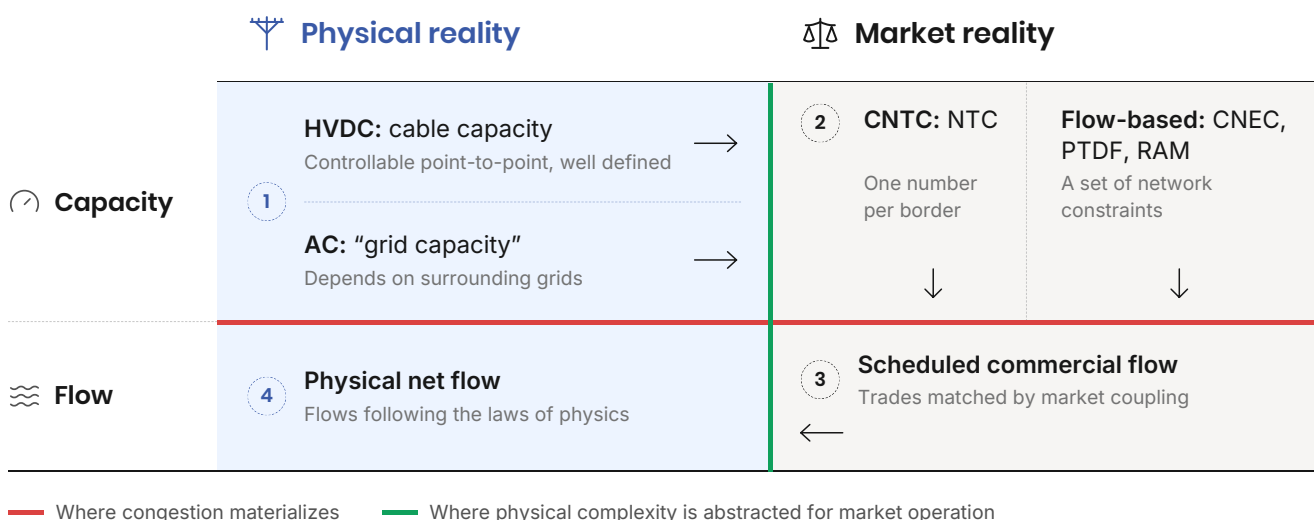
- **Shadow ATC:** a fallback capacity value used in shadow auctions, which are day-ahead explicit auctions run when the flow-based market coupling fails. Shadow ATC approximates what an ATC would have been for that border.
- **Maximum Bilateral Exchange (MaxBex):** the maximum trade possible within the flow-based domain between two bidding zones, assuming no other cross-border exchanges take place. It gives an upper bound on bilateral trading capacity before any CNE hits its limit.

These are approximations, not replacements for the full flow-based picture.

Our framework now becomes:

## Exhibit 11: Market capacity depends on the capacity calculation methodology

A single number under CNTC, a set of network constraints under flow-based



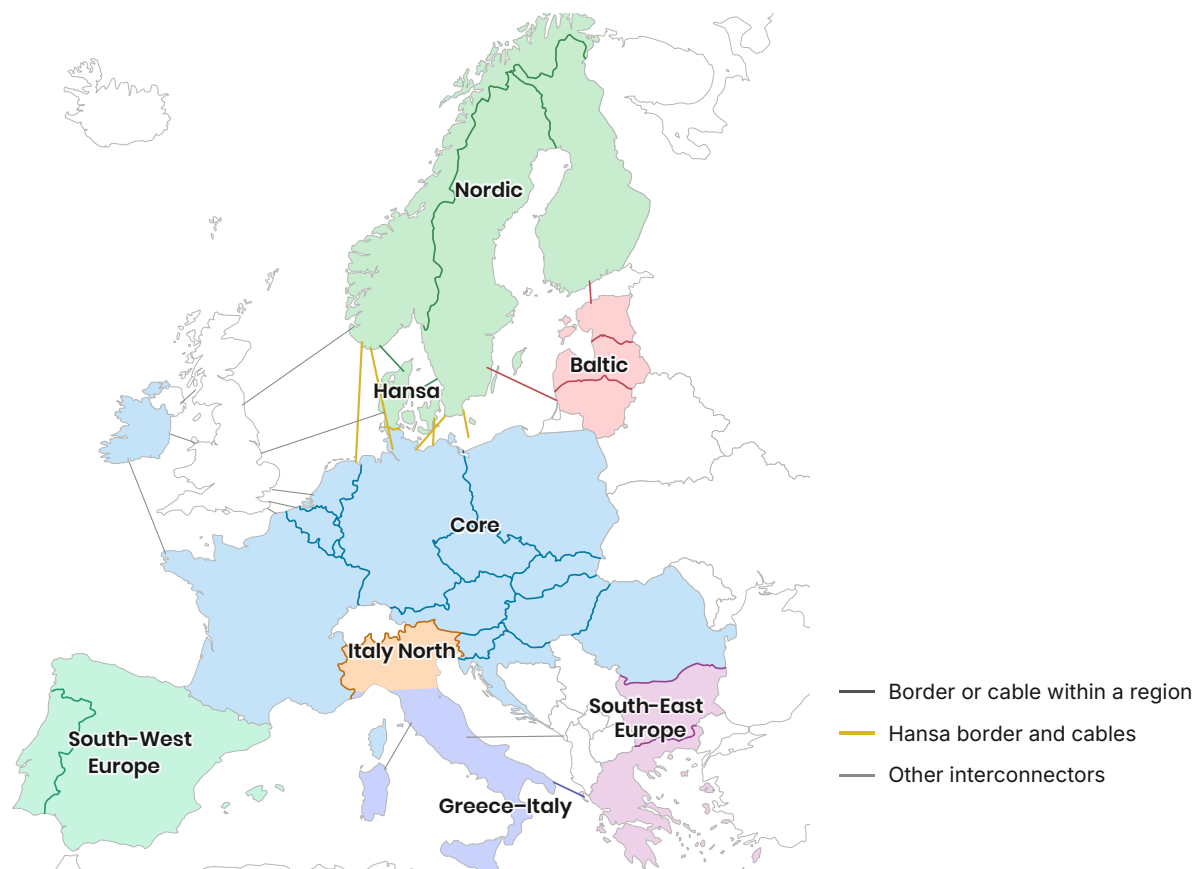
Source: Electricity Maps analysis.

# Navigating complexity from one border to the next

The flow-based methodology is not applied uniformly across Europe. Cross-border capacity is calculated within defined regions called capacity calculation regions (CCRs), each of which uses a specific methodology. The SDAC spans multiple CCRs, which means it combines both flow-based and coordinated NTC approaches within the same pan-European auction.

## Exhibit 12: Cross-border capacity is calculated region by region

Capacity calculation regions (CCRs) in the European power system



Source: ENTSO-E; Electricity Maps analysis. Approximate rendering of regions and cable routes.

## 2015

first flow-based capacity calculation in Europe, extended to the Nordic CCR in 2024

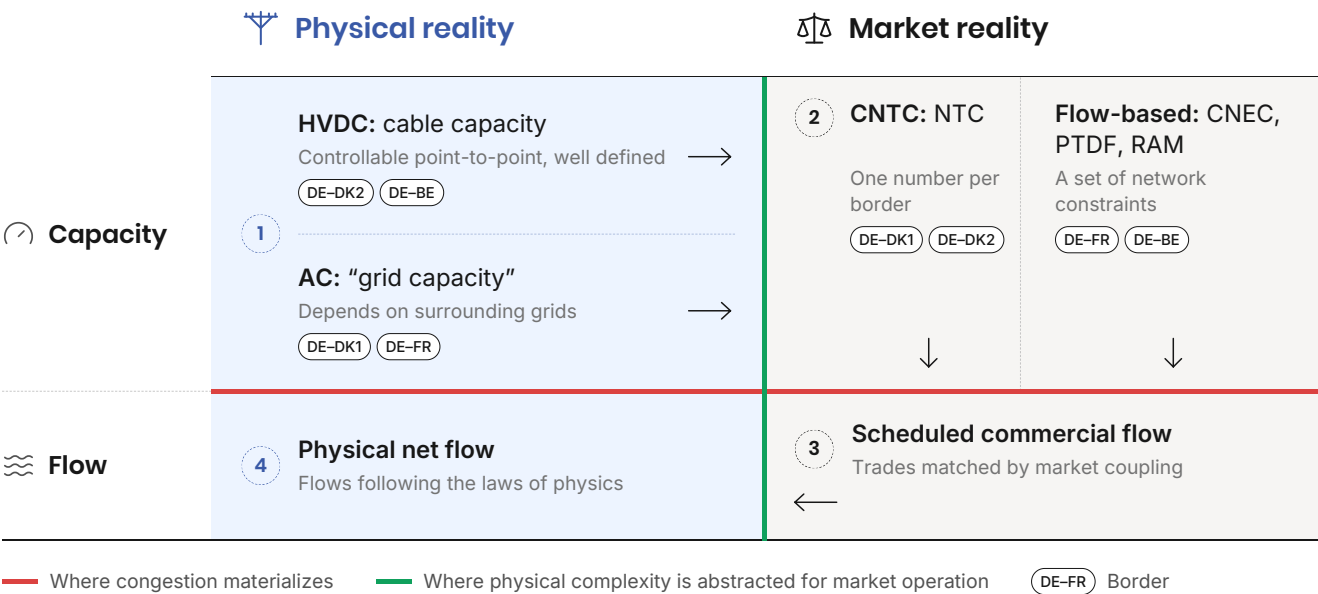
Flow-based capacity calculation was first introduced in Europe in 2015, initially covering Belgium, the Netherlands, France, and Germany. It has since been extended to the Core CCR, which covers most of central Europe and is shown in the map above. The Nordic CCR adopted flow-based calculations in 2024. Outside these two regions, coordinated NTC remains the methodology in use.

The practical consequence is that a single bidding zone can have borders governed by different methodologies. Germany is a clear example. It has several borders that fall within the Hansa CCR and use NTC, such as borders with DK-DK1, DK-DK2, SE-SE4, and NO-NO2. It also has several borders that are part of the Core CCR and thus use a flow-based methodology. This is the case for its borders with France, the Netherlands, and Poland, for example. A market participant trading across German borders cannot apply the same analytical approach to every border.

This is what makes it genuinely difficult to build an interconnector offering that anticipates congestion across every European border. You need to know which methodology applies to each specific border you are interested in, and interpret the available signals accordingly. Furthermore, a border linked with an HVDC can be governed by either the CNTC or flow-based methodology. The same applies to a border linked with AC.

**Exhibit 13: Each border combines an interconnection type with a capacity methodology**

Applicable capacity signals on four German borders



Source: Electricity Maps analysis.

# Electricity Maps' novel offering for anticipating interconnectors' congestion

Equipped with these learnings, Electricity Maps just introduced a new offering for power traders and analysts trading day-ahead and intraday spreads across European borders, to help them anticipate congestion on power grids and power markets. It builds on our historical, real-time, and forecasted net flow data by adding market and physical signals on both the capacity and flow dimensions.

All of these signals provide value in the following ways. Historical data helps derive insights and intuition to create novel trading strategies. It is also used as a feature in our flows and market price forecasts to make more accurate predictions. Real-time data gives market participants more references to monitor power grids and power markets. Forecasts help participants anticipate market behaviour and trade power accordingly.

Reach out to Julien Lavalley for early access to these signals. We're building this in the open and want input from the traders who'll benefit from it most.

CONTACT  
Early access: [julien.lavalley@electricitymaps.com](mailto:julien.lavalley@electricitymaps.com)

## Exhibit 14: Which signals are available depends on the type of border

Capacity and flow signals by interconnection type and capacity calculation methodology

|                                                                                                             |            | ⤵ Capacity                   | 🌊 Flow                                           |
|-------------------------------------------------------------------------------------------------------------|------------|------------------------------|--------------------------------------------------|
|  <b>Physical reality</b> | AC         | –                            | Physical net flow                                |
|                                                                                                             | HVDC       | Nominal capacity             | Physical net flow                                |
|  <b>Market reality</b>   | CNTC       | NTC, ATC                     | Day-ahead scheduled flow<br>Total scheduled flow |
|                                                                                                             | Flow-based | Shadow ATC, MaxBex, MaxBFlow | Day-ahead scheduled flow<br>Total scheduled flow |

Source: Electricity Maps analysis.

# The world's most comprehensive electricity data platform

Grid forecasts for power markets



## ABOUT ELECTRICITY MAPS

Electricity Maps provides global access to electricity mix, prices, load, and cross-border flows: real-time, historical and forecasted.

In 2026, we released **GridCast**, our forecasting engine that provides market predictions to power market participants. GridCast forecasts market fundamentals, prices, and soon congestion.

## CONTACT

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