METIS 2 - Technical Note T3

Power Transmission Module

METIS 2 Technical Notes
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1 ABBREVIATIONS AND DEFINITIONS

1.1 ABBREVIATIONS

Abbreviation	Definition
ACOPF	Alternative Current Optimal Power Flow
CC	Connected Component
CCGT	Combined Cycle Gas Turbine
DCLF	Direct Current Load Flow
DCOPF	Direct Current Optimal Power Flow
NP	Net Position
NTC	Net Transfer Capacity
OCGT	Open Cycle Gas Turbine
PATL	Permanent Admissible Transmission Limit
PTDF	Power Transfer Capacity Factor
PV	Photovoltaic
RAM	Remaining Available Margin
RES	Renewable Energy Sources
TATL	Temporary Admissible Transmission Limit
vRES	Variable RES

1.2 METIS CONFIGURATION

The configuration of the METIS model used to perform the transmission modelling in METIS 2 Studies is summarised in Table 1.

Table 1 - METIS Configuration

METIS Configuration	
Version	METIS v2.0 Beta (non-published)
Modules	Power system and transmission modules
Scenario	Study-specific
Time resolution	Hourly (8760 consecutive time-steps per year) for market model runs, and selection of snapshots for the transmission-level analysis
Spatial granularity	Member State (market) and grid-level (transmission)

2 INTRODUCTION TO THE TRANSMISSION MODULE

The decarbonisation of the European energy system is relying on a massive deployment of Renewable Energy Sources (RES) in the power system, in particular of solar PV and wind energy. The increase in renewable power generation results into several challenges, due to the specific characteristics of these sources.

A first well-known challenge is the balancing of the variability of RES on all timescales (from infra-hourly to seasonal timeframes), which requires an adequate deployment of flexibility solutions such as storage, demand response, flexible power plants, networks, etc.

A second challenge is linked to the fact that the transmission grid was initially designed to connect centralised generation systems based on thermal and hydro power plants with load centres and distribution grids dimensioned to ensure power supply meeting peak demand. Electricity networks were initially designed to absorb the flows coming from centralised production sources, and to dispatch large-scale power plants which are mostly thermal generation, nuclear and hydro power sources. The substantial deployment of decentralised renewable power generation technologies foreseen in all transition pathways will result in significant challenges in the way transmission networks are operated and planned for.

The design and configuration of the current transmission and distribution systems is therefore not fully adapted for a massive integration of RES: they can be subject to congestions – *a situation where power flows cannot be conveyed through the grid due to line overloads* - leading to curtailment of RES and requiring thermal generation based on fossil fuels to maintain the balance between load and generation. These *redispatch* and compensations measures have for example generated circa 1 billion euros of extra costs each year in Germany between 2017 and 2019.

The **transmission module** of METIS offers a better representation of the physics of electricity flows on the transmission grid, allowing to use a more precise representation of the European power systems when assessing the feasibility of integrating RES and studying the need for flexibility solutions. To achieve this, the transmission module includes two different elements:

- The first component consists in an explicit representation of the physics of the power flows in the transmission network, detailed more precisely in the Section 3.1.

- The second component is a complement to the zonal modelling existing in METIS which allows for a more complex representation of the exchanges between neighbouring countries to be used, via a "flow-based" representation of interconnection capacities between zones. This extension of the zonal model is detailed in Section 3.2.

In summary, the transmission grid models included into METIS have the purpose to extend the scope of power system modelling from a pure market-based approach to a more holistic assessment, integrating the transmission grid dimension. Transmission grid modelling is carried out by applying three different models, each of them pursuing a different objective and implementing a specific approach.

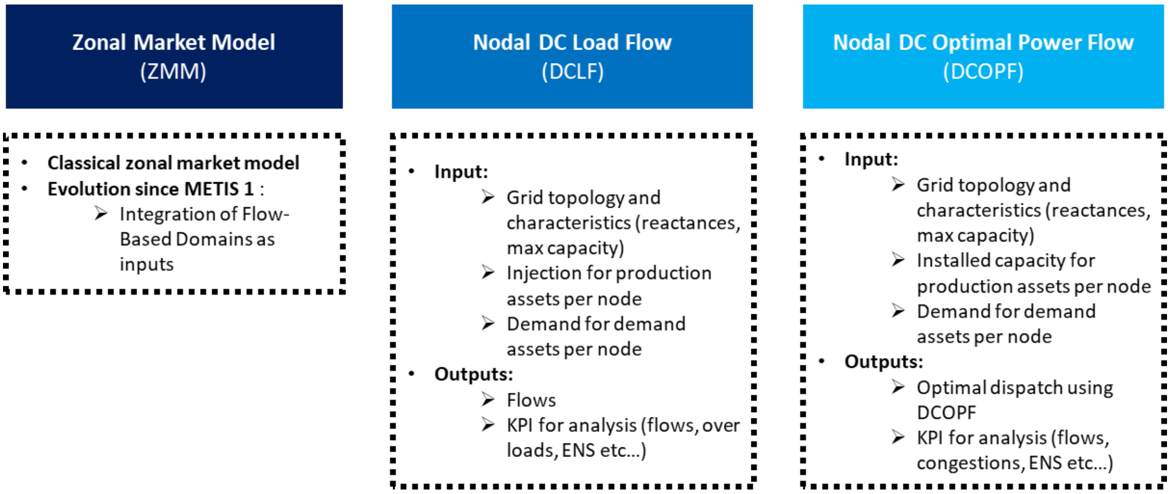

Figure 1 Three Main Models of the transmission module of METIS

This technical note covers the entire scope of the METIS transmission module:

- The specificities of the nodal transmission models compared to usual METIS models used in market modelling exercises
- The specificities of the “flow based” model (extension of the zonal market model)
- The description of the transmission-level datasets used in the nodal models.
- The description of the interactions between the METIS market model and the nodal transmission models.

3 GENERAL MODELLING PRINCIPLES

3.1 NODAL TRANSMISSION MODULE (DCLF AND DCOPF)

3.1.1 ASSET LIBRARY

The transmission module library includes a set of assets that can be used to represent the power production, demand, storage and transmission infrastructures. The usual assets of the METIS market model have been enhanced to work with the transmission module. They include additional behaviours that allow the user to add transmission network specific constraints.

The updated METIS assets work within a market model and within a nodal simulation, simply by changing the *context type* and their *behaviours*. These updated and integrated assets facilitate the communication between the market model and the transmission module (developed during the METIS 2 project). The power production assets that are available in the transmission module are the following:

- **Biomass fleet**
- **CAES fleet**
- **CCGT fleet**
- **Coal fleet**
- **CSP fleet**
- **Decentralized thermal fleet**
- **Derived gases fleet**
- **Geothermal fleet**
- **Hydro fleet**
- **Hydro RoR fleet**
- **Hydrogen fleet**
- **Lignite fleet**
- **Nuclear fleet**
- **OCGT fleet**
- **Oil fleet**
- **Other fleet**
- **Other renewable fleet**
- **Other thermal fleet**
- **Regulated coal fleet**
- **Regulated oil fleet**
- **Solar fleet**
- **Waste fleet**
- **Wind Offshore fleet**
- **Wind Onshore fleet**

The consumption, contract and storage assets available in the transmission module are the following:

- **Demand**
- **Export contract**
- **Generic storage**
- **Import contract**
- **Lithium-ion battery fleet**
- **Loss of load**
- **Power demand**
- **Pumped storage fleet**

- **Well**

To model the transmission grid, specific assets are added to the METIS library. The following assets can be used to represent the main infrastructures of the grid:

- **Transport node:** the METIS node from the market model has been enhanced to carry the **voltage level** information of the corresponding node. Transport nodes can be linked to transmission lines, production assets, storage assets, power demands. The supply-demand balance is automatically enforced at each node (taking into account transmission flows).
- **Bidirectional transmission:** these assets can represent an AC or a DC line. Their parameters include: the reactance and the capacity of the transmission lines. The asset is used to link two nodes of the same voltage level. Flows are bidirectional on these lines, meaning that it can be positive or negative. A bidirectional transmission is defined with a conventional direction between its source node and its target node. Positive flows are defined from the source endpoint to the target endpoint, and negative flows are defined from the target endpoint to the source endpoint.
- **Transformer:** transformer assets links two nodes of different voltage levels (at the same physical location). They also include a reactance parameter and are bidirectional. The sign convention for the flows is the same as for "Bidirectional transmissions". The role of a transformer is to convey power from one voltage level to another.
- **Phase shifting transformer:** these assets are transformers that have a controllable phase angle that can vary between two limits, which are to be provided as parameters of these assets.

The nodal transmission module includes two context types:

- **DCOPF**, which solves a DC Optimal Power Flow problem. The DCOPF model aims at minimizing the overall production cost, respecting the power supply-demand balance and the DC approximation of the Kirchhoff laws on the transmission grid on one snapshot.
- **DCLF**, which solves a DC Load Flow problem. The DCLF model aims to represent unconstrained flows (i.e. capacity limits are not enforced) and to evaluate the resulting congestions from a set of injections and withdrawals at each network node.

These context types enable to activate additional behaviours listed in Table 2.

Behaviour	DCLF	DCOPF	Dedicated assets	Description
OPTIM_FLOW		x	All	Enable assets to work with DCOPF scope
LOAD_FLOW	X		All	Enable assets to work with DCLF scope
DCLINE	X	X	Bidirectional Transmissions	Identifies DC lines. Bidirectional transmission lines are AC if the behaviour is not active.
LINEAR_LOSS		X	Bidirectional Transmissions	Activate linear losses on bidirectional transmissions
REMOVE_THERMAL_LIMIT		X	Bidirectional Transmissions	Removes the thermal limit constraint of a line in the DCOPF problem
PHASE_SHIFT_TRANSFORMER		X	Phase Shift Transformer	Enable phase shift transformer to optimize phase shift angle

Table 2 - Description of the behaviours of METIS Transmission module

Additional assets have been included in the library to ease the modelling of different configurations of redispatch:

- **Fixed net position (FIXED_NET_POSITION):** in a DCOPF model, it forces the net position of each market zone to equal a given value, for instance the one resulting from a zonal market model simulation
- **Set Market Dispatch (SET_MARKET_DISPATCH):** in a DCOPF model, it forces the total production for each technology for each zone to equal a given value (e.g. inherited from a zonal market model run).
- **Storage Flexibility (STORAGE_FLEXIBILITY):** in a DCOPF model, it can activate the optimization of storage assets. An individual storage asset can optimise both its injection and generation levels depending on minimum and maximum values given at national level stored in the model object. This asset has been introduced to be able to represent the redispatch of storage technologies in a context that only considers snapshots.

3.1.2 Horizon and objective

The METIS transmission module allows to simulate power flows on a transmission grid on a selection of **snapshots**. A snapshots is equivalent to a specific time step (one hour).

The objective of the module is to enable users to explore phenomena that may occur on the transmission grid on a relevant selection of snapshots. The visualisation of market simulation results (zonal model) can provide indicators to facilitate the selection of snapshots. For example, in Figure 2, we presents snapshots that are defined based on considerations on the value of the residual load.

- T1: Minimum of residual demand
- T2: Maximum of residual demand
- T3: Minimum of residual demand in winter
- T4: Maximum of residual demand in summer
- T5: Average wintertime time-step
- T6: Average summertime time-step

Users can easily select the snapshots they want to explore.

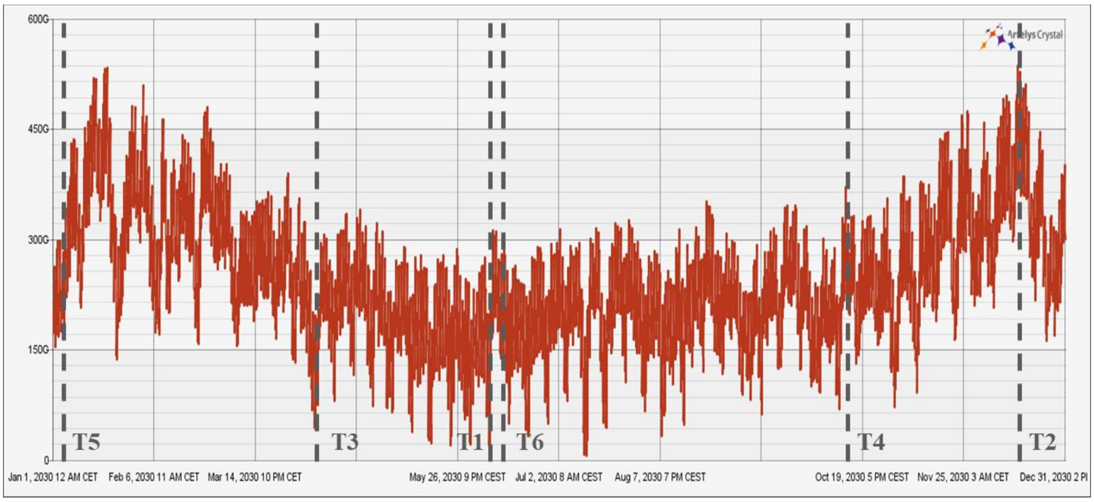

Figure 2 - Analysis of the residual load on EUCO3232.5 scenario (EU28)

3.1.3 OPTIMIZATION PROBLEM

The DCOPF and DCLF model use the standard DC assumptions of the power flow equations (Kenneth Van den Bergh, 2014), which are good approximations for high-voltage systems. The following assumptions are made in this approximation:

- The voltage magnitude is close to 1 p.u. on all buses (no voltage drops)
- The resistance of transmission lines is negligible compared to their reactance
- Voltage angle differences between adjacent nodes are small. More explicitly: $\sin(\theta_i - \theta_j + \phi_{ijc}) \approx \theta_i - \theta_j + \phi_{ijc}$ where θ is the phase of the nodes i and j, and ϕ the phase shifting angle of the connection c between i and j.

DC Optimal Power Flow problem (DCOPF)

The full DC optimal power flow equations implemented in the model can be found in the article Collection of Power Flow models: Mathematical formulations[1] (Tang & Ferris, 2015). The main equations of the optimization problem are shown on Figure 3.

- The objective function is the total production costs (composed of all linear costs of each asset).

- Constraint (C67) imposes the Kirchhoff laws: the flows on a line are proportional to the phase angle difference between the two nodes of the line, to one shifting constant.

[1] https://neos-guide.org/sites/default/files/math_formulation.pdf

- Constraint (C68) enforces the supply-demand balance at each node of the grid.

- Constraints (C69 – C70) are the bound constraints on the power productions and on the flows on the lines.

$$F_{ijc} = \frac{-1}{x_{ijc}}(\theta_j - \theta_i + \phi_{ijc}), \forall (ijc) \in E \qquad (C67)$$

$$\sum_{k \in G_i} P_k + \sum_{(jc):jic \in E} F_{jic} = \sum_{(jc):ijc \in E} F_{ijc} + \sum_{d \in D_i} d, \forall i \in N \qquad (C68)$$

$$\underline{P_i} \leq P_i \leq \overline{P_i}, \forall i \in G \qquad (C69)$$

$$\underline{F_{ijc}} \leq F_{ijc} \leq \overline{F_{ijc}}, \forall (ijc) \in E \qquad (C70)$$

Figure 3 - DC Optimal power flow equations (Phillips, 2004)

To ensure a unique solution is found, a set of reference slack nodes (or reference nodes) where the voltage angle is defined as being zero $\theta i=0$ have to be identified. Our model is such that one slack node is automatically defined on each connected component of the network.

Modelling advanced components:

- **HVDC lines**

HVDC lines are specific transmission lines which are channelling direct current. HVDC lines can be considered as two isolated endpoints as the power flow on HVDC lines is fully controllable. An HVDC line can be modelled as a combination of a controllable positive and negative power injection at the source and the target endpoints of the line.
In the DCOPF model, HVDC components can be modelled using the behaviour "DCLINE" which will deactivate the constraint linking voltage angles and power flows (C67).

- **Phase shift transformers**

Phase Shift Transformers (PSTs) can change the voltage angle between two adjacent nodes. They are represented as transformers with an additional behaviour "PHASE_SHIFT_TRANSFORMER" that can regulate the voltage angle by introducing a given offset. In the DCOPF equations, this means that the offset φijc is promoted from being a parameter to being a variable:

$$\underline{\phi_{ijc}} \leq \phi_{ijc} \leq \overline{\phi_{ijc}} \qquad (C73)$$

DC Load Flow problem (DCLF)

Strictly speaking, the load flow problem is not an optimisation problem as it has no objective function. The objective is to compute power flowing on each of the lines for a given set of injections and withdrawals at each node of the network (inputs of the model). DCLF problems respect the Kirchhoff laws but does not constraint the flows to respect the transmission line capacities (expressed in MW).

As in the DCOPF problem, one node per connected component of the network has to be designated as **slack node** and sets the voltage angle reference. These nodes are called "slack nodes" or "reference nodes".
In the DCLF problem, these nodes can absorb and inject power to maintain the balance between production and demand. To sum up, DCLF equations are:

- C67
- C68

Modelling advanced components:

In a DCLF model, **HVDC** lines are modelled as a combination of a positive and negative power injection at each of its endpoints. These injections are inputs that must be provided by the user. Their default value is 0.

In a DCLF model, **PSTs** are not optimised and their tap ratio value is set to 0.

3.1.4 MODEL STRUCTURE

The structure of the model is similar to the one of the zonal market model of METIS. Figure 4 describes the global architecture and the way assets interact with each other in a DCOPF or in a DCLF simulation:

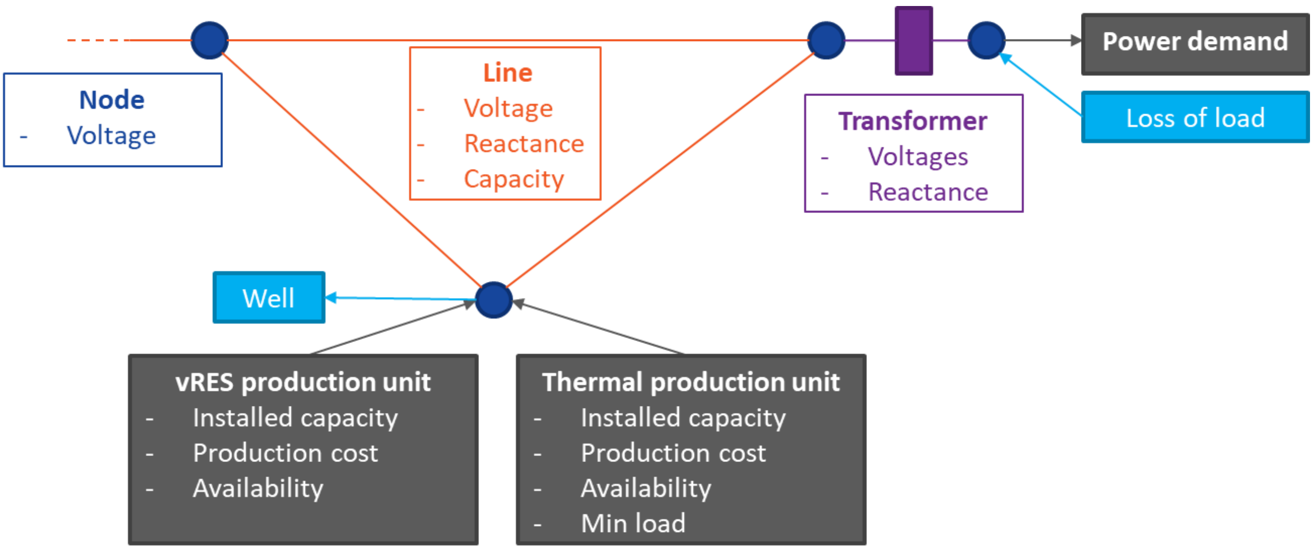

Figure 4 - Representation of a simplified transmission network

3.1.5 Detailed assumptions per asset

Table 3 provides an overview of the assumptions that have been adopted for each category of assets in the METIS transmission models.

<table>
<tr><th>Asset</th><th>DCOPF</th><th>DCLF</th></tr>
<tr><td>Power production assets (fleet assets)</td><td>Inject power to the network "p" [MWh] respecting:
$\text{minLoad} * \text{pmax} * \text{availability} \leq \mathbf{p}$
$\mathbf{p} \leq \text{pmax} * \text{availability}$

At cost:
$\mathbf{p} * \text{prodCost}$</td><td>Inject power to the network "p" [MWh] respecting:
$\mathbf{p} = \text{injection}$</td></tr>
<tr><td>Power demand assets</td><td colspan="2">Consume power from the network "c" [MWh] respecting:
$\mathbf{c} = \text{demand}$</td></tr>
<tr><td>Storage assets</td><td colspan="2">Act both as a producer and a consumer.</td></tr>
<tr><td>Well</td><td>Can absorb production surplus at a given cost.
Constraint:
$\mathbf{wellConsumption} \leq \text{TotalProductionOnNode}$</td><td>Can act as a consumer if not positioned on a slack node.
If positioned on a slack node, can absorb production surplus.</td></tr>
<tr><td>Loss of load</td><td>Can compensate consumption surplus at a given cost.
Constraint:
$\mathbf{LossOfLoad} \leq \text{TotalDemandOnNode}$</td><td>Can act as a producer if not positioned on a slack node.
If positioned on a slack node, can compensate consumption surplus.</td></tr>
<tr><td>Import/Export contract</td><td colspan="2">Fixed import / export value.
Export contract: acts as a producer.
Import contract: acts as a consumer</td></tr>
<tr><td>Bidirectional transmission</td><td>Transport flow "f" from its source endpoint to its target endpoint in both directions with same voltage levels.
$\mathbf{f} \leq \text{capacity}$
$-\text{capacity} \leq \mathbf{f}$</td><td>Transport flow "f" from its source endpoint to its target endpoint in both directions with same voltage levels.</td></tr>
<tr><td>Transformer</td><td colspan="2">Transport flow from its source endpoint to its target endpoint in both directions with different voltage levels.</td></tr>
<tr><td>Phase shifting transformer</td><td>Transformer which can control its shift angle.</td><td>Acts as transformer</td></tr>
</table>

Table 3 - Assumptions per asset

3.2 Flow-based market coupling on the zonal market model

In the day-ahead market, the market clearing is performed at the level of the bidding zones (most of the time at the national level). Therefore, it disregards the flows within zones (zones are treated as copper plates).

There can be different ways to constrain the exchanges of electricity between zones during market clearing, some of which better represent the physics of the underlying phenomena. To model these constraints, a methodology aggregating the interconnections between countries is required to calculate (a) the capacity of exchange between zones and (b) the way electricity flows in the zonal model.

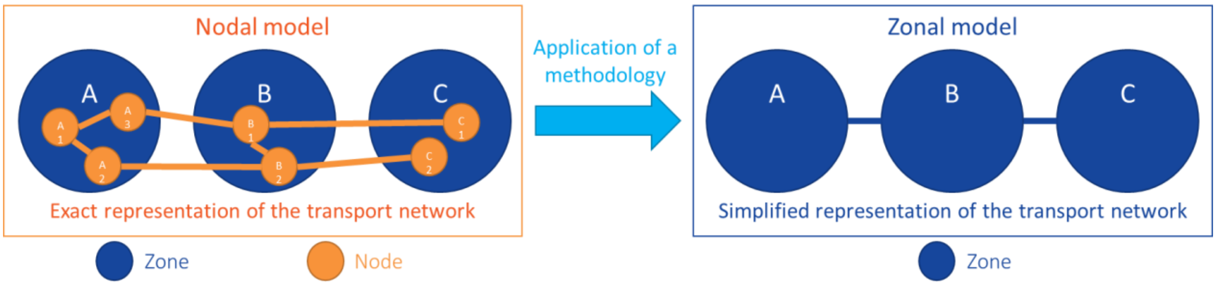

Figure 5 - Passage to nodal to zonal model

In Europe, two different methodologies are currently being used: the net transfer capacity (NTC) methodology, already implemented in the METIS market model, and the flow-based methodology, which has been implemented in METIS in the context of the work on transmission grids. This section briefly describes both methodologies and provides an overview of the way the flow-based methodology is implemented in METIS.

It has to be noted that **both methodologies can coexist in the same power market.** In the current day-ahead power market, the interconnections between AT, BE, DE/LU, FR and NL are using the flow-based market coupling approach while the other interconnections are using an NTC approach.

3.2.1 NTC AND FLOW-BASED METHODOLOGIES

3.2.1.1 NTC methodology

The NTC methodology couples the power market zones by setting one NTC in MW per interconnection between each pair of adjacent market zones. In a situation without losses, one NTC constraint applied to the optimisation problem can be written as

$$Flow_{A \to B,t} \leq NTC_{A \to B,t}$$

With

- $Flow_{A \to B,t}$ (MW) the positive variable of the optimisation problem representing the power commercial exchanges of electricity between zones A and B at the timestep t

- $NTC_{A \to B,t}$ (MW) one input of the optimisation problem representing the NTC associated to the interconnection between zone A and B at the timestep t.

The methodology to compute the NTCs is not further described in this technical note, as these parameters are often provided as inputs by scenario developers.[2] In market coupling exercises, NTCs are obtained by simulating the operations of the nodal network and analysing the effective transfer capacity between zones.

3.2.1.2 Flow based methodology

The flow-based methodology couples the power market zones by setting constraints on their flow-based net positions (exports through flow-based interconnections minus imports through flow-based interconnections). When it is activated on an interconnection, the cross-border constraints will be defined in METIS by a flow-based domain instead of the standard set of net transfer capacities (NTC).

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[2] For instance, ENTSO-E provides the NTCs of the different scenarios of the TYDNP at the following link https://tyndp.entsoe.eu/maps-data/

In a simulation that uses the flow-based module of METIS, each timestep is associated to a **flow-based domain**. One flow-based domain is constituted of a certain number of constraints applied to the optimisation problem, called the **Critical Network Element Contingency (CNEC)[3] constraints** and representing the limitations on one critical internal network transmission, given a given contingency occurs. One CNEC constraint applied to the optimisation problem can be written as

$$\sum_{zone} PTDF_{zone,CNEC,t} * NP_{zone,t} \leq RAM_{CNEC,t}$$

With

- $PTDF_{zone,CNEC,t}$ (MW/MW) one input of the optimisation problem representing the **Power Transfer Capacity Factor** of a zone connected to a given CNEC of the flow-based domain applied to the timestep t. The PTDF can be seen as the increase of flow (in MW) through the CNEC if the corresponding zone increases its Net Position by 1 MW.

- $RAM_{CNEC,t}$ (MW) one input of the optimisation problem representing the **Remaining Available Margin** of the CNEC of the flow-based domain applied to the timestep t. The RAM can be seen as the remaining capacity that the critical internal network transmission can support.

- $NP_{zone,t}$ (MW) the variable of the optimisation problem representing the Net Position of one zone of the flow-based domain applied to the timestep t

The methodology to compute the PTDFs and the RAMs are not further described in this technical note, as these parameters are often provided as inputs of the model[4]. In practice, simulations are undertaken and analysed to assess the effective ability of the network to exchange electricity between zones.

Note that by replacing the Net Position by their formulation in terms of commercial flows, one alternative formulation can be written as

$$\sum_{zone\ A,B} (PTDF_{A,CNEC,t} - PTDF_{B,CNEC,t}) * Flow_{A \rightarrow B,t} \leq RAM_{CNEC,t}$$

With $Flow_{A \rightarrow B,t}$ (MW) the positive variable of the optimisation problem representing the power commercial exchanges of electricity between zones A and B at the timestep t.

It should be noted that the flow-based methodology is not enough to uniquely determine the commercial flows through the flow-based interconnections, as loop flows could be added to any existing solution of the optimisation problem as illustrated below.

[3] Also called Critical Branch Critical Outage (CBCO)

[4] For instance, the Joint Allocation Office provides the historical PTDFs & RAM in its Utility Tool at the following link https://www.jao.eu/implict-allocation

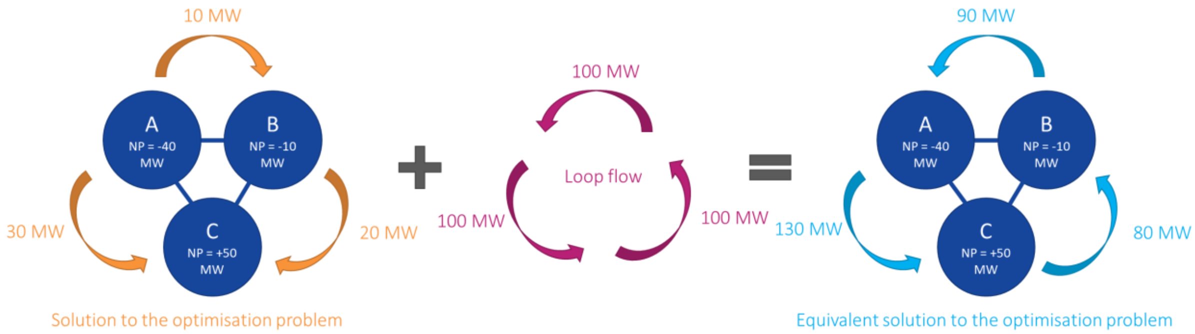


Figure 6 - Illustrative case of the equivalent solutions of one flow-based model without an additional constraint on the flows

To obtain one unique commercial flows solution, several options can be considered:

- Solve a post analysis problem, for instance choose the solution of a least-square optimisation problem on the sum of the square of all flows (roughly corresponding to minimising losses).
- Implement additional constraints or costs in the optimisation problem, for instance implement a small additional cost in the objective function proportional to each of the commercial flow. This is the solution that has been chosen in METIS, as it closely mimics the one adopted in the NTC market model.

3.2.1.3 Illustration

The following illustration depicts a situation where part of the network is coupled via flow-based and part via NTCs. In this case, three zones are represented. The zones A and B are linked through an interconnection modelled with the NTC methodology and the zones B, C and D are linked through an interconnection modelled with the flow-based methodology.

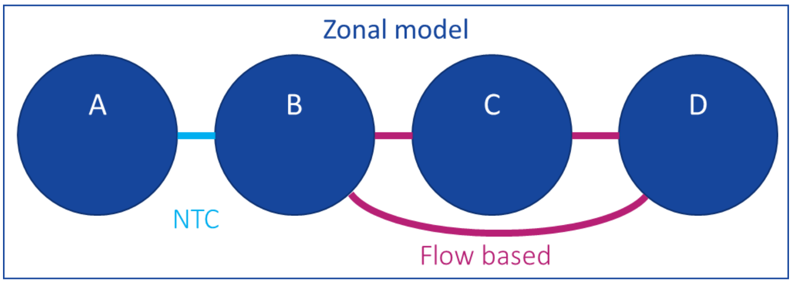


Figure 7 - Illustrative case where both methodologies are used

The input parameters of the model for the timestep t are the following:

- The NTC between A and B is 1 000 MW, without losses
- The NTC between B and A is 1 500 MW, without losses
- The flow-based domain for B, C and D is the following
  - One CNEC constraint which has the following parameters:
    - The PTDF of B is 0.5
    - The PTDF of C is -0.3

    - The PTDF of D is 1
    - The RAM is 500 MW
  - Another CNEC constraint which has the following parameters
    - The PTDF of B is 0.4
    - The PTDF of C is 0.7
    - The PTDF of D is 0
    - The RAM is 2000 MW

Thus, the following constraints for timestep t are written in the optimisation problem:

- $Flow_{A\to B} \leq 1000\ MW$
- $Flow_{B\to A} \leq 1500\ MW$
- $0.5\ NP_B - 0.3\ NP_C + NP_D \leq 500\ MW$
- $0.4\ NP_B + 0.7\ NP_C \leq 2000\ MW$

- It has to be noted that the net positions only concern the flow-based imports and exports. An alternative formulation using only the flows variables can be written by replacing NP_B by $Flow_{B\to C} - Flow_{C\to B} + Flow_{B\to D} - Flow_{D\to B}$, NP_C by $Flow_{C\to B} - Flow_{B\to C} + Flow_{C\to D} - Flow_{D\to C}$ and NP_D by $Flow_{D\to C} - Flow_{C\to D} + Flow_{D\to B} - Flow_{B\to D}$,:
  - $Flow_{A\to B} \leq 1000\ MW$
  - $Flow_{B\to A} \leq 1500\ MW$
  - $0.8\ Flow_{B\to C} - 0.8\ Flow_{C\to B} - 0.5\ Flow_{B\to D} + 0.5\ Flow_{D\to B} + 1.3\ Flow_{D\to C} - 1.3\ Flow_{C\to D} \leq 500\ MW$
  - $-0.3\ Flow_{B\to C} + 0.3\ Flow_{C\to B} + 0.4\ Flow_{B\to D} - 0.4\ Flow_{D\to B} - 0.7\ Flow_{D\to C} + 0.7\ Flow_{C\to D} \leq 2000\ MW$

3.2.2 THE FLOW-BASED MODULE IN METIS

This section describes how the flow-based market coupling has been integrated in METIS, and how users can input their domains to solve a zonal market model using a flow-based approach.

3.2.2.1 Flow-based features

METIS has been expanded to include new features necessary to implement the flow-based methodology. The three new objects are the following:

- The flow-based domains
- The flow-based domain map
- The flow-based behaviour of interconnections

A **flow-based domain** contains all the parameters used to implement its constraints:
- One RAM for each CNEC
- One PTDF for each zone included in the flow-based domain and each CNEC

The flow-based domains are set by importing a csv file into METIS through a dedicated operation.

Each simulation using the flow-based module has one unique **flow-based domain map**. This object associates to each timestep of each test case[5] of the simulation an ID of a flow-based domain. Several timesteps can be associated to the same flow-based domain if needed.
The flow-based domain map is set by importing a csv file into METIS through a dedicated operation.

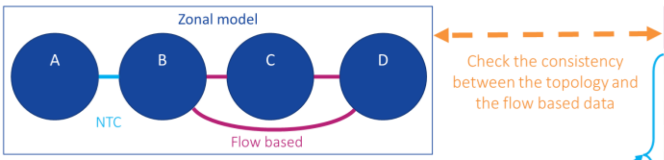
In METIS, by default, interconnections are modelled with the NTC methodology. When activated, the **FLOW_BASED behaviour** removes the parameters associated to the NTC methodology (losses and capacity) and prevent the writing of the NTC constraints in the optimisation problem, and add the constraints related to flow-based market coupling.

3.2.2.2 Optimisation process

Once the flow-based behaviour is activated, and its parameters are correctly set, one can launch a simulation which will:

- Associate each timestep of each test case to one flow-based domain by reading the flow-based domain map,
- Write for each timestep of each test case the corresponding CNEC constraints by reading its parameters in the corresponding flow-based map,
- Run a certain number of checks to ensure the flow-based parameters are consistent (for instance, to ensure that both zones attached to an interconnection with the FLOW_BASED behaviour are included in the flow-based domains).

The following figure provides an overview of the additional features and their interactions when running a simulation with the flow-based features being activated:



Timestep	Test case	Flow based domain
1	1	1
2	1	2
1	2	1
...	...	...

Flow based domain	CNEC	Parameter	Zone	Value
1	1	PTDF	B	0,5
1	1	PTDF	C	-0,3
1	1	PTDF	D	1
1	1	RAM	-	500
1	2	PTDF	B	0,4
1	2	PTDF	C	0,7
1	2	PTDF	D	0
1	2	RAM	-	2000
2	1	PTDF	B	0
2	1	PTDF	C	0,5
2	1	PTDF	D	-0,5
2	1	RAM	-	100
...	...	...	...	...

Figure 8 - Features of the flow-based module and their interaction. The flow-based domain 1 has the parameters used in the illustrative case above

4 Datasets and scenarios used in the METIS transmission module for METIS 2 Studies

To be able to run simulations using the METIS transmission module, two "nodal" datasets representing the European transmission network have been developed. Both datasets depict the European transmission network, with different levels of details. This section of

[5] In METIS, a simulation can have several test cases representing a variation of several parameters, typically different climatic years with different demand and renewable energy source availability timeseries

the technical note focuses on the first of these datasets. In the next section, we will see how alternative datasets can be generated within the METIS transmission module.

4.1 PAN-EUROPEAN TRANSMISSION GRID DATA SOURCE

The METIS pan-European nodal dataset is built based on ENTSO-E's TYNDP 2020 grid dataset, provided in the CGMES format. The CGMES (Common Grid Models Exchange Standard) dataset is assembled by ENTSO-E from data provided by European and extra-European TSOs under an IGM (Individual Grid Models) format and merged by the ENTSO-E into the CGMES format.

The CGMES dataset is distributed by ENTSO-E[6]. ENTSO-E also enhances it and writes guideline in order to facilitate exchange between diverse and multiple system operators.

The dataset is exchanged using a specific format based on the CIM (Common Information Model) standard which is used to share information about the electrical network between software using the XML language[7].

Once the network information gathered from European TSOs under the IGM format (Individual Grid Models) is validated by the ENTSOE, it is added to the CGMES dataset.

The standard and the electricity grid are in constant evolution in order to represent with as much accuracy as possible the state of the network. The METIS team has obtained the TYNDP 2020 dataset through a request validated by ENTSO-E on the online application portal for network datasets[8].

4.1.1 CONVERSION INTO METIS TRANSMISSION MODULE

The CGMES dataset has been analysed and converted to a format readable by the METIS model. Table 4 gives the association that was chosen between the CGMES components and the METIS assets:

[6] entsoe.eu

[7] The full documentation (ENTSOE, Detail description of the CGMES profiles : version 2.4.14, 2014) exhaustively describing the standard of CGMES and CIM from the IEC and ENTSOE are available at the following link: https://webstore.iec.ch/publication/61124

[8] Accessible at the following link: https://www.entsoe.eu/publications/statistics-and-data/#entso-e-on-line-application-portal-for-network-datasets

CIM classes	METIS
VoltageLevel	Transport Node
EnergyConsumer, ConformLoad, NonConformLoad	Power demand
GeneratingUnit, NuclearGeneratingUnit, SolarGeneratingUnit, WindGeneratingUnit, HydroGeneratingUnit, ThermalGeneratingUnit	Fleet asset
Internal lines : AcLineSegment	Bidirectional transmission
Interconnection: AcLineSegment & EquivalentBranch belonging to different zone with common node.	
HVDC: AcLineSegment with common geographical information about Boundary Node and referenced as external or DC.	
Power transformer: PowerTransformer with two PowerTransformerEnds and a TapChanger Associated.	Transformer
Three-Winding transformer: PowerTransformer with three PowerTransformerEnds and a TapChanger Associated.	
Phase Shift Transformer: PowerTransformer with two PowerTransformerEnds and PhaseTapChanger associated	Phase Shifting Transformer

Table 4 - Association CGMES - METIS asset

The converted dataset format is similar to other METIS contexts. The original CGMES files have been parsed using the same methodology as is used by the CIMpy tool[9] from Fein Aachen (Fein Aachen, s.d.), which was configured to directly generate METIS scenario files.

The dataset includes a description of the network topology (lines, nodes, and transformers), a list of generating units and the results of a simulation on one time-step corresponding to a winter hour.

An analysis of the network has been done, leading to a three phases work, the first phase consisted in comparing extracted data to expected data with respect to specification and Artelys expertise in power network, the second phase was about network topology analysis and correction, the third phase was a power flow simulation and assessment.

The current dataset describes the transmission systems of 28 countries (including Albania) corresponding to two synchronous regions: Continental Europe and Baltics (see Figure 9). Due to confidentiality issues: the Nordic Zone and the GB/IE data were not available in the provided dataset.

[9] https://www.fein-aachen.org/en/projects/cimpy/

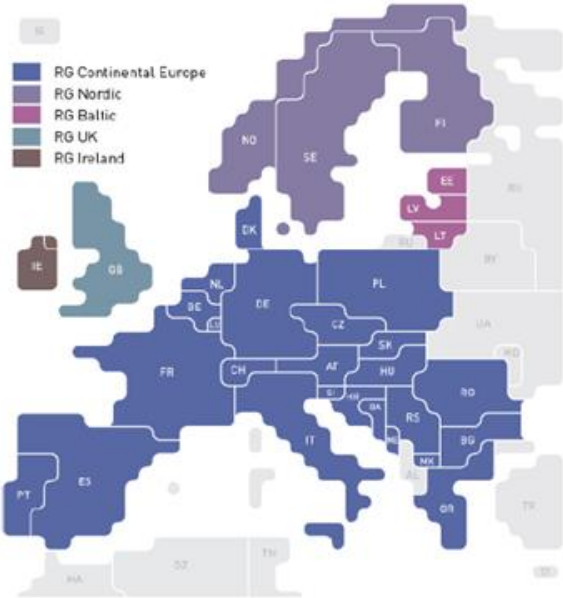


Figure 9 - ENTSO-E network regions. Source: TYNDP 2018 ENTSO-E dataset specification

4.1.2 DESCRIPTION OF THE DATASET

The CGMES dataset includes the input grid datasets for the preparation of the TYNDP 2018 and describes the situation of the TYNDP Best Estimate 2025 scenario (ENTSOE, Detail description of the CGMES profiles : version 2.4.14, 2014). As the data is collected from various TSOs, some heterogeneity in the accuracy of the provided data have been found and processed.

4.1.2.1 Work done

Artelys consultant led a three-phase analysis of the CGMES dataset as to provide a quality dataset for simulating power flow. The first phase consisted in analysis of data provided, both for physical characteristics, installed capacities or load and injection per country. The second phase consisted in analysing the network connectivity, and eventually if considered necessary to operate modification in order to repair connectivity problem. The third and last phase consisted in analysing a DCLF result (flows) and assess the result w.r.t to the data received.

Finally, a post process has been done in order to place as rightfully as possible assets on the map based on their neighbours with an iterative process. (Geographical position information are based on the data received with the CGMES 2018 dataset)

4.1.2.1.1 Data extraction & comparison

The first phase consisted in comparing extracted data with expected data using the dataset specification, expert knowledge and other reference such as the electricity grid map[10]or the data from the TYNDP 2020[11]for the scenario National Trend and the year 2025.

The element of comparison used were Installed Capacities per Country and technologies, national injection & loads and network assets such as line or transformer.

[10] https://www.entsoe.eu/data/map/

[11] https://public.tableau.com/shared/XQ39ZDMWQ?:display_count=n&:origin=viz_share_link&:embed=y

When comparing with the dataset specification we had a nearly absolute match on installed capacities with the biggest difference being -898 MW for LT, +93 MW for DK and +19.5 MW for LV, aggregated to a total difference of -775 MW (-0.07%) for the whole EU-28.

Then comparing expected load, we also had small divergence from the specification with the biggest loads difference being located in 290 MW (13%) in SI, -25 MW (0.07%) in FR and -21 MW (1.55%) in LV that difference was totted up to a 311 MW (0.08%) for the whole EU-28.

Coming to the injection we noticed also small divergence from the specification with the biggest loads difference being located in PT for -299 MW (-4%), also 100 MW (1.55%) in DK and -2 MW (0.00%) in FR that difference was totted up to a -196 MW (-0.05%) for the whole EU-28.

More generally national balance for installed capacities, loads & injection were extracted and fitted well with the expected data.

When comparing with the NT 2025 TYNDP scenario the main difference on the total installed capacity were in Greece, Germany, Italy, France and Spain were more than 40 GW was added (+11GW, +11GW, +14GW, +8GW, +5GW) with respect to CGMES. All the other countries present in the CGMES have a lesser difference with an average of -85MW more than the TYNDP-BE2025 and a maximum of +1200 MW and a minimum of -1225 MW.
The global differences compare to NT-2025 for the installed capacities for the 28 countries is casted up to +51318 MW.

Moreover, some minor correction about physical value (e.g., resistance & reactance) were done on line and transformers, conversion of Phase Shifter Transformer (PST) parameter to degree and thermal capacity extracted from PATL (Permanent Active Transmission Limit) in Ampere to MWe capacity for line, transformer and PST.

As some computed capacities were considered as too small, we decided to setup a threshold depending on the voltage level (lowest voltage level for transformer):

Voltage level	Minimum capacity in MW
Greater or equal than 0 kV and less or equal than 100 kV	35
Greater than 100 kV and less or equal than 200 kV	70
Greater than 200 kV and less or equal than 300 kV	140
Greater than 300 kV	280

Table 5 - Capacity threshold per voltage level for transmission assets

The use of PATL for transmission assets was sometime too low for the original dataset as the testcase provided within the CGMES dataset was representing a network under heavy load. For example, export from Norway or GB are in some case greater than the PATL capacity of the line but not of the TATL (Temporary Admissible Transmission Limit).

While expecting positive value for loads and negative value for injection some values were reversed even with respect to technology (We admitted that hydro assets are the only production asset that could have a demand).

We reversed those value while keeping track of them for the next steps. Changing reversed loads to injection or reversed injections to loads does not change the balance. However, the only loss is the installed capacities attached to the reversed injection.

When comparing the initial dataset with the final dataset including load & injection correction, we denote the following differences:

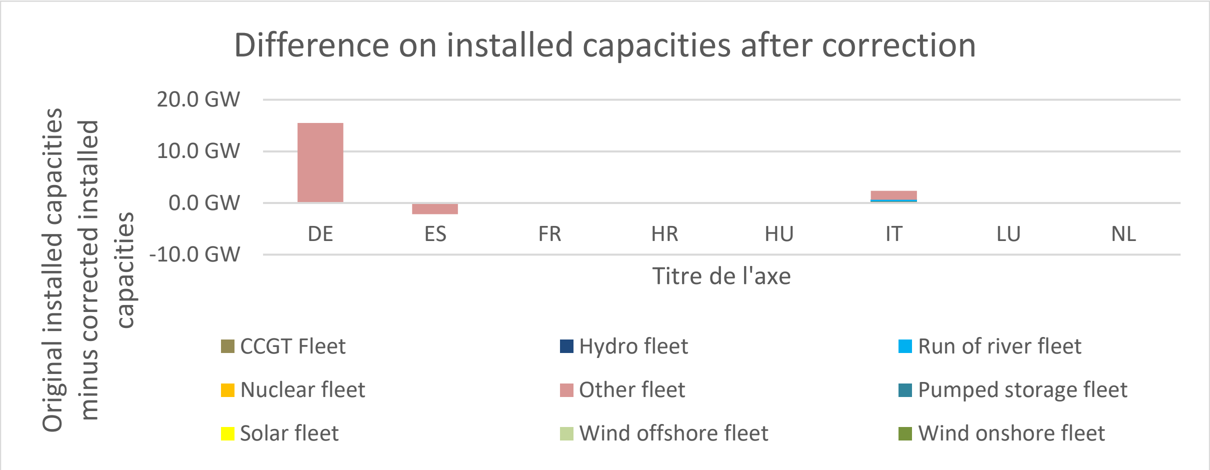


Figure 10 - Difference of installed capacities after reversing values for injections & loads

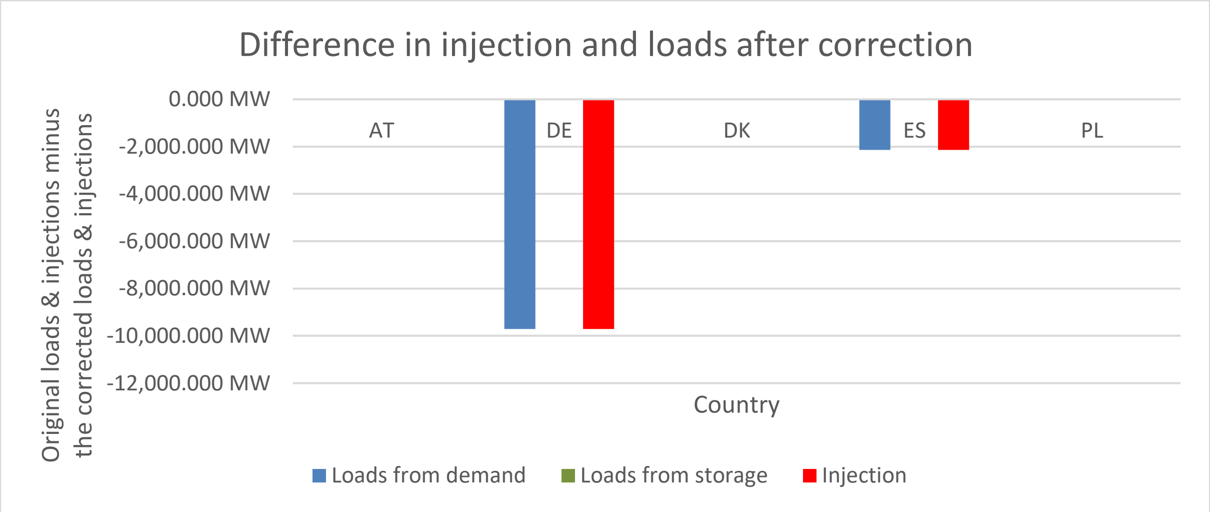


Figure 11 - Difference of injections & loads after reversing values for injections & loads

The main part of this phase consisted in establishing a workflow to reassemble interconnection. The high divergence of possible modelling for interconnexion led to an exhaustive study of the possible case resulting in a workflow of possible conversion including 7 possible cases.

For each of the 835 topological nodes denoted as boundary node we collect all lines (e.g., ACLineSegment), artificial lines (e.g., EquivalentBranch) and flows (e.g., EquivalentInjection):

- Two lines linked to the boundary could be associated and are both declared as AC
    - Exported as AC line with no forced flow.
        - 287 matches
- One line and one artificial branch linked to the boundary could be associated and are both declared as AC
        - Exported as AC line with no forced flow.
            - 2 matches
- More than two lines linked to the boundary node could be associated and are all declared as AC.
    - Creation of a middle point connecting all the lines and no forced flow is exported
        - 5 matches
- Boundary node with only one line associated:
    - We try to find the symmetrical boundary node within the other boundary node with one line associated:
        - If we find it and that only two nodes have been associated:
            - One line and one artificial branch linked to the two boundary nodes could be associated and are both declared as DC
                - Exported as DC line with flow if equal or average forced flow if different flows are declared.
                    - 8 matches
            - Two lines linked to the two boundary nodes could be associated and are both declared as DC
                - Exported as DC line with flow if equal or average forced flow if different flows are declared.
                    - 18 matches
        - Else:
            - Export the line and forced flow to the end of the line.
                - 98 matches
- Boundary node with one line associated:
    - We do not export data.
        - 417 matches

4.1.2.1.2 Network connectivity

The second phase was focusing on the network analysis of the dataset, mainly a corrective workflow for rebuilding interconnection, boundary flow and external network injection (with respect to the dataset geographical scope) was implemented.
First, we use the PowSyBl software[12] and its OpenLoadFlow tool, to compute the number of connected components into the grid model. For each of these components, we calculate the number of nodes and generating units inside it. We obtained the same results with the grid model we extracted from CGMES data, confirming that we have correctly assessed the number and the size of connected components.
Finally, an extended analysis was done on the connected components emerging from the corrective workflow.
After one correction consisting in adding the SA.PE.I. DC connection from Fiume Santa (Sardinia, Italy) to Latina (Latium, Italy) in order to connect Sardinia, from the 44 connected component (CC) found, the largest CC was concentrating more than 99,3% of assets and 99,9% of the injection and load, moreover every CC was balance w.r.t loads and injections.
Further investigation on the remaining 43 CCs led to their removals as they concentrated incoherencies or did not bring any additional information to the main CC. In fact, most of the CC concentrated the reversed load/injection or an abnormal number of lines given the number of nodes (e.g., 44 lines for two nodes).

When comparing the initial dataset with the final dataset including load & injection correction and only the main CC, we denote the following differences:

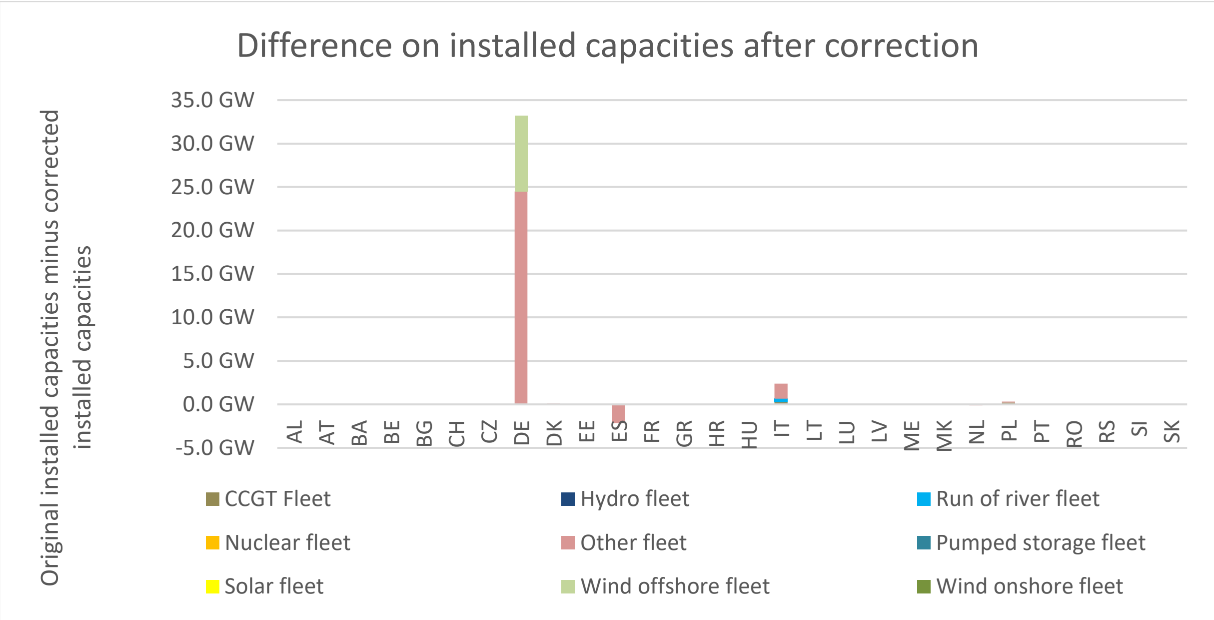


Figure 12 - Difference of installed capacities after reversing values for injections & loads

[12] https://www.powsybl.org/pages/overview/

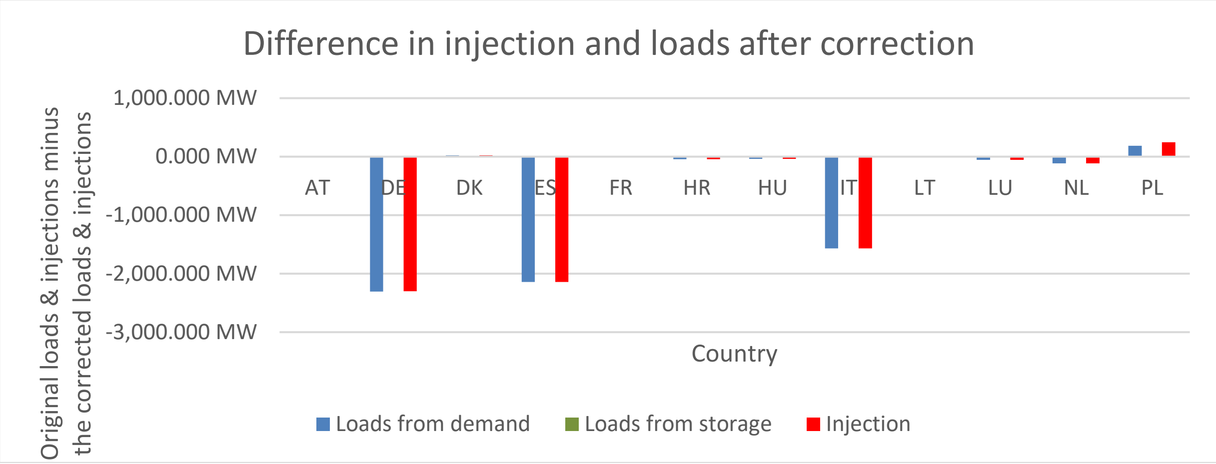


Figure 13 - Difference of injections & loads after reversing values for injections & loads

4.1.2.1.3 Direct Current Load Flow Assessment

The data resulting from phase two was then used to simulate a DCLF on Metis. The results were compared with the (uncomplete) expected result, zonal border flows were compared to specification data.

We notice that DC computations do not model heat losses on network lines. However, in CGMES data, consumption and production data integrate losses, therefore, the amount of energy produced equals consumption plus losses. To obtain a matching between consumption and production, needed to use a DC model, expected losses (10GW for the whole grid – around 3%) have been share among load except exports to non-modelled country.

	Injection	Loads	Loads from storage	Export	Import
Aggregated sum for EU-28 in Mwe	386451	386008	0	12468	3025

These 10 GW come from this upper table where exactly 9885 MW are missing if the balance is computed. These 9885 MW have been redistributed proportionally to their initial load on every load modelled (except export).

As the specification data could be incoherent, (e.g., Asymmetrical flow exchanges with Germany declaring a Danish export of 0 GW but Denmark declaring a German import of 3.2 GW, no exchange between Belgium and the Netherlands) we would mainly analyse:

- The flow between countries.
    - If flows are not reversed and their difference between expected and simulated is understandable.
- The congested transmission assets with respect to their capacities.

The comparison suggested that the dataset was of good quality and results were close to the expectations.

Finally, the disaggregation method implemented to generate a DCLF/DCOPF from a zonal (Simulation) context has been done in a way that every external country of the CGMES dataset is modelled as one delivery point (Transport node in DCLF/DCOPF context) and one export/import asset.
In the CGMES 2020 an external country can have multiple transport nodes, each one being associated to an export/import asset, which are not directly connected (i.e., No connection

such as GB1->GB2), although they are connected through the CGMES model (i.e., Only connection such as GB1->FR1->GB2).
In order to be compatible with the disaggregation a few operations have been done:

- For each external country with respect to the CGMES 2020:
    - Merge all import/Export asset in order to get one.
    - Merge all nodes of this external country to one node.
        - Leading to multiple line connected to this node.
    - For each line connected to this node:
        - Multiply their impedance by 10, this should help avoiding looping and unwanted flow through the line as they should depend only on the value of import/export.
    - We also rescale the zonal exchange capacity of CGMES with respect to EUCO3232_2030 in order to avoid infeasibility.
        - Depending on the capacity of each line and then upgraded with 25% security margin.

4.1.2.2 Network topology description

The current nodal network dataset contains 14972 nodes divided into the different zones, cf. Table 6.

Zone	Nb nodes	Zone	Nb nodes	Zone	Nb nodes
AL	307	FR	1688	MK	144
AT	545	GB	12	NL	1162
BA	278	GR	2262	NO	6
BE	543	HR	226	PL	307
BG	692	HU	90	PT	574
BY	12	IE	1	RO	115
CH	158	IT	1860	RS	1345
CZ	67	LT	450	RU	10
DE	1290	LU	37	SE	11
DK	252	LV	301	SI	171
EE	289	LY	1	SK	30
EG	1	MA	2	TN	2
ES	1175	MD	2	TR	3
FI	2	ME	224	UA	6

Table 6 - Number of network nodes per zone based on the CGMES dataset

Figure 14 shows the breakdown of the voltage nodes of the whole dataset of the transmission network:

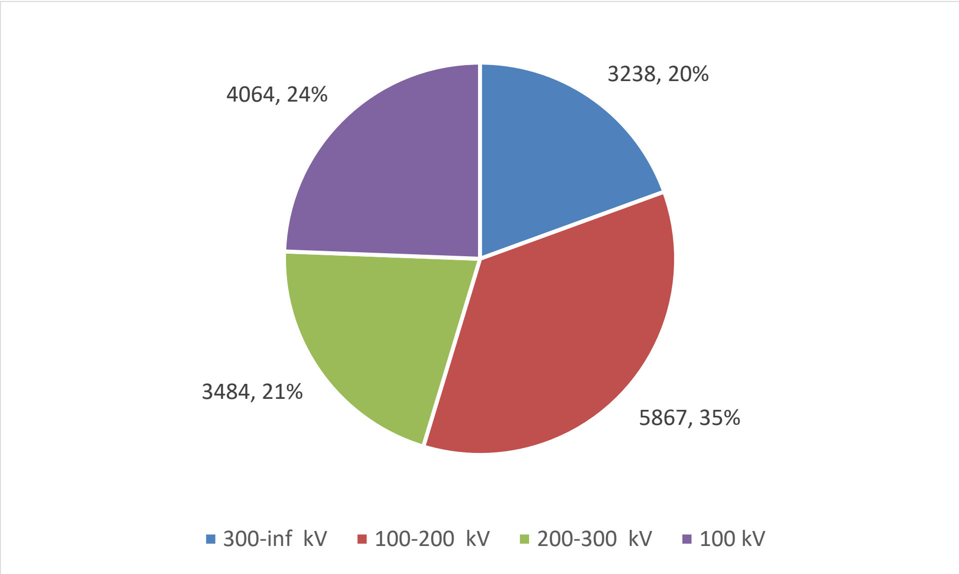


Figure 14 - Distribution of voltage levels

There are 14862 AC-transmission lines in the transmission network dataset, 264 of them are interconnections between different zones. The rest of them are internal lines divided into zones according to the following Table 7:

Zone	Nb of internal lines	Zone	Nb of internal lines	Zone	Nb of internal lines
AL	195	ES	1215	MK	147
AT	723	FR	2177	NL	1059
BA	292	GR	1798	PL	376
BE	730	HR	326	PT	596
BG	847	HU	88	RO	169
CH	268	IT	988	RS	763
CZ	100	LT	563	SI	264
DE	1492	LU	30	SK	41
DK	289	LV	328		
EE	324	ME	99		

Table 7 - Internal lines

There are 13 HVDC lines in the network, 66 of them are interconnection between different zones. The transmission network contains 7780 transformers plus 106 Phase Shifting Transformers (PST).
Network elements such as line, transformer and phase shifter have been compared, for this phase only Bulgaria and Hungary have diverged from the specification as no specification data was given for Bulgaria (BG) and that a huge number of both lines (792) and transformer (290) were expected but only 110 and 182, respectively, were extracted.

4.1.2.3 Generation and demand description

The nodal transmission description of the European transmission network is based on the CGMES dataset for the scenario "Best Estimate 2025" for the synchronous zones of continental Europe and Baltics. The original installed capacity of the generation plants located on the different nodes are based on the scenario "Best estimate 2025" of TYNDP 2020. As detailed in the disaggregation process described in the following section, they are used as weights to disaggregate zonal installed capacities on the nodal description.

The initial dataset provides the following generating unit types:

- GeneratingUnit,
- ThermalGeneratingUnit,
- HydroGeneratinUnit,
- WindGeneratingUnit,
- SolarGeneratingUnit,
- NuclearGeneratingUnit

After processing, the nodal description of the transmission network is composed of 9 different technologies: Nuclear fleet, Thermal fleet (to gather Coal, Lignite, Oil and Gas-powered generation plants), Solar fleet, Hydro Run-Of-River, Pumped storage fleet, Hydro reservoir, Wind onshore, Wind offshore and a generic type "Other fleet". This last type is used to gather the generation units that are not labelled in the CGMES dataset.

First comparison with respect to the dataset specification has resulted in low when aggregating at the national level, injection and loads have a maximum relative difference of 3% (for Slovenia where a load difference of 300MW was found).

The breakdown per country is as given by Figure 15.

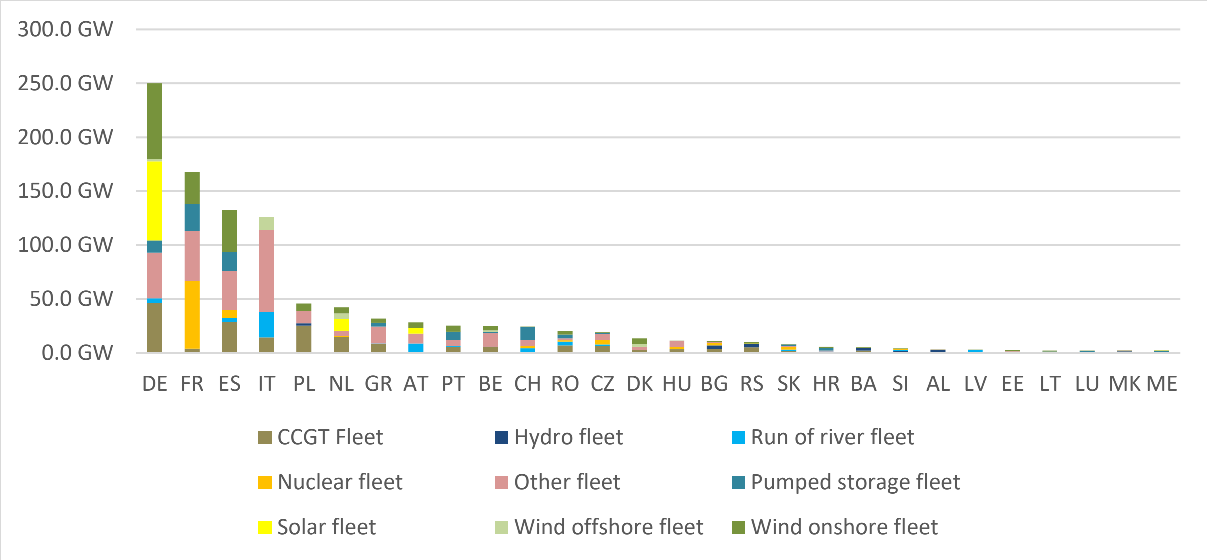


Figure 15 - Installed capacities per country based on the TYNDP20 2025 BE scenario, extracted and processed from the CGMES dataset

These installed capacities per technologies, per zone are used in the disaggregation process to weight the downscaling from the zonal model installed capacities to the nodal description (explained in the following part 5).

The demand is shared between zones based on the data extracted from the CGMES dataset that represents a simulation of a wintertime time-step over Europe as shown in Figure 16.

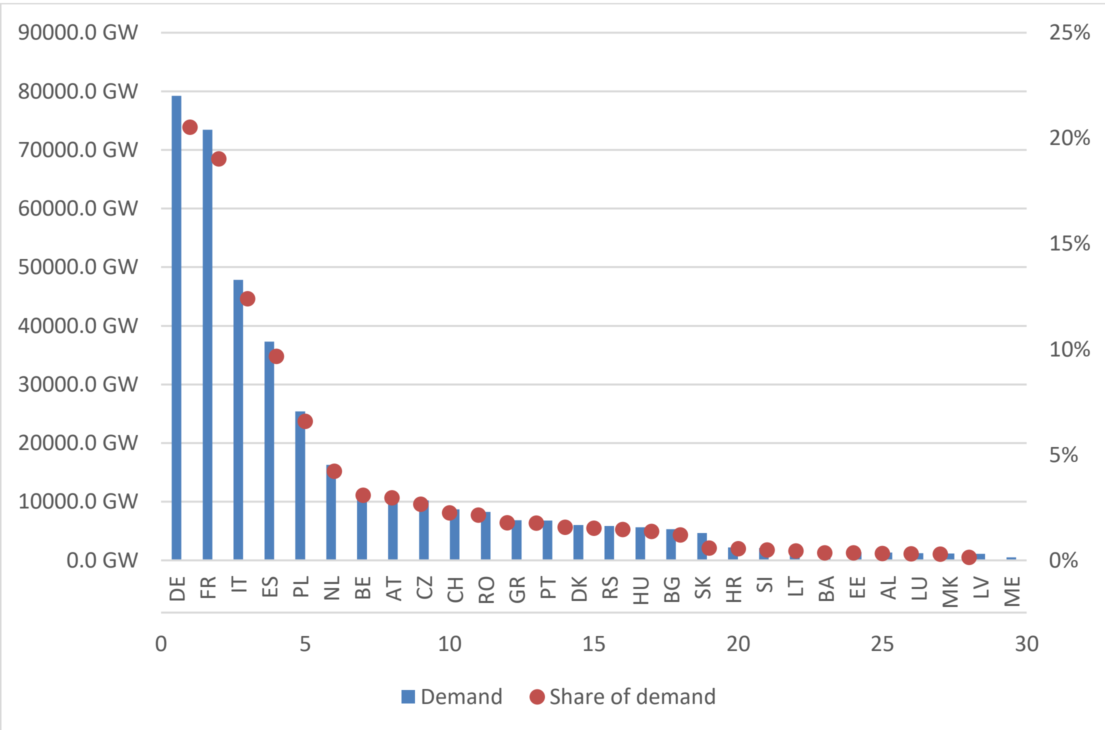


Figure 16 - Share of total demand over European countries

4.2 CLUSTERED TRANSMISSION GRID DATA SOURCE

On top of the pan-European transmission grid, a second representation of the European transmission network has been converted into the METIS format. This dataset entitled "clustered transmission grid model" is based on the data available from the "eHighways 2050" study supported by the EU Seventh Framework Programme which aimed at developing a methodology to support the planning of the Pan-European Transmission Network, focusing on 2020 to 2050, to ensure the reliable delivery of renewable electricity and pan-European market integration..

A transmission grid model with geographical clusters and connections between them has been created within the eHighways 2050 project. The technical parameters of the connections (line impedance for example) have been estimated from the transmission network data available, and are a result of an "equivalent impedance optimisation" technique. All transmission lines that already exists or are to be implemented until 2030 are considered for the grid model of the study. The Ten-Year Network Development Plan (TYNDP) serves as a basis for this data set. Further detailed information about the clustering technique and the study in general can be find in (Anderski & Betraoui, 2015).

The "eHighways 2050" study considers five different prospective scenarios for their analysis, each of them has a specific value for the clustered available capacities for production assets, and annual demands. Amongst them, we have selected the scenario "X-10: Big & Market" for the creation of the dataset in METIS, due to the similarities between the installed capacities with the ones considered in the EUCO3232.5 scenario of the European Commission, which is the scenario used in METIS 2 Study S1.

4.2.1 CONVERSION INTO METIS TRANSMISSION MODULE

The clustered grid model implemented in METIS contains 128 nodes that are connected by 245 transmission lines.

Via considerations on the impedances of the transmission lines, the "eHighways 2050" study defines five groups of lines and for each group an interval of potential impedances, with a maximum and a minimum value, to which the impedance is allocated (Anderski & Betraoui, 2015). Figure 17 shows the five groups defined within the eHighways 2050 network model. Maximum and minimum impedances correlate with the fact whether the grid is highly or weakly meshed (Anderski & Betraoui, 2015).

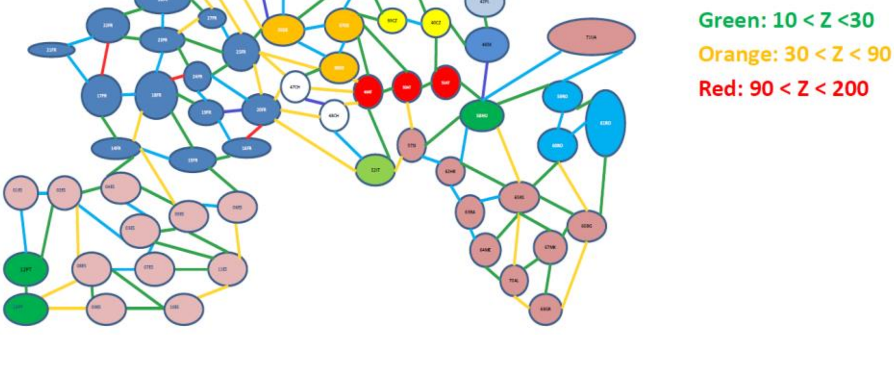


Figure 17 - Equivalent impedances defined in the eHighways 2050 study

To obtain a consistent attribution of the impedances for METIS, the impedance for each line was calculated by taking the line length, the capacity and the given interval for the correspondent group into consideration. The methodology is based on the approach used in (Dedecca, 2018). For each line the impedance was calculated using the formulas below.

$$L: \ line\ length$$

$$C: \ line\ capacity$$

$$Z: \ line\ impedance$$

$$0{,}5 \times \frac{L_{max} - L}{L_{max} - L_{min}} + 0{,}5 \times \frac{C_{max} - C}{C_{max} - C_{min}} = \frac{Z_{max} - Z}{Z_{max} - Z_{min}}$$

$$Z = Z_{max} - (Z_{max} - Z_{min}) \times (0{,}5 \times \frac{L_{max} - L}{L_{max} - L_{min}} + 0{,}5 \times \frac{C_{max} - C}{C_{max} - C_{min}})$$

The correspondence between the technologies of the eHighways 2050 study and the implementation in METIS is defined in Table 8.

Technologies eHighways 2050	Assets Metis
Wind (MW)	Wind onshore fleet
PV (MW)	Solar fleet
CSP (MW)	CSP fleet
Biomass I (MW)	Biomass fleet
Biomass II (MW)	Biomass fleet
Nuclear (MW)	Nuclear fleet
OCGT (MW)	OCGT fleet
Gas without CCS (MW)	CCGT fleet
Gas with CCS (MW)	CCGT fleet
Coal without CCS (MW)	Coal fleet
Coal with CCS (MW)	Coal fleet
Lignite without CCS (MW)	Lignite fleet
Lignite with CCS (MW)	Lignite fleet
Demand (GWh)	Power demand
RoR (GWh)	Hydro RoR fleet
Hydro with reservoir (MW)	Hydro fleet
PSP (MW)	Pumped storage fleet

Table 8 - Key of technologies of the eHighways 2050 study and the METIS assets

For the disaggregation operation from the zonal to the nodal level to work properly (see Section 5), several assets had to be added manually to the model to maintain consistency between existing technologies in the zonal model that were absent in the nodal dataset. Table 9 shows the number of added assets per country. To all missing assets a *relative Pmax*[13] was added in order to ensure the right conversion is used during the downscaling process.

Technology	AT	BE	BG	CH	CZ	DE	DK	EE	FI	GR	HR	HU	IE	LU	LV	ME	MK	MT	NL	NO	PL	SE	SI	SK
Biomass fleet											1			1				1						
CCGT fleet																		1		7				
Coal fleet	3	1	1		2		2	1		2		1	1		1								1	1
Hydro fleet						7							1						1		5		1	1
Hydro RoR fleet																	1							
Lignite fleet					2			1	2	2	1	1				1						4	1	1
Nuclear fleet				2															1					
OCGT fleet					2		2	1						1			1	1		7		4	1	
Pumped storage fleet							2															4		
Solar fleet																		1						
Wind onshore fleet																		1						

Table 9 - Manually added assets to complete the model

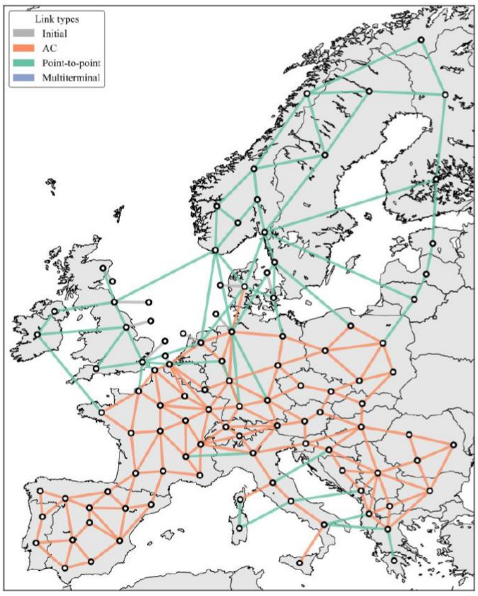


Figure 18 - Grid model and offshore production sites used in [8]

To connect the 25 additionally added offshore wind farms to the grid model the correspondent lines were implemented. The production sites of the offshore wind production sites are based on (Dedecca, 2018) and is shown in Figure 14. The number of added offshore wind production sites for METIS are listed in Table 10 and illustrated in Figure 19.

[13] In our model, the *relative Pmax* of one production asset represents the "share" of the installed capacity of this asset related to the total installed capacity of the zone in which it belongs, for the given type of production asset. For example, if there are 3 times more Nuclear capacity on node A in country "AT" compared to node B, then the relative Pmax of "Nuclear" on node A will be 3, and on node B will be 1.

Country	Number of added offshore wind production sites
GB	4
BE	1
NL	1
DE	1
DK	2
NO	1
SE	1
GR	1
IT	2

Country	Number of added offshore wind production sites
FR	3
ES	1
EE	1
FI	1
IE	1
LT	1
LV	1
PT	1
PL	1

Table 10 - Offshore wind production sites added to the model

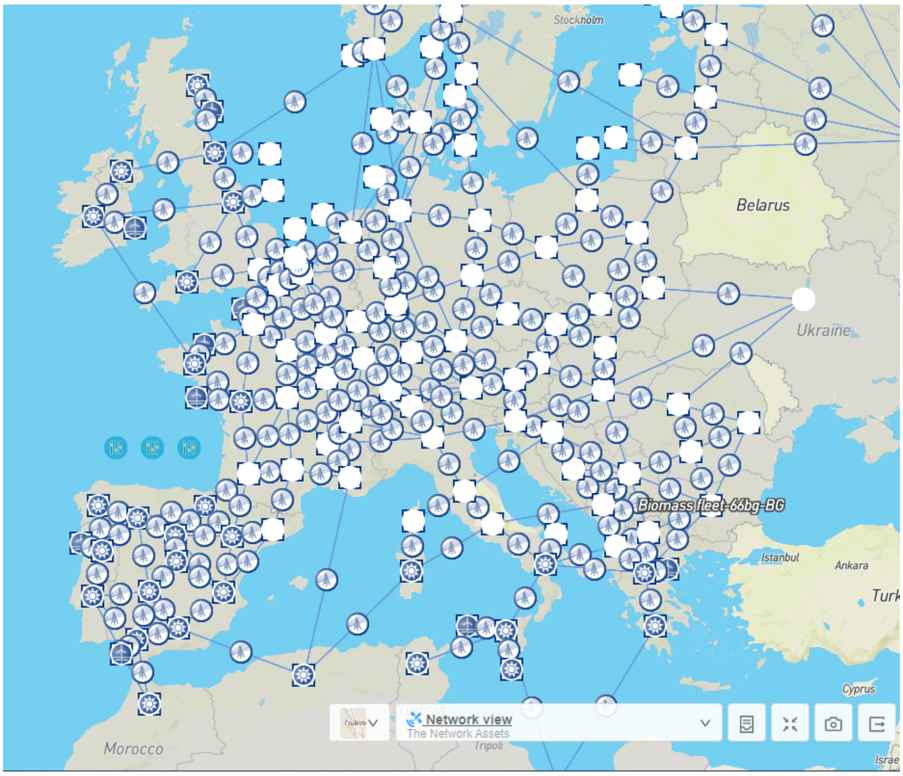


Figure 19 - Network view in METIS with added offshore production sites

This dataset can be easily configurable in case of specific modelling.

4.2.2 DESCRIPTION OF THE DATASET

The implemented 128 nodes grid model for METIS contains 245 transmission lines, consisting of 92 HVDC lines and 153 AC lines. The HVDC lines are used for the interconnection lines between countries. For countries with no grid data available, exchanges between nodes have been modelling using HVDC lines too, as shown in Figure 14 above (United Kingdom, Sweden, Norway, and Finland). All lines are modelled at a 400 kV voltage level. The eHighways dataset of the grid model does not include PSTs. The number of lines within each country is displayed in Table 11.

Zone	Nb of internal lines	Zone	Nb of internal lines	Zone	Nb of internal lines
AT	2	LT	1	NL	1
BE	1	LV	1	NO	9
CH	1	ES	19	PL	8
CZ	1	FI	2	PT	2
DE	14	FR	30	RO	3
DK	3	GB	10	SE	4
EE	1	GR	2		
IT	7	IE	1		

Table 11 - Number of internal lines per zones

The following generation technologies are represented in the model: OCGT, CCGT, Lignite, Coal, Nuclear, Solar, Pumped hydro storage, Hydro ROR, Hydro, Biomass, Wind onshore and wind offshore.

The breakdown per country is displayed in Figure 20.

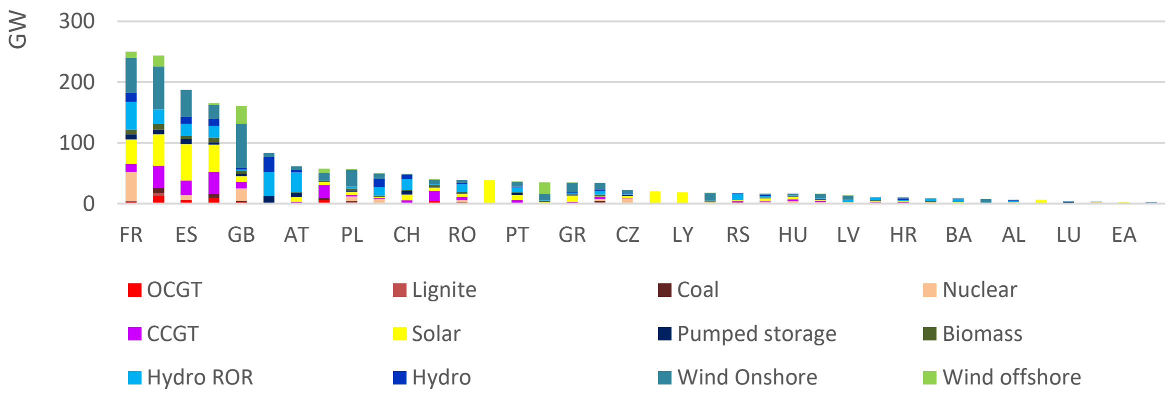


Figure 20 - Installed capacities per country in METIS

The demand side of the model is also based on the “Big & Market” scenario of the eHighways 2050 study. The allocation of demand per country is shown in Figure 21.

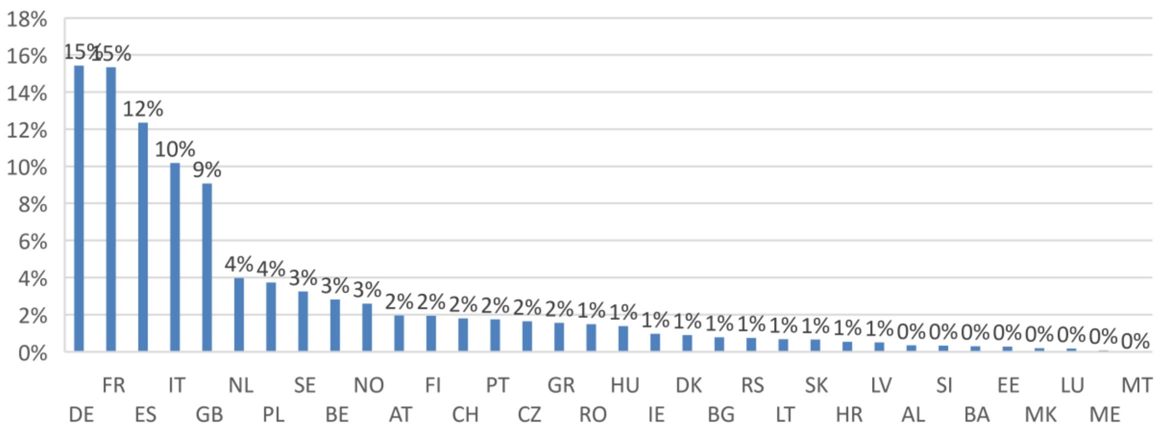


Figure 21 - Share of total demand over European countries in METIS

5 INTERACTION WITH THE ZONAL MARKET MODULE

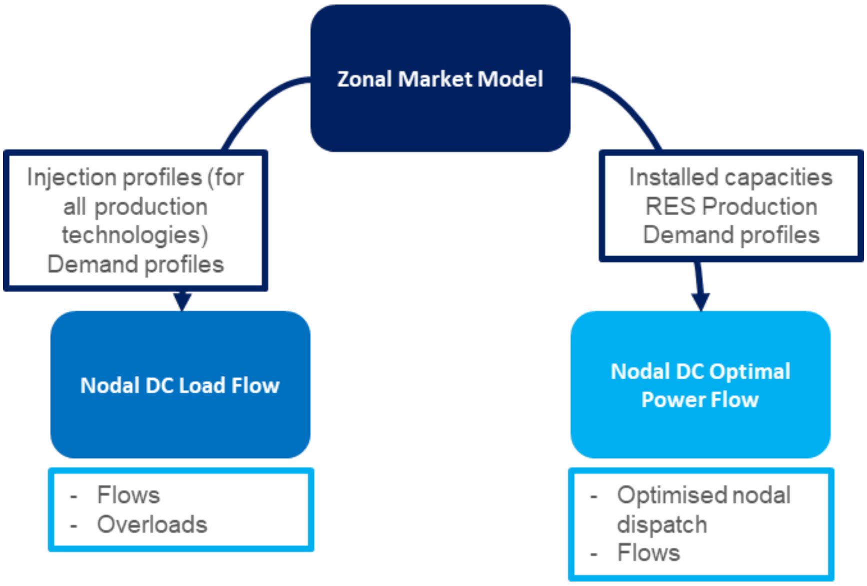


Figure 22 - Disaggregation from zonal to nodal model

5.1 DISAGGREGATION PROCESS

Transmission grid modelling in METIS has the purpose to extend the scope of power system modelling from a pure market-based approach (as in METIS 1) to a more holistic assessment, integrating the transmission grid dimension. The METIS transmission module aims at explaining how the results of the pure market-based approach (which will also be called "zonal market model" in the following sections) can differ from a simulation at a nodal level that takes into account internal transmission network constraints. The transmission module enables the user to study topics such as nodal market configurations or redispatch.

The overall framework relies on following the sequence of electricity markets: first the wholesale market produces a dispatch for each bidding zone of the system. Since the market does not take into account the physical constraints of internal networks, it cannot prevent from potential unfeasible dispatches. To overcome this issue, TSO have mechanisms to alleviate congestions on transmission networks through remedial actions such as redispatching/countertrading where part of the production and/or demand schedule is modified compared to the outcome of the market clearing. The transmission module aims at better capturing the techno-economic stakes of this process.

The METIS transmission module enables the user to simulate the operations of a transmission grid defined by a projection of the "zonal market model" onto a nodal level, including the transmission network for each European country that includes internal transmission lines, interconnections, transformers, aggregated generation capacity per technology per node and aggregated demand per node. The "nodes" of the network are aggregated per voltage level and represent the network substations. They are linked either to an asset (generation, demand) or to another node via a transmission or a transformer. This process is called "disaggregation", and aims at **transferring information from a zonal model**, **to a nodal model** to create consistent representations of the same scenario, enabling the user to simulate the same situations in both models.

How does the transmission disaggregation work?

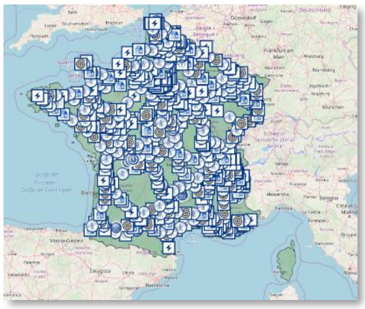
 

Figure 23 - Zonal market model (left) - nodal transmission model (right) for France

The disaggregation from the zonal market model to the nodal transmission model is done in 4 steps:

(a) Mapping from zonal technologies to nodal technologies

(b) Disaggregation of installed capacities of generation technologies for each node

(c) Disaggregation of demand for each node

(d) Disaggregation of commodity prices and production costs.

The disaggregation principle relies on a projection of the zonal market model to a nodal transmission model. The nodal description of the grid is composed of the following elements:

- Transmission lines (internal and interconnections):
  - Maximum capacity in MW
  - Reactance in Ω
- Transformers:
  - Maximum capacity in MW
  - Reactance in Ω
  - For Phase Shifting Transformers: minimum and maximum phase shift angles in degrees
- Generation assets per node and per technology:
  - Disaggregation capacity in MW
  - Minimum load in % of available capacity – if applicable
- Demand assets per node:
  - Disaggregation demand in MW

The outputs of the disaggregation process are the results of the projection of the characteristics of the zonal scenario on the nodal transmission model. More precisely, the disaggregation process outputs are:

- **Installed capacity in MW** per generation asset per node, disaggregated from zonal modelling *(based on the initial "Disaggregation capacity" assumption in the nodal representation)*

- **Commodity prices** from zonal modelling (CO2 emissions costs, fuel costs)
- The **availability timeseries** that set the available capacity for each timestep of the simulation per asset, derived from zonal modelling
- **Production costs** for each nodal technology derived from the results of the zonal market model.
- **Net-positions** (exports – imports) for each zone given by the zonal market model simulation
- **Power production by asset and by zone** given by the zonal market model simulation

Description of the disaggregation steps:

- **(a) Mapping zonal and nodal technology**:

  This first step is important because the description of the technologies might vary from one zone or dataset to another. Thus, the mapping process enables to link the zonal market model conventions (in our case, the METIS list of technologies), with the nodal transmission model description. It is based on the data that is used for the nodal transmission representation of the transmission network.

  Example of a technology mapping for the disaggregation process:

Zonal technology	Nodal technology
Coal fleet	Other fleet
Decentralized thermal fleet	
Derived gasses fleet	
Geothermal fleet	
Lignite fleet	
OCGT fleet	
Oil fleet	
Other renewable fleet	
Other thermal fleet	
Regulated Coal fleet	
Regulated Oil fleet	
Waste fleet	
Wind offshore fleet	Wind offshore fleet
Wind onshore fleet	Wind onshore fleet
CCGT fleet	CCGT fleet
Hydro fleet	Hydro fleet
Pumped storage fleet	Pumped storage fleet
Hydro RoR fleet	Hydro RoR fleet
Nuclear fleet	Nuclear fleet

  The mapping must be provided for each zone, as the accuracy of the network description can vary from one zone to another.

- **(b) Disaggregation of installed capacities of generation technologies for each node**

  The second step of the disaggregation is the adjustment of installed capacities at the nodal level, for every nodal technology. The mapping realized in the first step enables to compute the total capacity per nodal technology that has to be disaggregated between the nodes of each zone.

A nodal coefficient for disaggregation is computed for each technology, based on the "disaggregation installed capacity" that is given in the default nodal description of the grid, as described in Section 4.1.2.2. This value is used as a "weight" to compute the share of a given nodal asset over the total capacity of its zone to be consistent with the zonal scenario.

The example below is a simplified version for the "Wind onshore fleet" technology in the case of a 3-nodes representation of France's transmission network and a total zonal installed capacity of 30 GW:

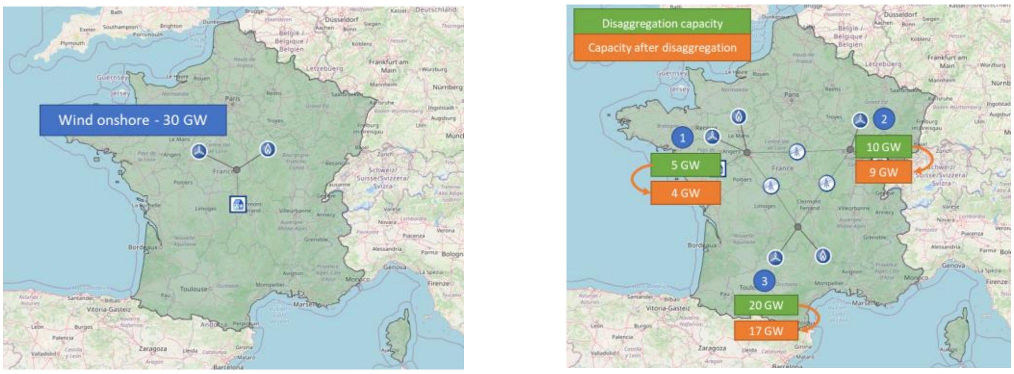


Figure 24 - Illustration of capacity disaggregation (simplified model)

	Disaggregation capacity	**Disaggregation coefficient**	**Nodal capacity**
Wind onshore 1	5	14% = 5 / (5 + 10 + 20)	4
Wind onshore 2	10	29% = 10 / (5 + 10 + 20)	9
Wind onshore 3	20	57% = 20 / (5 + 10 + 20)	17

The availability (which represents the maximal "load factor") for generation assets in the nodal description is taken from the corresponding zonal market model asset.

- **(c) Disaggregation of demand for each node**

The disaggregation of the demand is based on the same principle as the disaggregation of the installed capacities of power generation. Each node has a determined coefficient for the share of the demand of the zonal model, which comes from the CGMES dataset. The demand is split between the nodes based on this coefficient provided in the nodal description of the grid for each zone.

- **(d) Disaggregation of commodity prices and production costs**

The last step is the disaggregation of the costs from the zonal model to the nodal model. For CO_2 emissions, and fuel costs (gas, oil, coal, lignite, biomass etc.), they are retrieved from the zonal model and implemented in the nodal model depending on the zone (costs might vary from one zone to another).
As production costs are not provided in the implemented nodal description of the transmission network, they are computed on top of the results of the zonal market model, per nodal technology (according to the mapping provided in step 1). For each zone, and each nodal technology, the generation cost in €/MWh is equal to the production costs of the corresponding zonal assets computed over the year of simulation (€), divided by the production corresponding zonal assets over the year (MWh)

5.2 SET INJECTIONS AND WITHDRAWALS FOR DCLF MODELLING

When the objective is to perform a DCLF simulation, injections and withdrawals have to be calculated for each node and provided to the DCLF algorithm.

In order to carry out the disaggregation of the model from a zonal to a nodal level, an additional operation was implemented in METIS. The operation, that is executed after the disaggregation process described above, allows the user to generate a number of random draws, representing different injection configurations that are compatible with the market outcome.

The national market dispatch determines the amount of electricity produced and consumed by each type of the asset in each zone. The distribution of the determined national dispatch on zonal level to the individual assets within the asset categories is based on random draws respecting:

- The national market dispatch (by type of asset and zone)

as well as the technical constraints of each asset like:

- Minimum load
- Maximum available capacity

First, the minimum load of every asset is allocated to ensure that the constraint that every asset produces at its minimum load is met. Afterwards, the remaining amount of the production given by the market dispatch is allocated randomly within the technical limits of every asset (maximum available capacity).

The possibility to allocate the dispatch per zone and per technology on a random basis has been implemented in order to mimic phenomena such as contingencies, like for instance operational maintenance on power plants. In addition, the random allocation of injections and withdrawals allows to analyse different scenarios representing different network situations which are compatible with the market outcome.

The workflow of the operation is visualised in Figure 25:

Country	Technology	Market dispatch value
France	Nuclear	10 GWh

Draw	FR – 1 *Nuclear*
Draw 1	4
Draw 2	0
Draw 3	0
Draw 4	5

Draw	FR – 2 *Nuclear*
Draw 1	6
Draw 2	3
Draw 3	0
Draw 4	0

Draw	FR – 3 *Nuclear*
Draw 1	0
Draw 2	4
Draw 3	4
Draw 4	0

Draw	FR – 4 *Nuclear*
Draw 1	0
Draw 2	3
Draw 3	6
Draw 4	5

Figure 25 - Operation to distribute the injection from zonal level to the assets

6 MAIN OUTPUTS INTERFACE

In general, existing KPIs of the METIS platform are available for the transmission module. The specificity of the module is that simulations only cover 1 timestep, thus the temporal scale is different than usual simulations.

The following KPIs are interesting in the study of transmission networks:

- **Transmission usage** (%): the usage rate of each line can be computed and analysed as a distribution to get a macro vision of the overall network situation. The usage rate is defined as the *hourly* flow on each line divided by the line capacity.
  This KPI can be used to count the number of congested lines in the network. A line can be considered as congested if its transmission usage is greater than 99,9 %. In DCLF, the transmission usage of lines can go beyond 100% as there are no capacity constraints on the bidirectional transmission assets.

- **Curtailment** (MWh): total curtailed energy due to overloads on the network. Congestions on the network will cause production curtailment on some nodes. Curtailed energy must be balanced with "loss of load" production, or un-served energy at another network location.

- **Loss of load** (MWh): total unserved energy due to overloads on the network. Similar to curtailment, congestions on the network will prevent electricity demand at some nodes to be served. This un-served energy must be balanced with curtailed energy.

- **Production mix** (MW): the analysis of the production mix shift between two simulations will relate the effects of congestions on the dispatch (in DCOPF simulations where production is optimised).

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