APPENDIX ON CROSS-BORDER EXCHANGE CAPACITIES

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28/10/2022

1. INTRODUCTION

Belgium's central location in Europe means that the country's import and export capabilities are defined following the principles of flow-based capacity calculation and capacity allocation within market coupling, as introduced by the European guideline on Capacity Allocation & Congestion Management (CACM), hereafter referred to as the 'FB CACM' [ENT-1]. In the FB CACM, Belgium's net position is linked to the net position of the other countries in the Core region and to the flow-based domain which defines the possibilities for energy exchanges between those countries. It is only by replicating the functioning of the electricity market that adequacy and economic indicators can be accurately calculated. The flow-based method makes it possible to properly take into account interactions between market outcomes and the transmission grid. In the market simulations performed for this study, the commercial exchange capacities are modelled in three different ways, as outlined below.

- **For exchanges** between two countries **outside the Core region**, fixed bilateral exchange capacities (also called NTC – Net Transfer Capacities - as described in Section 2) is applied.
- **For exchanges between the Core region and bidding zones outside the Core region**, fixed bilateral exchange capacities are used. A flow-based modelling (also known as 'Advanced Hybrid Coupling'- AHC) is applied from 2025 onwards. Prior to that date, the links are treated in a similar way to the first category. More information can be found in Section 3;
- **For exchanges** taking place **inside the Core region,** the flow-based methodology (described in Section 4) is applied.

2. NTC MODELLING BETWEEN TWO NON-CORE COUNTRIES

The commercial exchange capacities between non-Core countries is modelled using 'Net Transfer Capacities' (NTC), corresponding to fixed maximal possible commercial exchange capacities between two bidding zones.

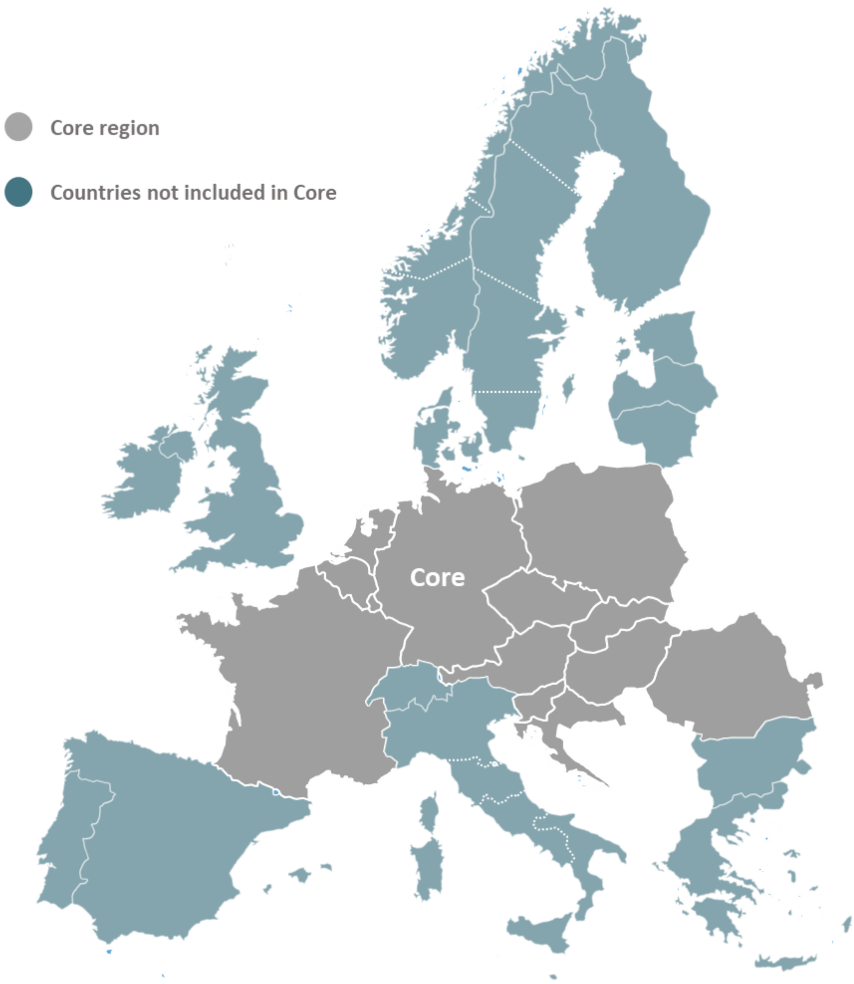

Figure 1 - Core region where flow based modelling is applied

3. TREATMENT OF EXTERNAL FLOWS: EXCHANGES BETWEEN CORE AND NON-CORE COUNTRIES

3.1. SHC & AHC for non-Channel borders to Core

External flows are flows in the Core grid which are induced by exchanges across bidding zone borders that do not belong to the Core region. As an example, the Nemo Link straddles such a border. External flows can be linked to the flow-based region in one of two ways:

- through **Standard Hybrid Coupling** (SHC) where a capacity margin is reserved on all Critical Network Element and Contingencies (CNECs) to accommodate for the external flows prior to flow-based market coupling;
- **Advanced Hybrid Coupling** (AHC) where the external flow is part of the flow-based optimisation variables.

Generally, this means that SHC grants priority access to these external flows into the meshed AC transmission grid of the Core Capacity Calculation Region (Core CCR) by means of the above mentioned reserved capacity margin. Under AHC, however, these external power flows are treated on an equal footing as power flows created by commercial exchanges between Core bidding zones. This results the flow-based domain calculation and allocation becoming more complex as any external border considered in AHC will add an extra dimension to the flow-based domains. AHC introduces a major conceptual and methodological change; under SHC, the impact of the external exchanges as an external flow through each CNEC is reserved from the capacity margin of the CNEC (hence the Remaing Available Margin or RAM of the CNEC is reduced to account for this external flow). However, under AHC, those external flows are considered explicitly as a degree of freedom of the flow-based domain. The difference is illustrated in the Figure 2, which highlights the impact of the AHC modelling since incorporates new dimensions resulting hence in a visually larger flow-based domain.

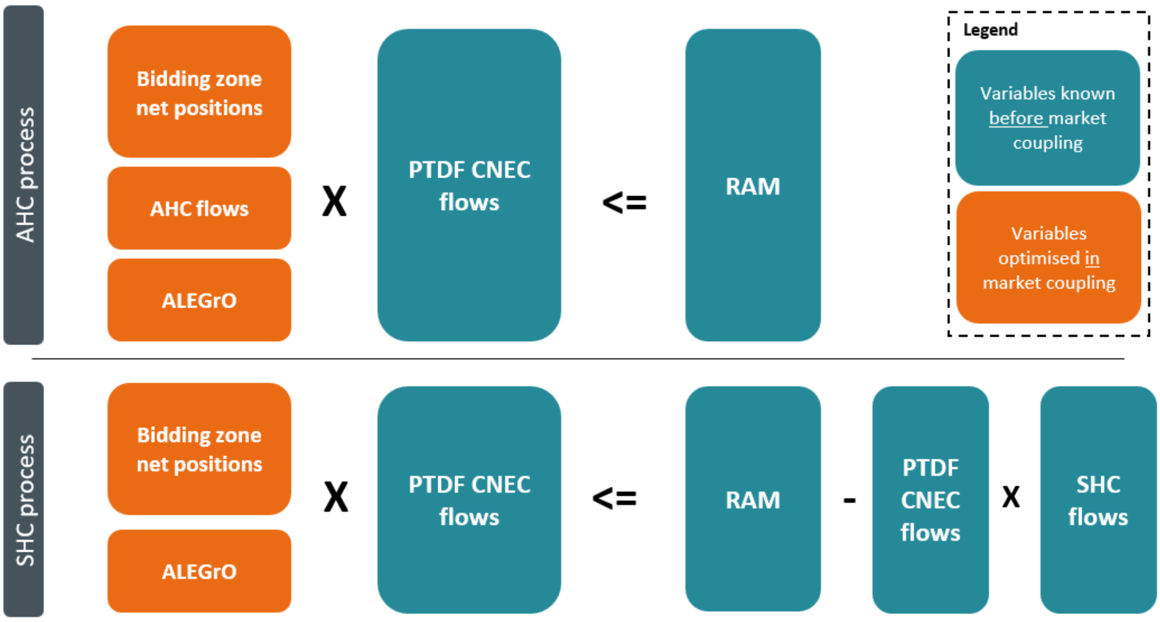

Figure 2 Handling of external flows: AHC vs SHC

The target model for the Core-CCM states:

"[Art 13 of Core CCM] '*Core TSOs shall take the impact [..of electricity exchanges outside the Core CCR..] into account with a standard hybrid coupling (SHC) and where possible also with an advanced hybrid coupling (AHC)*' ".

Although the flow-based market coupling was launched in the CORE region in June 2022, AHC is not expected to be fully operational in 2025 and hence to be used as from the year 2025-26. Note that SHC flows are considered commercial flows, and therefore are a part of the 70% minRAM that has to be offered to the market. In other words, the minRAM rule has to be applied on CNECs before the RAM is later further reduced to account for SHC flows, *i.e.* minRAM is applied in SHC on the RAM + the SHC flows component.

3.2. Treatment of Channel interconnectors

Due to the withdrawal of the United Kingdom from the European Union, the United Kingdom, more appropriately the Great-Britain (bidding zone), no longer participates, since 1 January 2021, to the SDAC / SIDC and in general to the IEM [see Ref 17 of REF CREG MR 2021].

Section 5.1.3 "Post-Brexit trading arrangements with the United Kingdom" (page 53) of the Belgian Regulator (CREG) Monitoring Report 2021 [REF CREG MR 2021]) mentions that as a result, capacities on the Nemo Link interconnector (between the Belgian and Great Britain bidding zones) are no longer allocated in an implicit manner and instead, market participants trading electricity between both bidding zones, need to follow an explicit allocation process.

Also as mentioned by CREG in its report, such explicit allocation clearly brings disadvantages and may increase significantly the inefficiencies in the allocated flows. Within such explicit allocation, market parties will have to forecast the price delta between the concerned bidding zones themselves first and then based on its own estimate, 'allocate' the capacity:

- In case of big spreads the allocated flow direction will likely be right, then only the forecast value might be wrong (higher/lower)
- But if spreads are small (~around 0), then it will even be difficult to also forecast the right flow direction and hence exchanges could be nominated & allocated against the actual market spread.

While these observations by the CREG refer to the Nemo Link interconnector, the same inefficiencies and 'wrong' nominations are to be expected for all interconnectors between IEM bidding zones and Great Britain (Nemo Link, IFA1-2, BritNed, North Sea Link, etc...)

Therefore the modelling of all these interconnectors will be adapted in this study to consider in the best possible way the change from implicit to "explicit allocation".

3.3. External (allocation) constraint

Currently within the Core CCM [REF Core CCM], Belgium, Poland and the Netherlands are allowed to use external constraints also referred sometimes as allocation constraints. These are additional constraints in the flowbased market coupling that are not related to line overloading but to other effects (such as steady state or dynamic voltage issues).

External constraints are expressed as a limitation on the Core net position. This practice is applied currently by the Netherlands.

Allocation constraints are expressed as a limitation on the global net position. This practice is applied currently by Belgium (in the import direction) and Poland (both import and export direction).

There exist also external constraints related to the DE-BE HVDC interconnector ALEGrO. These external constraints are of a different nature i.e. they describe the 1000 MW technical capacity of the interconnector and are ignored in the main simulations in this study.

In this context, Belgium allocation constraint is expected to evolve:

— Since the go-live of ALEGrO end 2020, a maximum import of 6500 MW is allowed;

— After the commissioning of additional shunt capacitors within the 'Voltage Control II' program, expected by Q1 2023, this limit can be further increased to 7500 MW;

— Furthermore, the commissioning of these shunt capacitors seems to allow an increase of the allocation constraint to 8.000MW or even 9.000MW in 2024. Therefore the assumption in this study is to assume that no allocation constraint is needed for Belgium after 2024.

— In case it is observed that the maximal simultaneous import in the simulations is systematically much higher than 9.000MW, sensitivities including the effect of an allocation constraint of around 9.000MW could be considered.

Finally, Poland used to have a fixed allocation import / export constraint on its global net position of:

— Maximum import: 2000 MW

— Maximum export: 3000 MW

This allocation constraint is now a dynamic one, thus no longer fixed to the import/export values of 2000/3000MW. The values to be used in this study will be derived from analysis of the monthly statistics reported in the JAO Publication Tool [REF JAO PUBL TOOL] regarding this dynamic allocation constraint for Poland.

Furthermore, the Netherlands has an import / export external constraint on its Core net position, which upon consulting Tennet can be set as:

— Maximum import: 6500 MW

— Maximum export: 6500 MW

4. FLOW-BASED METHODOLOGY

Information about the flow-based rules and methodologies are available by consulting the Capacity Calculation Regions webpage of ENTSO-E [CCR-1].

4.1. Flow-based operational process

The flow-based method implemented on the day-ahead market coupling uses Power Transfer Distribution Factors (PTDFs) that make the modelling of real flows through the physical network lines possible.

For each hour of the year, the impact of energy exchanges on each Critical Network Element (also called critical 'branch' in the past) taking into account the N-1 criterion is calculated (see later in this section the explanation on the N-1 criterion). The combination of Critical Network Elements and Contingencies (CNECs) forms the basis of the flow-based calculation.

A reliability margin on each CNEC is considered and, where appropriate, 'remedial actions' are also taken into account. These actions can be taken preventively, or after an outage has occurred, to partly relieve the loading of the concerned critical network element. Those actions make possible to maximise exchanges thanks to changes in the topology of the grid or by the use of phase shifting transformers.

This procedure finally leads to constraints which form a domain of safe possible energy exchanges between the 'flow-based' countries within the relevant Capacity Calculation Region (CCR) under consideration (this is called the flow-based domain).

Different assumptions are made for the calculation of this domain, such as the expected renewable generation, consumption, energy exchanges outside the CCR area, location of generation, outage of units and lines, etc.

For every hour there might be a different flow-based domain because:

- the topology of the grid can changes;
- outages or maintenance of grid elements can be present;

The operational calculation of the flow-based domain for a given day is started two days before real-time operation and is used to define the limits of energy exchange between countries for the day-ahead market.

The N-1 security criterion for the grid

Interconnection capacity takes into account the margins that transmission system operators (TSOs) must maintain in order to follow the European rules ensuring the security of supply. A line or grid element can be lost at any time. The remaining lines must be able to cope with the changes in electricity flow due to any such outage. In technical terms, this is called the N-1 rule: for a given number N of lines that are transmitting a given amount of energy, there cannot be an overloaded line in case of the outage of one of the lines. This is important to avoid that a chain reaction arises and, by extension, the network stability of the entire European network can be endangered. The flow-based domain calculation process therefore accounts for the N-1 principle.

Note however, that European rules stipulate that this criterion must be fulfilled at each moment, including in the event of maintenance or repair works. In such cases, it is possible that interconnection capacity available for exchanges will have to be reduced. Wherever possible, maintenance and repair works are avoided during the most critical periods, e.g. around the peak consumption times of the year, but cannot be ruled out, especially after winter weather conditions.

4.2. Flow-based adaptation in the simulation

The bidding zones act as 'copper plates' from a market perspective. Within a bidding zone the market price is the same for all market participants (the 'copper plate assumption' entails unlimited transmission capacities within the zone). A higher resolution is required in order to simulate the internal flows and consequently assess the loop flows. A finer grid resolution is provided by 'small zones', subsets of the bidding zones which also serve as copper plates. An initial simulation involving these small zones is required in order to take account of the loop flows caused by internal exchanges (between small zones).

Finally, due to the extra complexity arising from the large number of constraints induced by the modelling of flow-based in this adequacy study, the complexity of the problem must be reduced to a level that is solvable in due time by today's computers. This whole process will be detailed further in the sections below.

4.3. Calculation of PTDFs

The first step is the calculation of PTDF factors within a given FB geographical area (network parameters and topology are defined).

The PTDF factors estimate (the increase of) the flow that can be expected in the different Critical Network Elements as a function of a position change of a bidding zone, controllable device.

Let's assume the simplified grid example below:

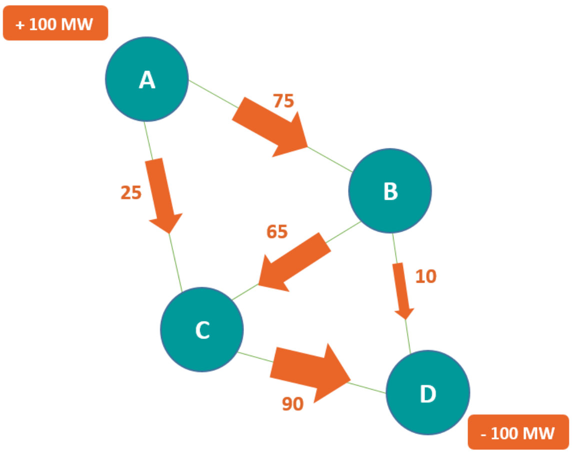

Figure 3 Representation of a nodal system and distribution flows

For example, if an exchange from Node A to Node D of 100 MW occurs, the PTDF factors could be:

- 75% of the injection in Node A goes to Node B and 25% of the injection in Node A goes to Node C;
- 65% of the injection from Node A goes from Node B to Node C and 10% of the injection from Node A goes from Node B to Node D;
- Finally the portion of the total injection in Node A passing through Node C is 25% + 65% = 90%, going to Node D.

The PTDFs thus indicate how the energy flows are (unevenly) distributed over the different paths between the different nodes of the network when the *X* MW injection/extraction occurs at two points of the network. The distribution given by the PTDFs is determined both by the topology of the grid and the technical characteristics (impedances) of the grid.
It should be noted that PTDF's are calculated for the flows over the grid elements in N state as well as when grid contingencies occur.

The PTDFs are represented as a matrix which is computed based on a reference grid model for the targeted time horizon. A PTDF matrix consists of lines/rows representing the different CNEC's that are taken into account, and columns representing the variables in the flow-based domain. Each CNEC refers to the combination of a Critical Network Element and a Contingency. The variables can represent the net positions of the market nodes under consideration, the HVDC flows, PST positions, etc.; depending on the degrees of freedom of the market coupling algorithm, *e.g.* whether Standard Hybrid Coupling (SHC) or Advanced Hybrid Coupling (AHC), etc... Aside from a PTDF matrix, the flow-based framework also requires the capacity of each Critical Network Element. These capacities correspond to the steady-state seasonal ratings of the network elements.

4.4. Calculation of zonal PTDFs from nodal PTDFs: applying GSKs

Bidding zones are zones where all generation and consumption within a given zone have the same wholesale price, hence one 'zonal' PTDF should be defined for the entire zone. Therefore, a mapping is needed between the market 'zonal' level and the grid 'nodal' level, in order to define those 'zonal' PTDFs. In the example below an illustration between the nodal and zonal representation is provided.

A 'zonal PTDF' is needed in order to calculate the effect that a commercial exchange between two market zones, will have on any grid element. The calculation of 'zonal PTDFs' from 'nodal PTDFs' is based on the so-called 'generation shift keys' (GSKs). With this GSK, the nodal PTDF can be converted into a 'zonal PTDF' by assuming that the bidding zone net position is spread among its nodes according to the GSK. Therefore a 'zonal PTDF' is the sum of all 'nodal PTDFs' weighted by their nodal GSK. Below an illustration (Figure 4) of this relation between 'zonal PTDFs', 'nodal PTDFs' and GSKs is provided.

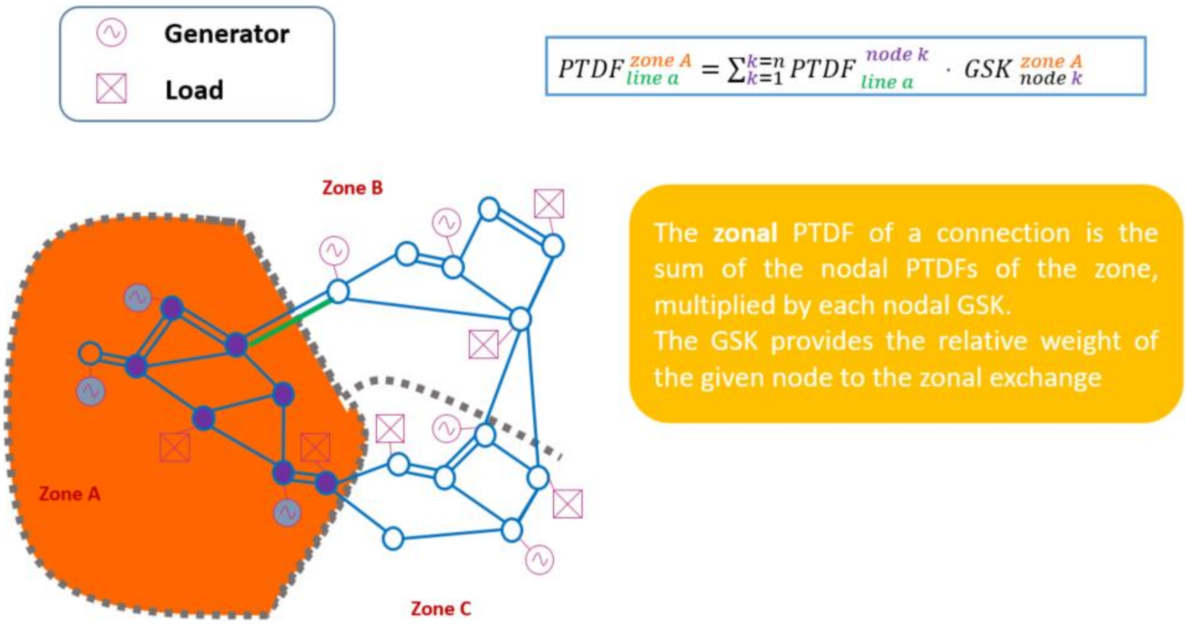

Figure 4 : Calculation of zonal PTDFs applying GSKs

Within each zone, the GSK can be defined as:

$$GSK_{Zone,Node} = \frac{P^{Nominal}_{Z,N}}{\sum_{N\in Z} P^{Nominal}_{Z,N}}$$

where $\sum_{N\in Z} P^{Nominal}_{Z,N} = NGC^{Z}$ is equal to the installed capacity within the corresponding zone Z and $P^{Nominal}_{Z,N}$ is equal to the installed capacity connected to the node N within zone Z.

These 'pro-rata distribution keys' are an important assumption for the calculation of the zonal PTDFs since, they fix the geographical distribution of generation units per type T at each node N with respect the total installed capacity per type for the given network topology. GSKs therefore define the weight of each of the nodal PTDFs in the definition of zonal PTDFs.

4.5. Calculating the initial loading of each CNEC

The notion of the initial loading of each CNEC is related to the so-called 'Reference Flow' (F_{ref}) in the operational Flow-based framework. The 'Reference Flow' (F_{ref}) is the physical flow computed from the common 2-Days Ahead Congestion Forecast (D2CF) base case and reflects the loading of the Critical Network Elements given the exchange programs of the chosen reference day, thus given the 'likely market direction' according to D2CF.

The 2-Days Ahead Congestion Forecast (D2CF) which is provided by each of the participating TSOs in the capacity calculation process for their grid, provides the best estimate of the state of the CCR (currently CWE) electric system for day D. This D2CF forecast provides an estimation of:

- the Net Exchange program between the zones;
- the exchanges expected through DC cables;
- planned grid outages, including tie-lines and the topology of the grid as foreseen for D+2;
- forecasted load and its pattern;
- forecasted renewable energy generation, e.g. wind and solar generation;
- outages of generating units, based on the latest generator availability info.

As it will be presented below, the flow-based methodology followed here replicates this principle when calculating the initial loading of each CNEC.

For each CNEC, a procedure is followed to calculate the Remaining Available Margin (RAM) (see Figure 5), which is the physical capacity on the CNEC that can be used by the market coupling algorithm to accommodate cross-border exchanges, and which is defined as follows:

$$\mathrm{RAM} = F_{max} - (FRM + F_i)$$
$$\text{with } \mathrm{F_i} = \mathrm{F_{Ref}} - \sum_j \mathrm{PTDF_j} \cdot \mathrm{NP_j}$$

- F_{ref} = Reference flow over the network element in the base grid model where cross-border exchanges are still present;
- NP_j = Net position (Balance) of Bidding Zone "j" inside the CCR (eg CORE) in the Reference situation;
- $PTDF_j$ = Zonal PTDF of bidding zone "j" for the considered CNEC branch "i";
- F_i = Flow over the network element "i" when cross-border exchanges within the CCR (e.g. CORE) are cancelled;
- FRM = Flow Reliability Margin, used by TSOs to account for the uncertainty due to forecast errors.
- F_{max} = The maximal allowable physical flow over the concerned CNEC branch "i" in order to comply with operational and thermal – structural limits.

An important factor determining the final RAM is therefore the 'initial flow' F_i, reflecting the flow over the network element when all zones within the CCR (e.g. CORE) are at zero balance. This flow therefore includes:

- the flows resulting from internal exchanges in the Bidding Zone where the CNEC is located (mostly relevant for CNEC's within a Bidding Zone, but much less important for cross-border (XB) CNECs;
- the flows resulting from internal exchanges in other Bidding Zones than the one where the CNEC is located (loop flows).

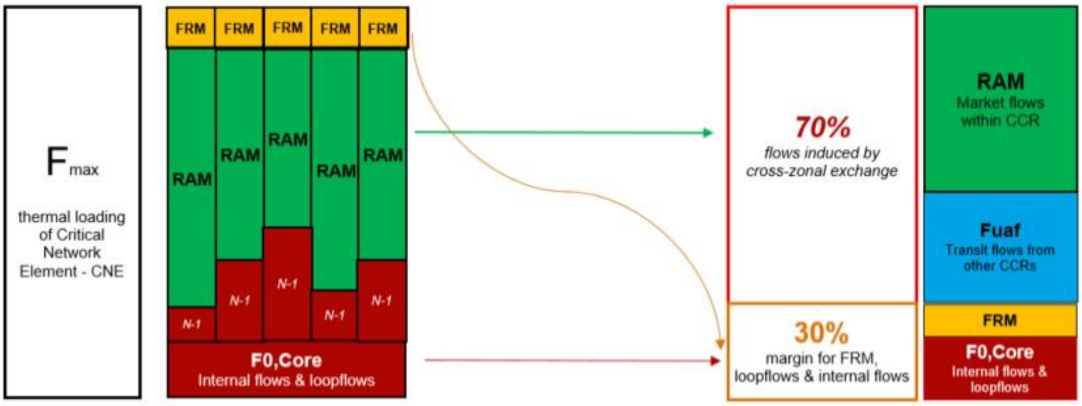

Figure 5 : Definition of Remaining Available Margin (RAM)

European legislation requires a minimum capacity of each critical network element (margin) to be made available to the market (minRAM) (See Figure 5). For this reason, every time a CNEC's margin after preloading is less than the required minimum margin given to the market, the minimum margin is enforced.

BOX 1 minRAM, derogations and action plans

Up to the end of 2019, a 20% minRAM requirement was in place in the CWE flow-based area. This minRAM relates to the minimum share of the CNEC's thermal capacity which has to be **offered to the market for CWE exchanges.**

Since the beginning of 2020, the 'Clean Energy for all Europeans Package' has been in effect. As a consequence, a 70% minRAM now has to be offered to the market for **any commercial exchange.** Countries are not expected to apply this minRAM change overnight; the package outlines 2 options: installing a national action plan or applying for a derogation. However, from 31/12/2025 onwards, the 70% minRAM requirement has to be applied rigorously to all CNECs. In addition, countries with an action plan have to meet a linear increase in their minRAM targets on the road to 70%.

4.6. Calculating the FB capacity domain

4.6.1. 2-dimensional flow-based domain

Figure 6 shows how the FB domain can be determined by combining the calculated remaining available margins (RAMs) and the zonal PTDFs for each relevant Critical Network Element and Contingency (CNEC) pair. The first constraint is determined for line 1, in a situation without contingencies. We draw from the table that the CNEC has a RAM of 150 MW, a zonal PTDF for zone A of -30%, for zone B of 25% and for zone C of 10%. The same exercise is now performed for all other lines and contingency pairs, ultimately resulting in a collection of constraints (RAM, PTDFA, PTDFB, PTDFC).

These constraints can be understood as geometrical planes in the dimensions defined by the balances of the difference zones: Balance(A), Balance(B), Balance(C), etc. For the purpose of illustration, the constraints can be plotted between two balances as the projection of these planes, so they reduce to lines. Figure 6 depicts such projection for Balance (A) vs Balance (B), where the constraints are represented by the grey dotted lines. Generally the convention is used where positive balances represent net exports and negative balances represent net imports.

As a final step, the total set of constraints can be reduced by removing all non-relevant constraints. Constraints are considered non-relevant when other constraints are always reached earlier. This procedure is also called 'pre-solving' the domain, and leads to the final combination of relevant constraints forming the secure domain, colored in yellow. Under perfect foresight conditions, every combination of secure exchanges between all different zones is part of this domain.

Critical network elements	Incident	Remaining Available Margin (MW)	Influence of the exchange on each line (PTDF)		
			A	B	C
Line 1	No incident	150	-30%	25%	10%
	Incident 1	120	-17%	35%	-18%
	Incident 2	100	15%	30%	12%
Line 2	No incident	150	60%	25%	25%
	Incident 3	50	4%	-15%	4%
Line 3	No incident	...	...	...	...
	Incident 4	...	...	...	...

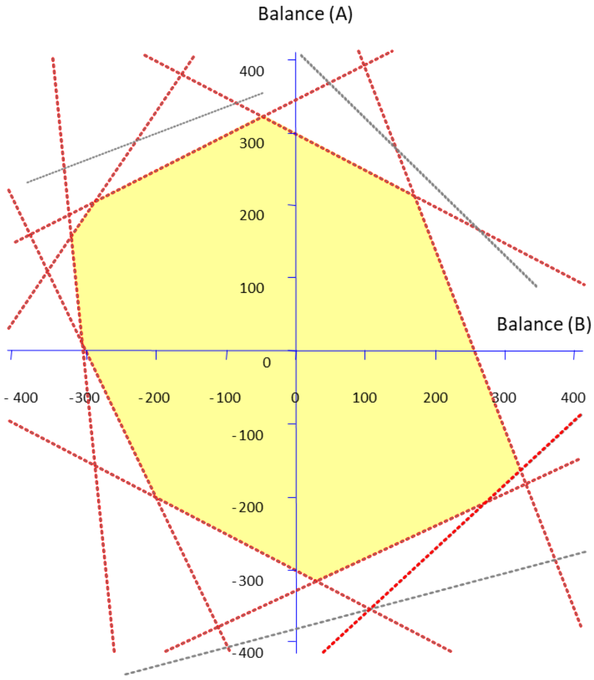

Figure 6 : Initial FB capacity domain calculation

4.6.2. Understanding 2-dimensional flow-based domain representations

The example of the previous subsections has been done for a region containing 2 countries, i.e. two dimensions, particular case of the study carried out. The flow-based domains used are polytopes having up to 44 dimensions. For a better understanding of the domains, a two-dimensional representation is used. This representation is to be seen as a projection of the higher-dimensional domain onto a two-dimensional plane.

To obtain this, first the domain polytope which is described by its planes is converted into its vertices. Then these vertices are projected onto the desired plane. A convex hull of these points, which can be seen as the smallest convex polytope which contains all points (or more graphically: the polygon you get when you wrap shrink wrap around all points) is then calculated. All points which are not on the convex hull are omitted. Figure 7 shows a theoretical example of such a projection [SCA-1]. Note that not all vertices are part of the convex hull.

The resulting 2-dimensional representation of the flow-based domain should be interpreted as follows: '*for any point within the 2-dimensional domain, for which the net positions of 2 countries can be read from the axes, a combination of net positions for the dimensions that are not depicted exists so that this point can be attained*'.

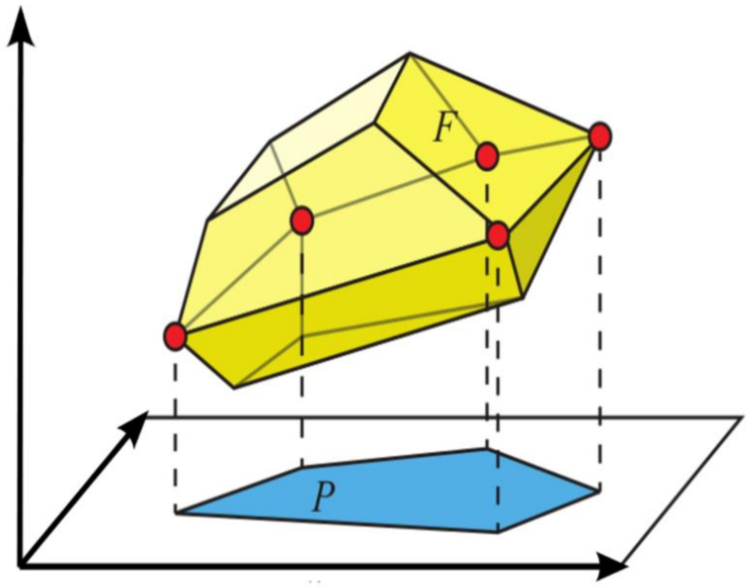

Figure 7 : Flow-based domain: 2D projection

Usually, the Belgian adequacy situation is closely related to French security of supply, it is preferable to show a projection of the flow-based domain onto the Belgium-France plane. By convention, export is depicted as positive, whereas import is negative. A positive net position thus means a net export position towards CORE.

In SHC, all flow-based domain representations only depict Core balances, as opposed to bidding zone balances. Hence, the import possibilities of Core countries from outside Core are not shown. In the ANTARES model used in this study for the SHC simulations, as well as in the day-ahead market coupling, France can for example import from other countries within the limits of the NTC constraints on the concerned borders.

For Belgium, this distinction is important as the Nemo Link HVDC interconnector is not part of Core and as mentioned above, its allocation is now through an "explicit" process before the implicit auctions of the market coupling algorithm. Two effects will be therefore visible in SHC and/or "explicit allocation":

- Maximum import cannot be depicted on the two-dimensional domain representation. Depending on the actual net position of Nemo Link, the Belgian Core balance can, vary between (max import -1000 MW) and (max import +1000 MW) corresponding to maximum import and maximum export over Nemo respectively;
- Belgium can even have a positive Core balance in times of scarcity, yet still have a net import position. In these situations, a positive Core balance is offset by a greater import flow over Nemo Link, resulting in a global importing position for Belgium.

It is worth to notice that these two points, specially the second one, could be more pronounced in the "explicit" allocation case, which in turn could lead to inefficient allocation of the flows through Nemo Link in times of scarcity.

5. Flow-based parameters

A number of parameters must be defined in order to create a flow-based domain. These parameters will be detailed in the next subsections.

5.1. CNEC selection for flow-based

The CNEC selection defines what lines from the common grid model can be taken into account in the calculation of the flow-based domain.

In CWE flow-based, the 5% PTDF rule (meaning the CNE is at least 5% sensitive to a net position change of any of the CCR bidding zones) has been typically used as threshold for the determination of CNECs. Similarly, since the go-live of CORE flow-based, the default 5% threshold is still considered. 18 months after the go-live of Core (from end 2023 onwards) and once the target model is expected to be operational, a different threshold might be considered.

The target model for Core flow-based is to have only cross-border CNE's limit the market. However, if a TSO can prove that it is more beneficial, from an economical point of view, to incorporate an internal CNE into the flow-based calculation, rather than perform extra RD, perform a bidding zone split or introduce network investments, this internal CNE could be allowed as a market constraint within the CNEC list. In addition, a recent decision of the European court puts into question the way the cross border capacities are calculated for the market exchanges. Such decision can impact the ability to import and export capacities of the different market zones [EU-JUST].

5.2. Controllable devices

5.2.1. Use of PSTs in capacity calculation

A cross-border PST is a controllable device, which can redistribute cross-border flows. In the context of CEP, TSO's can first use PST's to optimize loopflows to comply to minRAM requirements. If after this initial PST setpoint, some taps of the PST range are still unused, these PST flexibility can still be given to the market for further economic optimization (welfare maximization).

In the capacity calculation phase, that part of the range of the PST that can be optimized to increase the domain in the likely market direction is defined per PST.

5.2.2. HVDC in capacity allocation

Similarly to a PST, an HVDC is a controllable device that can redistribute cross-border and internal flows. Again, both loopflow optimization and welfare maximization are possible uses of an HVDC. For the latter, in the capacity calculation phase, the setpoint of the HVDC can be optimized to increase the domain in the likely market direction. Currently, there are no cross-border HVDC's that are optimized this way in capacity calculation. Here the market will determine its setpoint in order to optimize welfare at capacity allocation. ALEGrO is the only cross-border HVDC within the Core CCR and will be optimized in the capacity allocation. No other cross-border HVDC's are scheduled in Core until 2030.

6. Flow-based for Core countries

Flow-based capacity calculation is a complex process involving many parameters. Multiple approaches are possible when building market models where market exchanges adhere to the rules depicted in a flow-based coupled market. For short-term forecasts and analyses, a framework using the flow-based domains calculated within the SPAIC process was developed [SPA-1]. However, this framework relies heavily on historical data, and becomes more complex and less accurate when multiple parameters and inputs are expected to change between the historical flow-based data preparation and the targeted time horizon. It is also not possible to take major evolutions into account (such as AHC, the extension of the capacity calculation region (CCR) or the minRAM requirements) within this approach. Elia therefore developed a flow-based framework which does not rely on historical data; instead, it aims to mimic the operational flow-based capacity calculation workflow, for which the required inputs are forecasted for the targeted time horizon. One of the key advantages of using such a method is that it enables the modelling of several planned evolutions such as AHC and the impact of minRAM requirements on the domains.

BOX 2 Flow-based perimeter

The perimeter defines the zone in which flow-based market coupling (FBMC) is in effect. In 2015, the first European flow-based market coupling was established in the CWE region (BE+DE/LU/AT+FR+NL).

In 2018, the Germany-Luxembourg-Austria bidding zone was split into separate Germany-Luxembourg and Austria bidding zones. In 2020, the flow-based perimeter contained 5 bidding zones: BE+DE/LU+FR+NL+AT.

In June 2022, FBMC was implemented in the Core region.

The best way of incorporating Switzerland's grid limitations into the Core flow-based capacity calculation is currently being explored; it is likely to be implemented sometime between 2023 and 2025.

Similarly, ACER has asked TSOs to analyse whether it seems logical to move the bidding zone borders between Europe and the UK from the Channel CCR into the Core CCR. Next, a merger between Core, HANSA & Italy North may be investigated. The outcome of all of these projects is still quite uncertain.

The best estimate that could therefore be applied in this study was to consider the flow-based perimeter to be equal to the Core CCR up to 2034.

7. Flow-based domain creation process

The flow-based framework developed for this study aims to mimic the currently applied operational framework as well as integrate the predicted flow-based evolutions. This process is illustrated in Figure 8 and further explained in the following paragraphs.

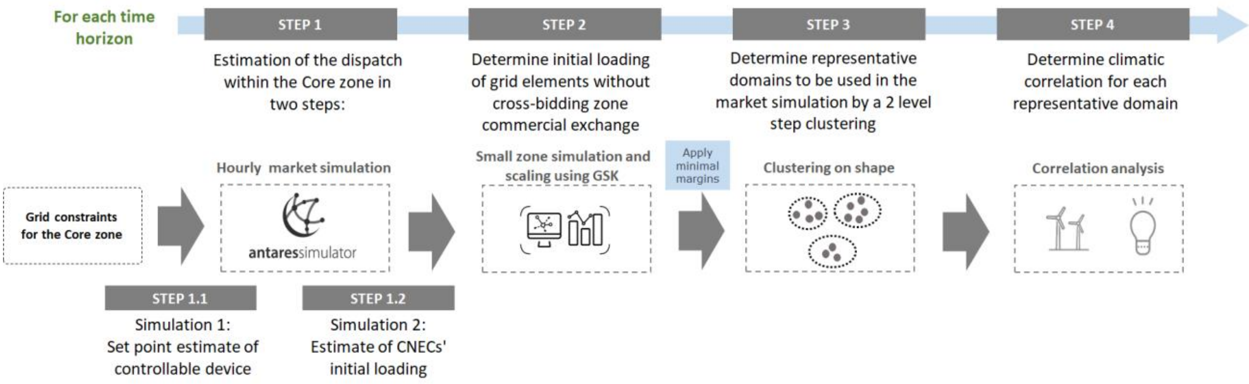

Figure 8 : Process for the development of the flow-based domains

When creating flow-based domains, the following assumption was made: no grid maintenance is planned throughout Europe in the winter periods. In other words, while the impact of single contingencies was taken into account through the CNEC definition process, it was assumed that prior to a contingency, the European transmission grid is always fully available and operational. For winter months (when focusing on the representation of scarcity events), this optimistic assumption was retained; for summer months, however, assuming that there wouldn't be any grid maintenance was deemed unrealistic. As a proxy for this reduced availability of the transmission grids, the domains generated for the summer months usually assume a specific percentage of fixed RAM applied to the available transmission grid. This approach does not impact the adequacy requirements calculated, as the stress situations occur during winter periods for Belgium.

1.1. Step 1 : Estimation of the dispatch

The first simulation, called 'flow estimation', aims to determine the set points of the different controllable devices, i.e. HVDCs and PSTs. This first run is crucial for grid feasibility.

The second run, or 'base case simulation' mimics the capacity allocation and congestion management (CACM) capacity calculation (CC) process and allows for a good estimation of the pre-loading on CNECs. Once fully set up, the flow-based framework performs an initial simulation to determine the initial loading of each CNEC. In general, around 1/2 of the PST tap ranges in Belgium and about 1/3 for other countries were used to optimise initial flows compared to their predefined set points in order to maximise the socioeconomic benefits of the system. The flows from this simulation determined the 'Reference Flows'.

1.2. Step 2 : Initial loading of grid elements

In a next step, combining geographical information on the location of load and generation within Core with the hourly market dispatch from STEP 1, the loadings of grid elements associated with the hourly commercial exchanges resulting from the market simulation in STEP 1 can be determined for each hour. For determining the market domain, initial loadings of grid elements in the absence of commercial exchanges are required. Using the bidding-zone GSK, the net position of each of the bidding zones is scaled to zero. Commercial exchanges between bidding zones are thus cancelled, and the remaining flow on grid elements equalled the initial loadings (loop flows and potentially some internal flows). The process used to scale the net positions of all bidding zones to zero is the same as the one used in flow-based operations today.

Such initial loadings could potentially pre-use a significant portion of the physical capacity of grid elements, and thereby restrict market operations. Since 1 January 2020, the 'Clean Energy for all Europeans Package' has been effective. It introduced specific requirements related to the availability of transmission capacity for market exchanges. To model the application of those rules for future time horizons, virtual minimal margins were applied to each grid element for determining the final hourly flow-based domains.

1.3. Step 3 : Creation of the domains

As the market simulation performed in STEP 1 creates an estimation of the dispatch and corresponding initial loadings within Core for each hour of the simulated year, this would result in 8,760 different flow-based domains. For the present study, the amount of flow-based domains was limited for each time horizon in order to obtain feasible computation times by reducing the complexity of the simulations.

1.3.1. Step 3.1 : Smart-Slicing

1.3.1.1. Smart-slicing : explanation

As the number of dimensions in the flow-based domain increases, so does the complexity. It becomes required to use simplifications in order to represent the flow-based domains in a human readable way e.g. by 2D projection.

Figure 9 illustrates the concept of smart slicing. The blue square represent a hyperplane that would cut the multi-dimensional polytope fixing hence the net positions of the other dimensions. Applying this so-called smart-slicing reduces the degree of freedom and results in the grey projections as 2D representations. Of course, the way the smart slicing is applied, i.e. which net position are chosen will visually affect the 2D representation. While building the flow-based domain, the net position chosen for the smart slicing were the ones from the market simulations at the precise hour considered.

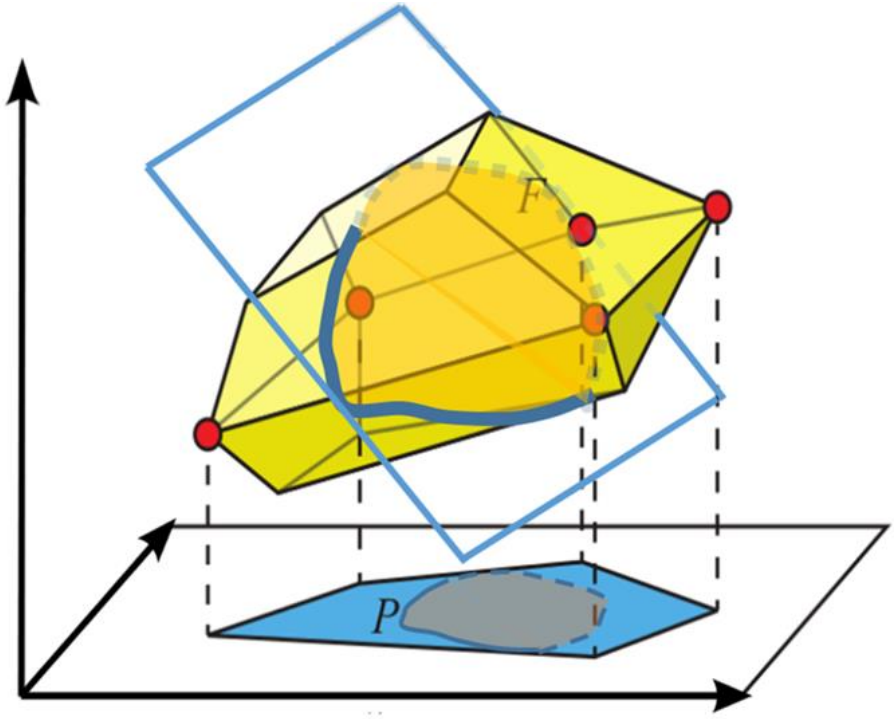

Figure 9 : Flow-based domain – Smart slicing

1.3.1.2. Use of smart-slicing

Smart-slicing can also be used for other purposes than visualization. Enumerating full-dimensional polytopes is impossible with the usual domain dimensionality (12 Core biding zones + ALEGrO + *(if applicable)* AHC dimensions). Nine dimensions (9D) were deemed most relevant to Belgian security of supply (CWE + ALEGrO + interconnectors BE-UK, NL-UK and FR-UK). The positions of the other dimensions were considered by the procedure of ‘smart slicing’ and thus fixed for each hour to the market simulation results obtained in STEP 2. Through 'smart slicing', the full dimensional polytope was then reduced to a 9D polytope describing the feasible net positions of these nine most relevant dimensions for Belgium. Vertices enumeration was then performed by considering these nine-dimensional polytopes at each hour.

1.3.2. Step 3.2 : Clustering of domains

Applying a clustering algorithm requires a metric that can be used to assess the similarity of domains. The clustering of the 8,760 domains is based on their geometrical shape by means of comparing the Euclidian distance between vertices. A pre-cluster data split is applied to reduce cluster group size and hence computational complexity whilst respecting time-related trends. In this split, summer and winter domains are separated, weekends and week days are separated, and within the week days the peak & off peak hours are separated as well. This resulted in the creation of 6 groups to be clustered individually.

Next, the number of centroids to retain are defined. For weekends, one centroid is calculated to represent the entire group, whereas for week days, per group, 2 clusters are created, each with its own centroid (see Figure 10). The clustering was performed by means of a k-medoid algorithm. Here the centroids were elements which were part of the initial domains, and therefore had physical meaning. This process was performed in two steps in order to be able to reduce the set and ultimately find the representative centroids.

The level 1 clustering produced a first set of medoids that were further refined in level 2 in order to reach the targeted number of clusters.

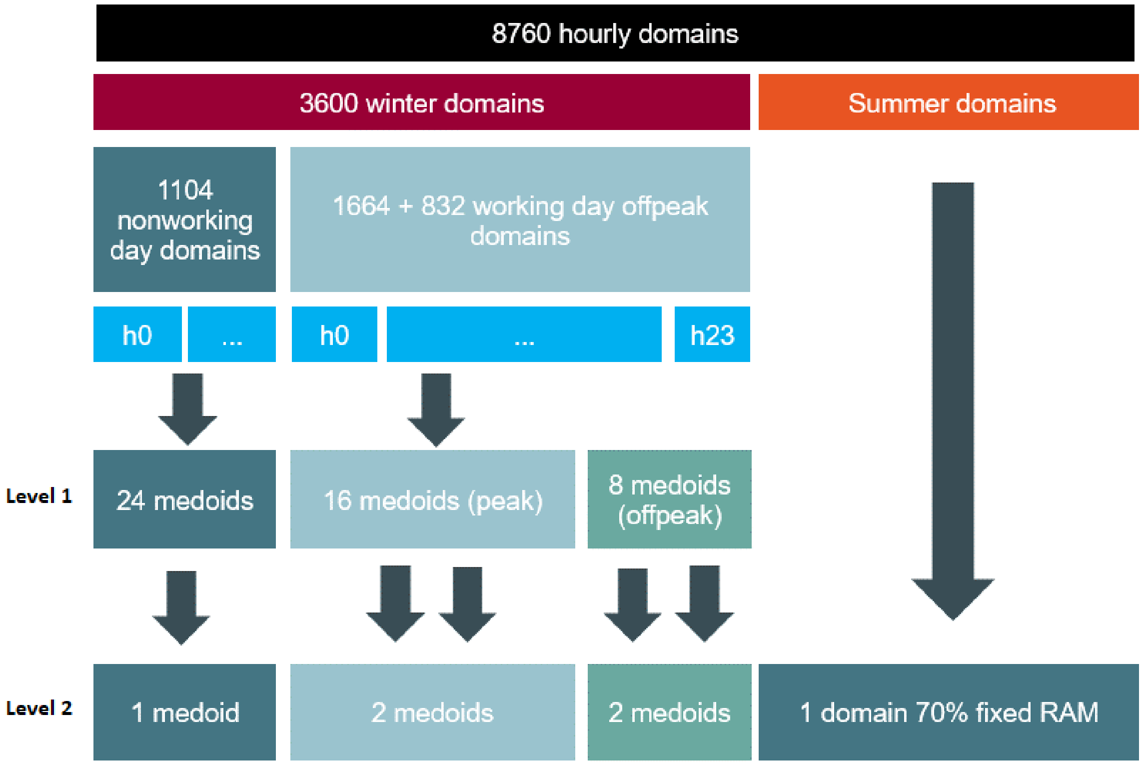

Figure 10 : Flow-based domain clustering process

1.3.3. Step 3.3 : Resizing and approximating the domains for computational efficiency

The domains are subsequently restored back to their full dimensions of 12 Core biding zones + ALEGrO + *(if applicable)* AHC dimensions prior to plugging them back into the ANTARES model. In general, the number of CNECs in the framework's domains is too large to be of practical use in market simulations.

A flow-based domain is defined by a certain number of inequality constraints representing the limits of critical network elements at a given time. Keeping the complexity at an acceptable level is key to successfully carry out the simulations. A simplification algorithm is therefore chosen based on the Manhattan distance of two hyperplanes. This step allowed the identification of the smallest set of CNECs that could be used to describe the entire domain, without any loss of quality or representativeness. Finally this set was kept as the PTDF-RAM linear constraints to be set into the model.

1.4. Step 4 : Incorporating multiple flow-based domains into adequacy assessment

The 'Monte Carlo' approach used in this study generated possible future states, called 'Monte Carlo' years. The method used for relating typical days to the climatic conditions as they occur in the 'Monte Carlo' years was developed by the French TSO RTE (see reference documents [ANT-1] and [ANT-2]), and was also implemented in RTE's adequacy study (*Bilan Prévisionnel* since 2017 [RTE-1]), as well as in the *Pentalateral Energy Forum - GAA 2020 Report* (PLEF 2020) and the MAF 2020 report [ENT-2].

This method can be understood as follows. The k-medoid algorithm not only selects the representative domains for each of the clusters, but also identifies for each day the cluster to which it belongs. Thus, for the climatic variables in scope, thresholds can be defined (typically at the 33rd and 66th percentiles) which lead to the creation of climatic groups. As such, it is possible to identify, for every day, the climatic group to which it belongs. By counting the amount of times a domain appears in a specific climatic group, it is possible to define a probability matrix. This matrix represents the probability of being in a given cluster of domains under certain climatic conditions. Using the climatic conditions encountered at a given hour in the model we can then map the clusters back to the hours in the model. It is this interpretation that is used when mapping the typical days onto the 'Monte Carlo' years.
This kind of systematic approach makes it possible to link specific combinations of climatic conditions expected in future target years, e.g. high/low wind infeeds in CWE (Germany, France, etc.) or high/low temperature and demand in France and Belgium, with the representative domains for these conditions.

2. Evolution of the flow-based methodology

Elia is a pioneer in the flow-based approach for adequacy studies, and has developed a methodology to model exchanges between countries in the capacity calculation region that replicates the day-ahead operation. Whereas in the first flow-based assessment of winter 2016-17 (the strategic reserve volume evaluation published end of 2015) only one domain was used to represent the entire winter. That domain was based on an historical situation. Since then, Elia has since improved its modelling by:

- adding more historical domains;
- relating the domains to the climatic variables in a systematic way;
- incorporating minRAM evolutions within those historical domains;
- correcting historical domains for historical grid outages;
- correcting historical domains for future grid upgrades;
- integrating the breakup of the DE-AT bidding zone on 1 October 2018;
- recalculating the domains to include the planned HTLS upgrade of the 380-kV Belgian backbone;
- modelling the ALEGrO interconnector, which provides additional freedom for the flow-based domain;
- adding the flow-estimation step in the process in which internal controllable elements' set points are estimated prior to simulating the FB process by mimicking the operational behaviour in D2CF;
- integrating the Advanced Hybrid Coupling (AHC) for any external border to the CCR considered (e.g. CORE).

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