e-HIGHWAY 2050

Modular Development Plan of the Pan-European Transmission System 2050

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WP 2			
D 2.2	**European cluster model of the Pan-European transmission grid**		

		Date & Visa
Written by	Thomas ANDERSKI, Yvonne SURMANN, Simone STEMMER, AMPRION Nathalie GRISEY, Eric MOMOT, Anne-Claire LEGER, Brahim BETRAOUI, RTE Peter VAN ROY, ELIA	June 6th 2014
Validated by	Thomas ANDERSKI, AMPRION	August 28th 2014
Approved by	Brahim BETRAOUI, Gérald SANCHIS, RTE	August 31st 2014
Updated by	Thomas ANDERSKI, AMPRION	July 20th 2015

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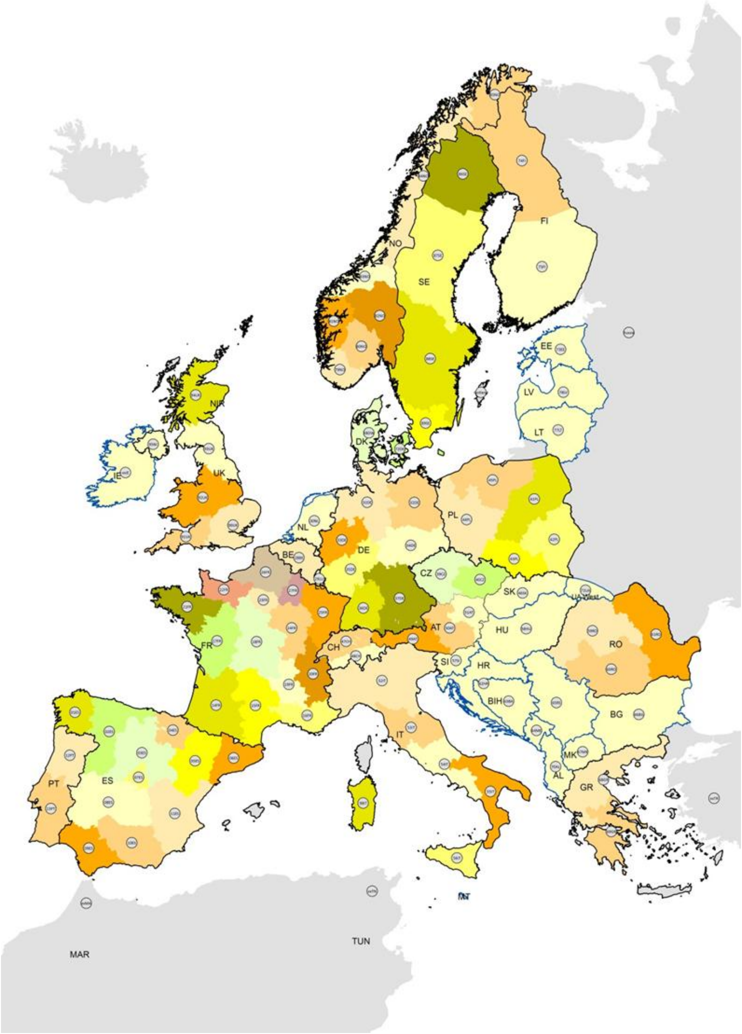
Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

EXECUTIVE SUMMARY

This deliverable report introduces the European grid model developed in within work package 2. It is a model derived from the pan-European transmission system and is used in the system simulations of the project and for further analyses. Given the long time horizon the project is faced with and the width of the system under study, the detailed pan European system is split into 106 geographical clusters, leading to a simplified interconnected system (see next figure). These clusters, which are considered as being free of grid constraints, and the equivalent connections between them, whose technical parameters have been derived from the real transmission network, are the basis for all analyses.



The technique for clustering intends to capture the contrasts in generation potentials and load on the European territory that will generate flows of electricity. The grid perspective is involved by a pool of TSOs, who have been consulted frequently to benefit from their knowledge of the local transmission system and to increase the acceptance of results. The grid model is then built in order to simulate properly the physical flows and the potential overloads on the simplified grid.

- The clustering technique combines both quantitative and qualitative components. Based on technical criteria a mathematical optimisation algorithm defines around one hundred clusters for the European system. The resulting cluster model is further specified and adjusted in a second (qualitative) step. The mathematical model proposed is adjusted in consultation with experts (such as Transmission System Operators, TSOs), who could contribute their specific knowledge. Around 100 clusters have been deemed as a good trade-off between accuracy of the study and the complexities that are inherent in such a wide and long term horizon study. With 100 clusters, one has a good approximation of flows and behaviour of the system and still manages the sophisticated task of allocating future generation capacities in the existing energy system.

- For the grid model the a transmission system has been used, that includes all transmission-lines, which either already exist or are likely to be implemented in the coming years up to 2030. As basis for this assessment served the Ten Year Network Development Plan (TYNDP) published by ENTSO-e. The grid model itself consists of assigned impedance and transmission capacity to each (in 2030) existing inter-cluster link. This method enables a good modelling of the flows between the clusters. The resulting model provides a calculation of transfer capacities for each equivalent link. The transfer capacities are suggested for discussion in a consultation of experts (TSOs), who can provide specific knowledge to adjust the transfer capacities in the model.

The result of the work described in this report is a simplified but solid model of the pan-European transmission system, which balances complexity and applicability in order to efficiently perform further research through system simulation and grid analysis. Furthermore the clusters, as basis for the grid model, have been defined in such a way that they can be regarded as being independent from the developments in the five e-Highway 2050 scenarios. This will allow a comparison of the final grid architectures and therefore give robust indications of the required expansions. It is the aim of the project work to identify links throughout Europe that proof their benefit across most or all scenarios and to provide recommendations to TSOs, which can use them as basis for further, more detailed grid development planning on shorter time frames.

A high acceptance of results of this study is required to support the decision processes of the national TSOs. Deliverable 2.2 (D2.2) is characterised by a high degree of consultation of results and inclusion of feedback by TSOs and the European Network of Transmission System Operators for Electricity (ENTSO-E).

Table of Contents

Table of Figures

Table of Tables

List of Abbreviations

CIM:	Common Information Model
COSMO:	Consortium for Small-scale Modelling
COSMO-EU:	A new application of the COSMO model
DUMP:	Dump-Energy – Energy produced at different points in time that exceeds the demand and therefore is not used (“opposite” of ENS)
DWD:	Deutscher Wetterdienst (Germany's National Meteorological Service)
ENS:	Energy not Served – Share of the demand that can’t be satisfied by available generation capacity (“opposite” of DUMP)
ENTSO-E:	European Network of Transmission System Operators for Electricity
GTC:	Grid Transfer Capacity
HVDC:	High voltage direct current
NTC:	Net Transfer Capacity
NUTS:	Nomenclature des unités territoriales statistiques
PNBEPH:	Portuguese National Program of Dams
PST:	Phase Shift Transformer
PTDF:	Power Transfer Distribution Factor
RES:	Renewable energy sources
SBCA:	Strategic Benefit-Cost Assessment
RMSE:	Root Mean Square Error
SDC:	System Development Committee – Body within ENTSO-e to plan and organize system development planning
TC:	Transfer Capacity
TSO:	Transmission System Operator
TYNDP:	Ten year network development plan (published by ENTSO-E)
MM:	man-month (or person month)

1 Introduction

WP1 has identified energy scenarios at 2050 (qualitative description at the European scale). WP2 quantifies more precisely these five possible scenarios, and analyses through system simulation the bottlenecks of the existing grid and the required network developments to accommodate this generation mix.

Given the time horizon and the width of the system, a simplified model of the pan-European electrical system appears necessary. The definition of this model is described in this deliverable.

After a review of the challenges and motives behind this task, this document presents the clustering technique used to split the European system into a hundred areas and its results. Finally, the calculation of a simplified, yet electrical, model of the equivalent grid is presented. All along the process, ENTSO-E has been consulted. Results of these consultation processes are also detailed along the document.

This simplified model of the system serves as basis for system simulations and network reinforcement analysis to be carried out in the following tasks.
This resulting deliverable can be divided into two parts. Basically, part one is about developing a geographical cluster model of Europe. Part two is applying a method to simplify the grid model.
In terms of internal processes, the following activities were conducted:

1. Development of starting grid 2030 (based on the actual grid and the ten year network development plan (TYNDP) enlargements),
2. Regionalisation/clustering of Europe (including the verification of clusters),
3. Definition of distances between the proposed regions/clusters,
4. Grid reduction to define and verify the transportation capacities between regions/ clusters,
5. ENTSO-E internal verification
6. Solution for national transmission grids that are not represented by the TSOs involved (i.e. Great Britain, Ireland and Hungary)

2 Objectives and challenges of the work

The key function of Task 2.2 “The Pan-European model of the Transmission System for 2050” is to provide a cluster model of the pan-European transmission grid.

This model will be used in the following processes and tasks of the project:

- ***Task 2.1 (scenario development):*** The European grid model shall enable a more detailed allocation of energy generation and demand for 2050 than at country level.
- ***Task 2.3 (system simulations):*** System simulations allow the calculation of hourly load flows for several years as well as the use of several time series for renewable energy generation and demand. Hourly calculations are necessary as they are used to analyse the correlation between different in-feed time series of renewable energy sources (RES) as well as to define how often congestions appear over one year. The use of several time series allows for in depth analysis of the different situations, in which the power system could be threatened due to the intermittency of RES and the variability of demand.
  The system simulation integrates grid constraints (limited capacities and repartition of the flows) in market simulations. There is no consideration of internal grid when identifying the exchanges. The results of the system simulations are the generation costs per cluster, security of supply indicators (ENS) / spillage of RES (DUMP), determination of necessary exchange capacity increases.
- ***WP4 (operational validation):*** Especially, WP4 will require information about the transmission lines between regions. In order to ensure a proper performance of alternating current (AC) calculations it is necessary to have technical data available describing the line(s) of the transmission system connecting the different regions defined.

2.1 *Justification of the clustering approach and consequences*

The e-Highway2050 project - among other objectives - aims at identifying the transmission system required to achieve the European Climate Targets by 2050. This leads to the challenge of facing a time horizon of more than 35 years up to 2050. In particular, this leads to uncertainties with respect to political developments (changes in national targets and directives), national efforts of grid reinforcing (regular efforts of local TSOs to reinforce the system) and in geographical aspects (localisation of new generation and demand sides). The level of uncertainties at this time horizon is such that a scenario approach was chosen to identify 5 possible outcomes of the European generation mix evolution (see D 1.1 and D1.2)
Nevertheless, even within each one of these macro scenarios, neither installed generation, nor load can be precisely allocated at substation level without introducing major combinatorial effects.
Moreover, the study aims at providing a global analysis of the **whole European system at once (from Portugal to Scandinavia, and from Ireland to Ukraine).** In order to capture the

limitations and the needs in network for a given generation mix, hourly probabilistic simulations of the system are needed. This is particularly valid with a high share of renewables. For these reasons, studies at substation level are unrealistic. On the contrary, studies at country level are too imprecise for grid planning purposes. Consequently, the spatial granularity of the study has to be adapted to minimise these issues and an intermediate level, called cluster level, appears to be the most suitable for the e-Highway study.

The proposed clustering consists of connecting all generation and demand within one cluster to one virtual node. In the meantime, all inter-cluster links are merged into an equivalent link. Each virtual node or cluster can also be seen as the connection point between the overlay structure and the existing transmission grid. Consequently, the study (Task 2.3) will only concentrate on inter-cluster links, assuming the inner network of each cluster is a copper plate. For the scope of the study, which is to identify the overlay structure to be built in Europe, this choice seems adequate.

A common clustering to all scenarios has been chosen. It eases cross comparisons between scenarios and identification of reinforcements potentially shared between scenarios.

The system clustering enables:

- **a compromise between inaccurate studies at country level and too uncertain studies at substation level,**
- **the focus on long distance infrastructures (inter-cluster links),**
- a simplified, yet **clearer communication of results,**
- several variations within scenarios (e.g. different allocations of RES by a given installed capacity),
- easier performance of analyses with and without the existence of major projects such as Desertec or a North Sea grid.

Important notice: The suggested clusters in this study must not be understood as a recommendation for market or even price areas. The clustering of the European transmission system is done in order to identify transportation requirements in 2050 and elaborating grid architectures. It is neither suited nor dedicated to provide any statement to the price-zone discussion.

2.2 *Description of Processes*

In order to perform the clustering of the pan European system, different processes were identified to achieve a proper grid model.

Process 1: Development of the starting grid and its challenges

The current European transmission grid consists of more than 10.000 nodes for the 220kV/ 380KV grid. This describes (start of the study, 2012) the latest status. Since the study aims at identifying the additional need for grid reinforcement, that are not already planned by the European TSOs, the starting grid needs to be extended by the projects that are foreseen in the TYNDP 2014 report. These reinforcements are expected to be realised in the announced way and have therefore to be included.
The challenge is to set hypothesis and assumptions on the interconnections with external areas, such as the North Sea, North Africa and East of Europe (Ukraine, Turkey etc.).

Process 2: Regionalisation / clustering of Europe and its challenges

In this process, different regional clusters are detected (see Figure 1). Here a schematic representation of the transmission system is shown. A geographical clustering is applied to this structure – implied as cycles – and all nodes within these clusters are summarized. Some counts for generation and demand. These clusters are later used as smallest parts of the analyses, thus scenario data are quantified on this level.
Some countries already used a similar approach of different clusters for their specific studies or in their operational processes. Nevertheless, to have a homogeneous and common approach, criteria to conduct the clustering have to be defined (e.g. load/generation and grid constraints). These criteria have to be adapted to the context of the e-Highway 2050 project, where forecasts will be made for a very long planning horizon and for different scenarios what leads to uncertainties. (This process is detailed in part 3 of this deliverable)

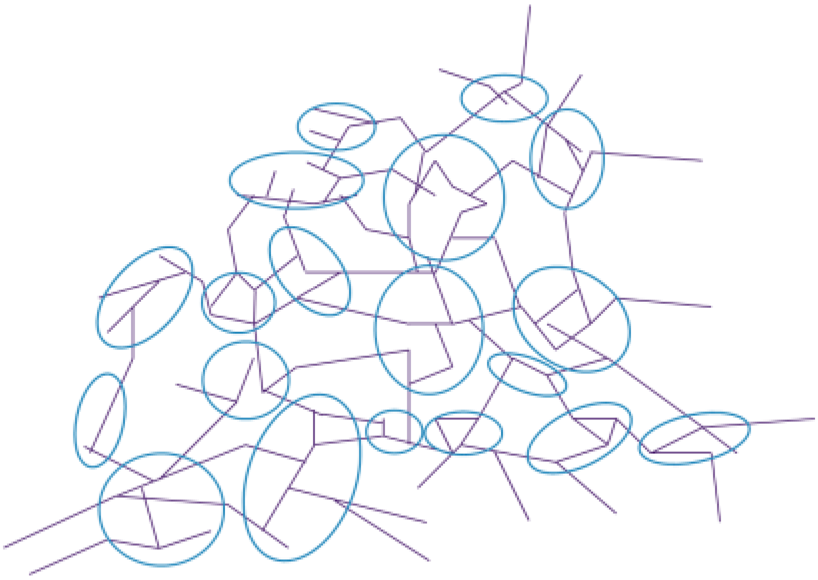


Figure 1: Scheme of a possible clustering of Europe

Process 3: Definition of distances between the proposed regions/clusters and its challenges

In order to conduct planning studies and assess right cost of reinforcements, it is necessary to define the length of the inter-cluster links. Length is usually one of the key factors that determine the best suited technology for transmission systems and highly affect their cost. To do so, the coordinates of the cluster centroids are used and their mutual distances calculated (direct line). This is an approximation, as the connection points of future lines within the clusters are unknown. For sure, it is a huge approximation to select one virtual node but this is inherent to the cluster model. (This process is detailed in part 3 of this deliverable)

Process 4: Grid reduction and technical description and its challenges

After the clustering, the European grid will be reduced to one node per cluster (see Figure 2). Inside the regions the grid is considered to be a “copperplate” (grid reduction on interconnectors). That means, that all real nodes are merged into one virtual node and that total generation and demand is aggregated. This approach allows to handle the uncertainties in forecasts of the allocation of installed capacity and demand, that cannot be exactly made, given the time frame of more than 30 years.[1] The critical questions which have to be answered in this process are:

> How can an appropriate modelling of the grid between the clusters be achieved?
> How will this modelling reflect the behaviour of the system in terms of flow repartition and grid thermal capacities limits?

Therefore defining an appropriate methodology to perform the grid reduction, i.e. calculating transmission capacities and data on flow repartition, is the most important part of this process. (This process is detailed in part 4 of this deliverable)

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[1] WP2 will not identify the constraints inside the clusters nor analyse voltage stability or undertake dynamic analysis of clusters for the whole system. Sanity checks after grid development are planned.

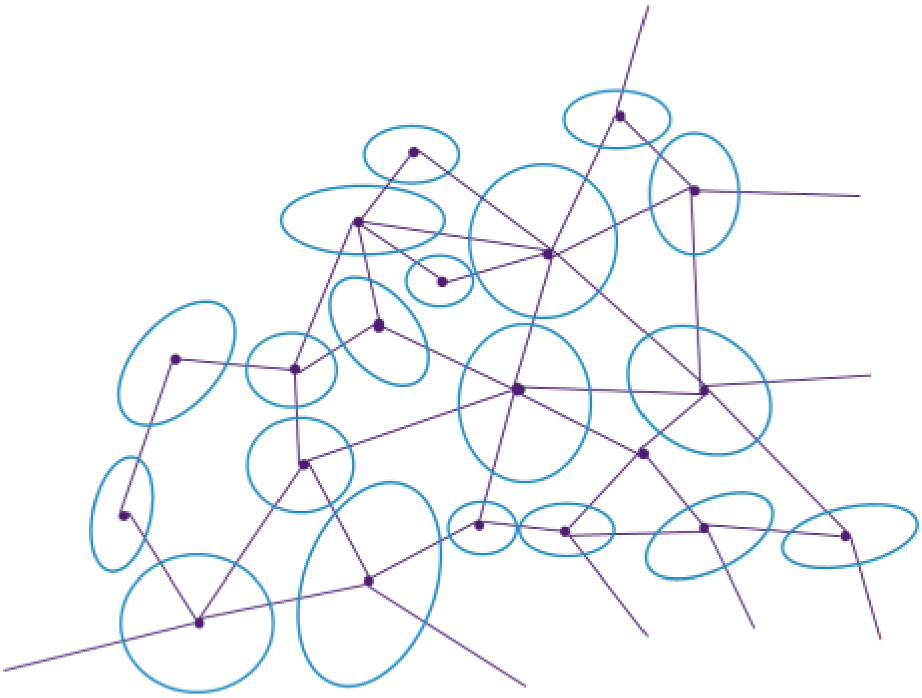


Figure 2 : Schematic illustration of grid reduction

Process 5: Consultation

Different types of consultation procedures are conducted for the proposed clustering model. The verification of the model by the TSO community guarantees a high acceptance of the results. Consultations are seen as most effective tool to receive latest information (especially concerning developments in the transmission grid status) from stakeholders and increase the acceptance of the approach.

(A more detailed description of the consultations can be found in chapters 3.3 and 5.4 of this report.)

3 Clustering of Europe

The clustering process is split into 3 sub-processes:

1. Definition of clustering criteria
2. Use of a clustering algorithm
3. Consultation of clusters through ENTSO-E

3.1 *Criteria to define clusters*

The criteria for clustering and thus for defining a cluster model have been elaborated by visualising the targets of the grid development. The following **key issues** have been identified in the definition of relevant clusters:

- Clusters should be valid among all scenarios to enable comparison between scenarios. Thus, they should reflect all possible development paths. Clusters should be defined with a common methodology for all countries.
- Clusters should highlight the main expected electricity flows.
- Clusters should be defined to allow the identification of key reinforcements. They should not be too wide in area, in order to be more precise when assessing grid reinforcements.
- Clusters should not be too small because it is impossible to locate generation and demand at a small scale.
- The number of clusters must be limited. Even though a model with a high amount of small presumably detailed clusters may appear to be a precise model, it actually causes the opposite. This accuracy is illusive.
- Clusters should respect the national boundaries. Indeed, national policies, such as nuclear phase-out, cannot be considered in cross-borders clusters. Moreover, many stakeholders are interested by results on national levels.

A two-step approach has been adopted (shown in Figure 3 below) comprising the development and application of a mathematical algorithm for cluster definition as well as a consultation of the TSOs to verify the calculated clusters:

- **Step 1:** Based on technical criteria a clustering algorithm is run to retrieve first version of clusters for all countries in Europe. For this part direct (measurable) criteria are necessary that can be integrated in a mathematical optimisation.
- **Step 2:** The results from the first step are suggested for discussion. In this second step, indirect criteria, local knowledge and political conditions can be integrated to improve the quality and acceptance of the clustering.

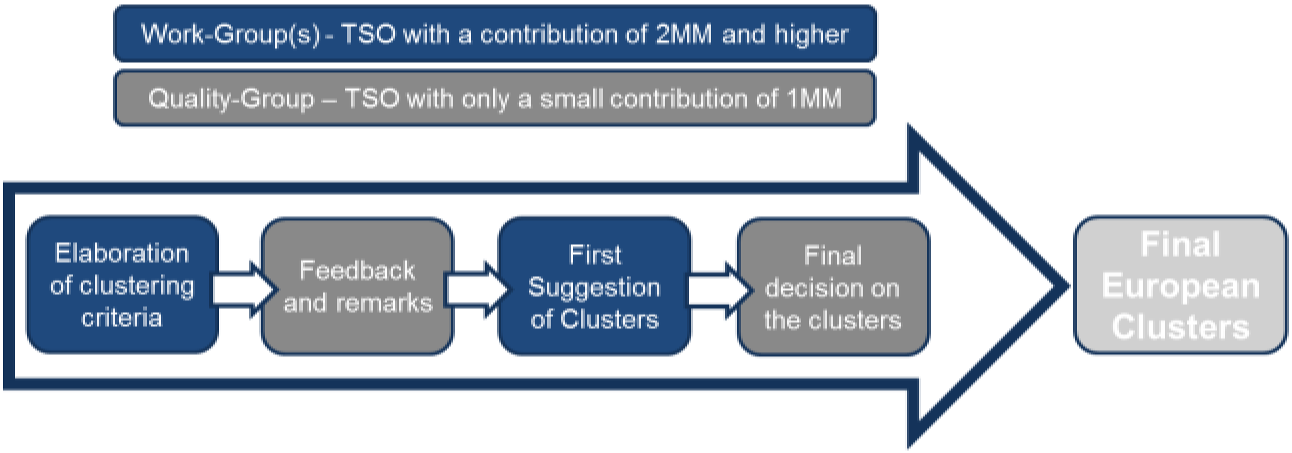


Figure 3: Scheme for TSO consultation/cooperation within process of clustering

When implementing the approach in this study, a high effort was given to a close interaction with the TSOs involved in the study. A frequent feedback from them was also requested. The criteria, basis for both steps, have been elaborated in a working group and were put to discussion. The final selected criteria have been distinguished into measurable criteria, used by the algorithm (see part 3.2.3) and non-measurable criteria taken into account during the consultation (see part 3.3.2).

Depending on their man-month (MM) contribution to Task 2.2, TSOs were split up into two different groups: a work-group with a contribution of 2MM and higher and a quality-group with a contribution of only 1 MM.

In order to reach a verified cluster model an intensive interaction between the work-group of TSOs and the quality-group was necessary.

3.2 *Clustering algorithm: formulation and results*

3.2.1 *Method for clustering*

To ensure an un-biased and common clustering of European countries, a mathematical algorithm is used to define a first proposal of clusters. The principle of this algorithm is to aggregate small regions with similar characteristics into clusters and, on the contrary, to set regions with different characteristics in different clusters. The idea behind this is to identify homogenous clusters, which are characterized by one or two main criteria. The characteristics considered are strongly linked to the consumption and generation potentials of the regions. The purpose is to catch the fundamental differences between regions regarding their electricity needs and so to create clusters that would probably have to exchange electricity with each other because of their differences.

Example to illustrate the clustering algorithm

The clustering starts with the assumption of a squared region, which is divided into symmetrical areas. (compare Figure 4) In later use these regions are the European countries which are split up in smaller regions (NUTS - Nomenclature des unités territoriales statistiques)

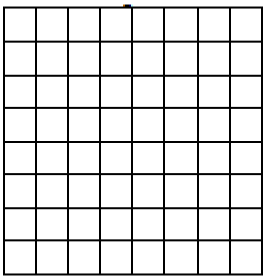
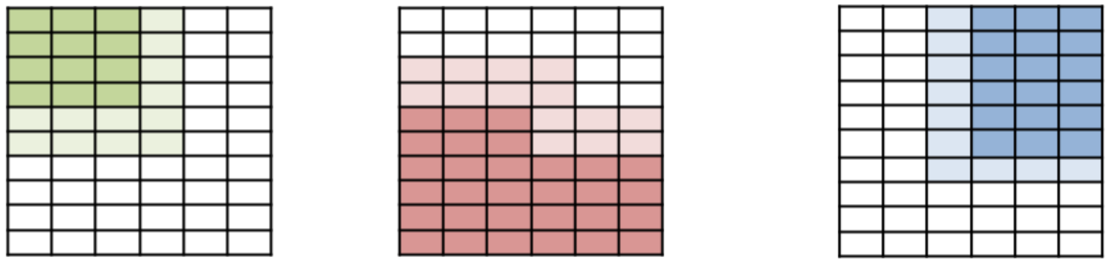


Figure 4: Assumption of a squared regions

This schematic country has key characteristics that will impact power generation and demand such as wind power, hydro generation and population. The following mapping of these characteristics within a country is considered by identifying the values of these characteristics on regional level. In Figure 5 a (random) allocation of characteristics is shown. We see in this example, that the region in the North-West of the country is mainly characterized by wind speed (and thus production). North-Eastern area shows potential mainly for hydro-production and in the southern part the population and thus the demand is located.



Average wind speed

(Green: High, White: low)

Population

(Red: High, White: low)

Hydro power and pumped storage

(Blue: High, White: low)

Figure 5: Mapping of key characteristics

If one would consider the whole country as one cluster a mistake concerning the transportation requirements would be made. Since for analyses the clusters are assumed as a copper-plate it is implicitly assumed, that energy can be exchanged freely inside. This means, that in the analyses now grid constraints will be seen and thus security of supply problems are overlooked. To prevent this clusters are not allowed to be too heterogeneous.

Combining these layers leads to the results in the figure below, which provides an appropriate clustering of a country (on the right- Figure 6).

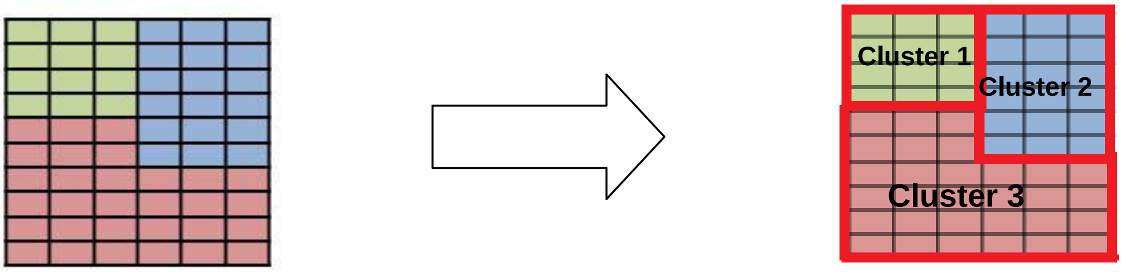


Figure 6: Combined mapping of key characteristics

This clustering considers the need for exchange of electricity inside a country. From an energy perspective the country might be self-supplying. But it is the target of e-Highway2050 to look at the need for overlay structures and the issues of electricity transport need to be addressed. The problem of underestimating the need for transportation does increase with the size of a cluster. Thus large countries need to be clustered, while in cases of smaller countries it can be sufficient to look at them as one cluster.

3.2.2 *The clustering algorithm*

While respecting the given number of clusters, the algorithm creates clusters that minimise the following objective function:

$$\boxed{\min \sum_{j=1}^{N} \sum_{k=1}^{L} W_k * \left(k_j - M_{k_j}\right)^2}$$

Where:

- ***N*** *is the number of initial zones (NUTS 3 regions, see below)*
- ***L*** *is the number of different features such as population or wind speed*
- $\boldsymbol{k_j}$ *is the value of feature k in zone j*
- $\boldsymbol{W_k}$ *is the weight of the feature k*
- $\boldsymbol{M_{k_j}}$ *is the average of feature k in the cluster of zone j.*

The algorithm can only merge adjacent regions into clusters. If no other geographical constraint is put into the algorithm, the resulting clusters can have very lengthened or very non-convex shapes. However, these kinds of shapes are not suitable for the purpose of the study. To avoid such results, two geographical features are added to the ones presented in part 3.2.3: latitude and longitude of Nomenclature of Territorial Units for Statistics (NUTS) regions.
To minimise this function, an algorithm from the ClusterPy[2] library is used. It is based on both a k-means algorithm and a Tabu-search algorithm.

3.2.3 *Inputs for the algorithm*

NUTS 3 regions

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[2] Duque, J.C.; Dev, Boris; Betancourt, A.; Franco, J.L. (2011).ClusterPy: Library of spatially constrained clustering algorithms, Version 0.9.9. RiSE-group (Research in Spatial Economics). EAFIT University. http://www.rise-group.org

The algorithm works on aggregating small areas into clusters. Therefore, to provide a basis for the algorithm, each country has to be subdivided into small regions.

The European Commission has defined three levels of administrative subdivisions for most European countries. These regions are called “NUTS” (Nomenclature of Territorial Units for Statistics). They are, for example, used for the Eurostat database. The smallest level of these subdivisions (“NUTS 3 level”) has been chosen to run the clustering algorithm (Figure 7). A description of these NUTS levels is available online[3] and the borders of the regions are also downloadable from EuroGeographics[4]. The main reasons for starting from NUTS 3 level regions are:

- They cover all the countries that need to be clustered;
- Their boundaries are clearly defined and available for any interested stakeholder;
- They enable to use some European databases defined at this level.

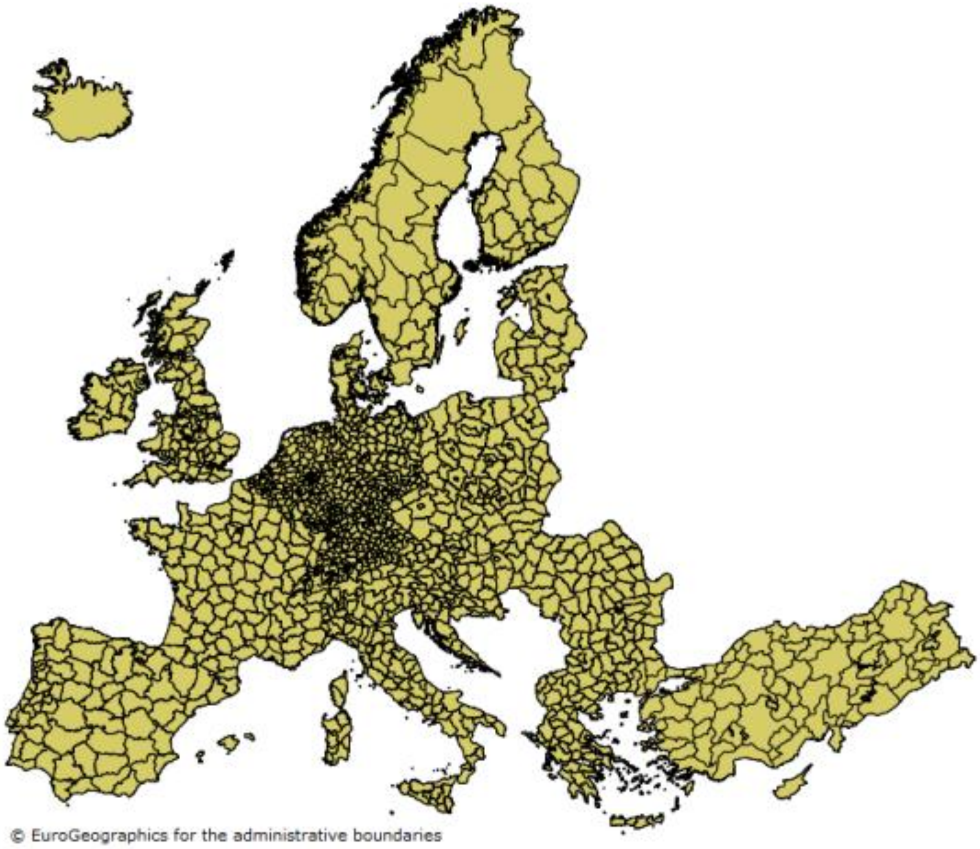
© EuroGeographics for the administrative boundaries

Figure 7: Representation of the NUTS 3 regions (©EuroGeographics)

Number of clusters per country

The number of clusters envisaged for Europe has been set to around 100. This number appears to provide an appropriate balance between receiving a sufficient amount of clusters in order to get a reasonable representation of each country, without sacrificing the ability to allocate load and generation. It was chosen to run the algorithm country by country in order to avoid clusters

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[3] http://epp.eurostat.ec.europa.eu/cache/ITY_OFFPUB/KS-RA-07-020/EN/KS-RA-07-020-EN.PDF

[4] http://epp.eurostat.ec.europa.eu/portal/page/portal/gisco_Geographical_information_maps/popups/references/administrative_units_statistical_units_1

that cross boundaries. Therefore, one important input parameter to start the algorithm is the number of clusters for each country.

The distribution of these 100 clusters among the countries has been estimated in three different ways: proportionate to load, proportionate to population and proportionate to the area of the respective countries. The average of these three calculations gave an objective number of clusters per country for the algorithm (see table in Annex A).

Features to describe the NUTS 3 regions[5]

The algorithm needs a set of features to assess the similarities or differences between the NUTS 3 regions. These features are chosen to reflect the demand of each region but also its generation potentials. Each of them is given a weight, depending on its significance for the clustering. These features are:

- **Population:** The population and its development are main indicators for the development of load. Therefore, (future) population centres are considered as demand centres. The Eurostat database provides population data of 2011 for each NUTS 3 region and also a growth projection for 2030 for each NUTS 2 region. These two data sets have been computed together to get a rough estimation of the population per NUTS 3 region in 2030, which are used for the algorithm. It is assumed that the distribution of the population in 2030 also provides a rough picture of the population in 2050. A weight of 2 is used for this parameter.
- **Wind speed:** In order to reflect the potential of wind for each region, mean speed is considered. Average yearly values have been computed for each region with 2011 and 2012 historical data provided by the COSMO-EU database[6]. Wind is already a key factor influencing power exchanges in some countries (e.g. in Germany) and its influence will probably increase in all countries with growing installed capacities. Moreover, mean wind speed can vary significantly within a country and therefore is very substantive when defining the clusters. This is why the highest weight (3) is given to this parameter.
- **Solar irradiation:** In order to reflect the potential of solar influences for each region, mean solar irradiation was considered. Average yearly values have been computed for each region with historical data for the years 2011 and 2012 provided by the COSMO-EU database. Irradiation does not vary as much within a country as does wind speed (e.g., from 122 W/m² to 144 W/m² in Germany). It mostly depends on latitude which is therefore taken into account by the algorithm. Finally, in some regions, solar generation may additionally be influenced by factors such as roof areas available (which is basically

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[5] If criteria were not provided by TSOs data were gathered from publicly available sources like Enipedia (http://enipedia.tudelft.nl/) or internal sources like COSMO weather database.

[6] COSMO-EU: A new application of the COSMO model. The COSMO model is the regional component of the numerical weather prediction system of Germany's National Meteorological Service (Deutscher Wetterdienst, DWD). The configuration COSMO-EU calculates regional weather forecasts for an area covering most of Europe with a horizontal grid resolution of 7 km for up to 78 hours forecast (compare Deutscher Wetterdienst: http://www.dwd.de).

linked to population) or land available rather than by the irradiation itself. Therefore, irradiation is given a weight of 1.

- **Thermal installed capacity:** Partners agreed that future thermal plants will more probably be located near existing ones because of public acceptance issues or because of the proximity to key sites such as gas pipelines, LNG terminals, coolant water sinks etc. The geo-localisation of all existing plants is not easily available due to confidentiality issues. For France and Germany, the plant locations could be provided by RTE and Amprion. For the other countries, the Enipedia free access database has been used, although it is rather incomplete.
  As the installed capacity in a region can be quite high, whereas for neighbouring regions it may be zero, many NUTS regions would end up being alone in a cluster (e. g. the Seine Maritime region in France), in case this parameter would be given a strong weight. Due to this fact, only the smallest weight (1) is given to thermal installed capacity.
- **Hydro installed capacity:** Hydro generation can only exist in very specific regions, such as mountainous areas or river sites. Due to this fact, future hydro plants will very likely be located near existing ones. However, the geo-localisation of existing plants is not easily available due to confidentiality issues. For France and Germany, plant locations have been provided by RTE and Amprion. For the other countries, except Poland (where Global Energy Observatory data has been used), the Enipedia free access database has been used, although it is rather incomplete.
  The power exchanges between regions with hydro generation and the others may be very significant. Therefore, the definition of “hydro clusters” is quite relevant and hydro generation was given the highest weight (3).
- **Agricultural areas and natural grasslands:** Wind speed alone does not completely reflect the wind power potential. Thus, wind farms cannot be installed in cities, forests or even mountains. On the contrary, agricultural areas and natural grasslands are suitable for wind farms. To take this into account, the area of agricultural land and natural grasslands is also considered in the algorithm. Data was extracted from the European “CORINE Land Cover” database. Because wind potential is already represented by mean wind speed, the criterion agricultural land is given the smallest weight (1).

3.2.4 *Results after algorithm*

The output of the algorithm is a set of clusters for each country, consisting of aggregated NUTS regions and thus containing a particular value for population, RES-potential and thermal- and hydro capacity.

As an example, the following figures illustrate the results for Germany. Figure 8 shows the main data for each cluster with its different characteristics, and Figure 9 shows the geographical illustration of the clusters.

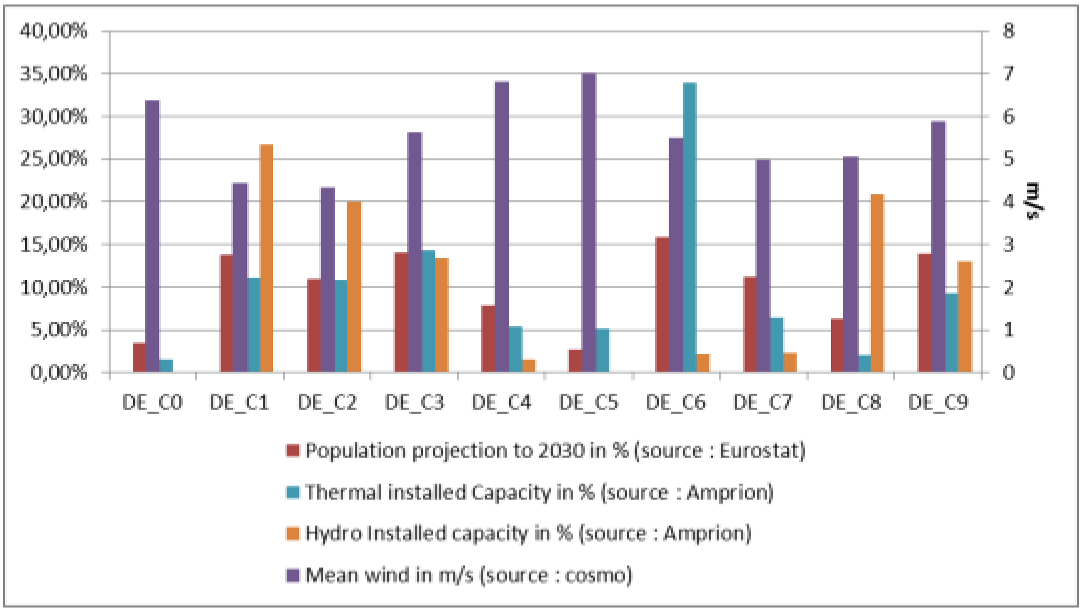

Figure 8: Main cluster data after algorithm – Example Germany

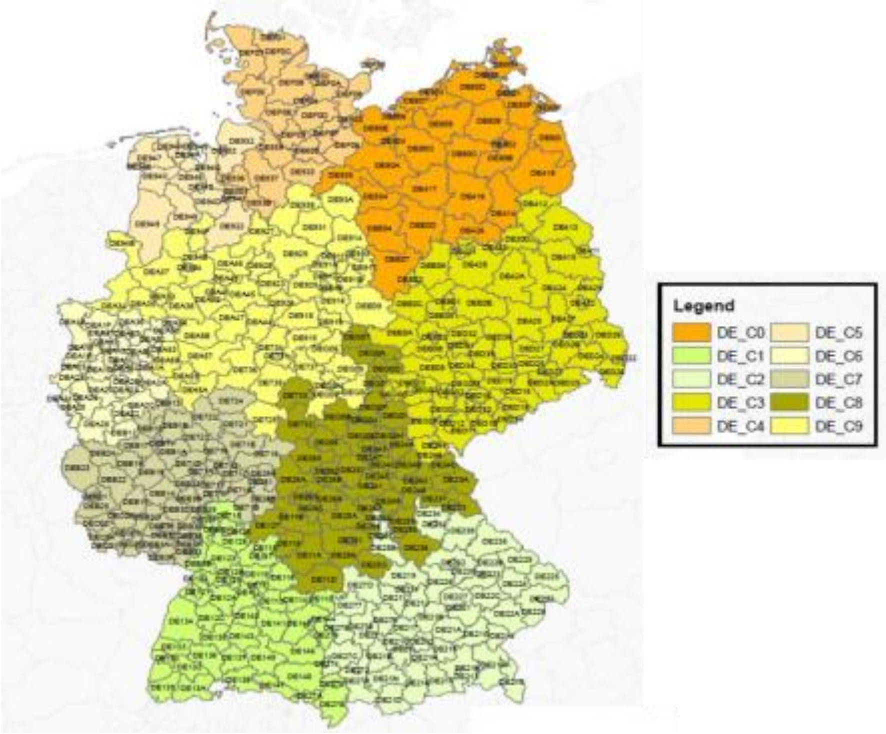

Figure 9: Graphical presentation cluster Germany – Results after algorithm

As a direct result of the clustering algorithm performed for 31 European countries, 91 clusters have been identified:

France:	12 clusters
Germany:	10 clusters
Spain:	10 clusters
Italy:	10 clusters
United Kingdom:	9 clusters
Sweden:	5 clusters
Poland:	5 clusters

Norway: 4 clusters
Austria: 3 clusters
Finland: 3 clusters
Czech Republic: 3 clusters
Romania: 3 clusters
Portugal: 2 clusters
Switzerland: 2 clusters
Belgium: 2 clusters
Netherlands: 2 clusters
Hungary: 2 clusters
Bulgaria: 2 clusters
Greece: 2 clusters

Besides these 91 clusters, there are additional 13 clusters. These directly represent single countries with only 1 cluster. These countries are:

Baltic States: Estonia, Latvia and Lithuania
Balkan states: Croatia, Bosnia-Herzegovina, Serbia, Montenegro, Albania, Macedonia
Others: Ireland, Slovakia, Slovenia, Luxemburg

At this point of the analysis, the clusters sum up to 105. Special circumstances in Denmark lead to two synchronous areas in the country. Therefore, Denmark is split into two clusters, dividing these two synchronous areas. Therefore, the starting point is 106 clusters.

These 106 clusters were used as a first suggestion for consultation of the TSOs (see Figure 10).

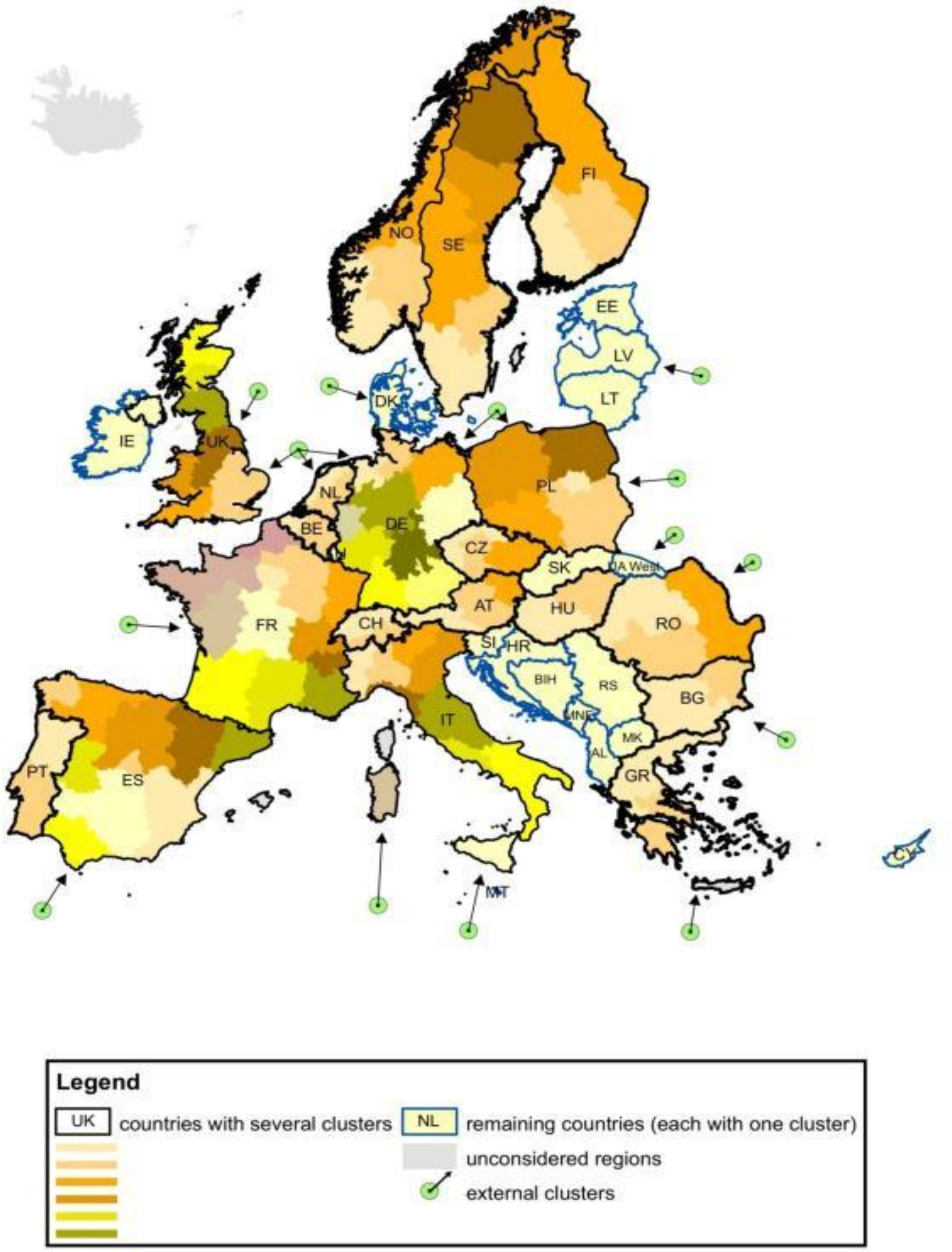

Figure 10: Graphical presentation of results from step 1 of the clustering approach

3.3 *Consultation on clusters*

3.3.1 *Indirect criteria used during consultation*

Some indirect criteria are not taken into account by the mathematical clustering algorithm. Thus, TSOs have been asked to adjust the clusters according to their specific knowledge of their country. Especially, the following indirect criteria have been identified:

- **Network density (degree of meshing and grid constraints):** This criterion includes the existing transmission system in the task of clustering. Even though based on direct criteria it is reasonable to introduce a cluster in a particular area, it is possible that, due to a high meshing in the existing system, constraints seem unlikely. Therefore it could be necessary to further merge clusters identified by the algorithm. The opposite situation is possible – meaning that an insufficient network density causes a further splitting of clusters.
- **Assignment of RES priority areas:** The algorithm provides for an estimation of potential for RES deployment and, based on this, a suggestion for a clustering. However, political issues concerning RES deployment plans or areas that have been assigned as RES priority areas will not be feasible to solve in this sense. In order to add these aspects to the clustering, the expert knowledge of local TSOs is necessary.
- **“Forced” grid areas or market areas:** In some countries market and grid areas are already existing or planned to be introduced. As stated at the beginning, it is not the objective of this study to provide indications for price zones. Therefore, if a TSO expert figures that, independent of the scenario, the forced grid / market areas will remain the same in 2050, the expert can include these aspects in his or her considerations for clustering.
- **External cluster:** Another important aspect is the assignment of clusters, which will be affected by large scale imports of offshore wind power or solar power from North Africa or other exchanges with countries outside the EU (Turkey, Russia etc.). A first proposal is at disposal; however, TSOs´ expertise for their respective countries is expected to provide further input.

3.3.2 *Consultation process*

As described above, based on the direct and measurable criteria, the comprehensive algorithm was run to receive an initial figure of the respective clusters.

In order to complete the cluster model by implementing these indirect criteria in the final clusters and to receive reliable results for further calculations, a consultation process among the TSOs has been conducted. The preliminary clusters from the clustering algorithm have been presented to the TSOs involved. Each TSO has been asked to adapt the cluster for its country with regard to indirect criteria. In order to also improve and verify the clusters for countries without any TSOs involved, a consultation via the ENTSO-E SDC among all ENTSO-E TSOs has been conducted. Therefore, a description of the process, the results and a questionnaire (see Annex B) has been sent to each TSO in order to receive a feedback about the complete clustering process and especially the clusters themselves.

As each TSO has sovereignty about its grid area, the final clustering has been determined according to the TSOs’ direct answers. Their expert knowledge about their country and the respective data made it possible to adjust the cluster in order to have an appropriate representation of the country and to allow for performing a system analyses based on calculations of transfer capacities and equivalent impedances between the clusters.

It was left to each TSO to cluster the transmission system as it deemed most suitable with regard to the indirect criteria defined above. Hence, TSOs could merge or split the clusters by a re-allocation of the NUTS regions, but had to justify this step (see Annex C for a detailed illustration country by country, including comments/explanations).

3.3.3 *Results after consultation*

Figure 11 shows a map of Europe with the final clusters. Due to the changes done by the TSOs involved, the total number of cluster was reduced.

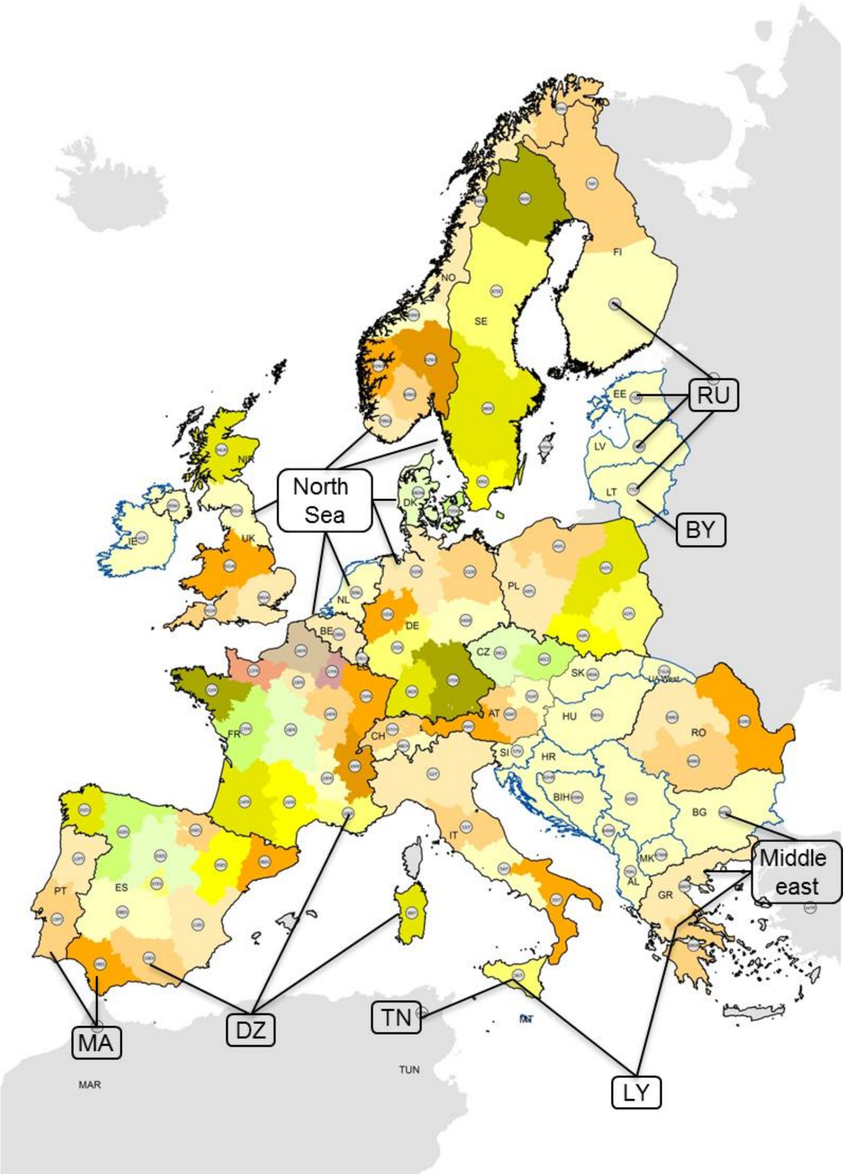

Figure 11: Final European clusters

3.3.4 *Example Germany*

Similar to the example given for Germany in chapter 3.4.3, the following two figures outline the results after the consultation. The entire results are depicted in Annex C of this report.

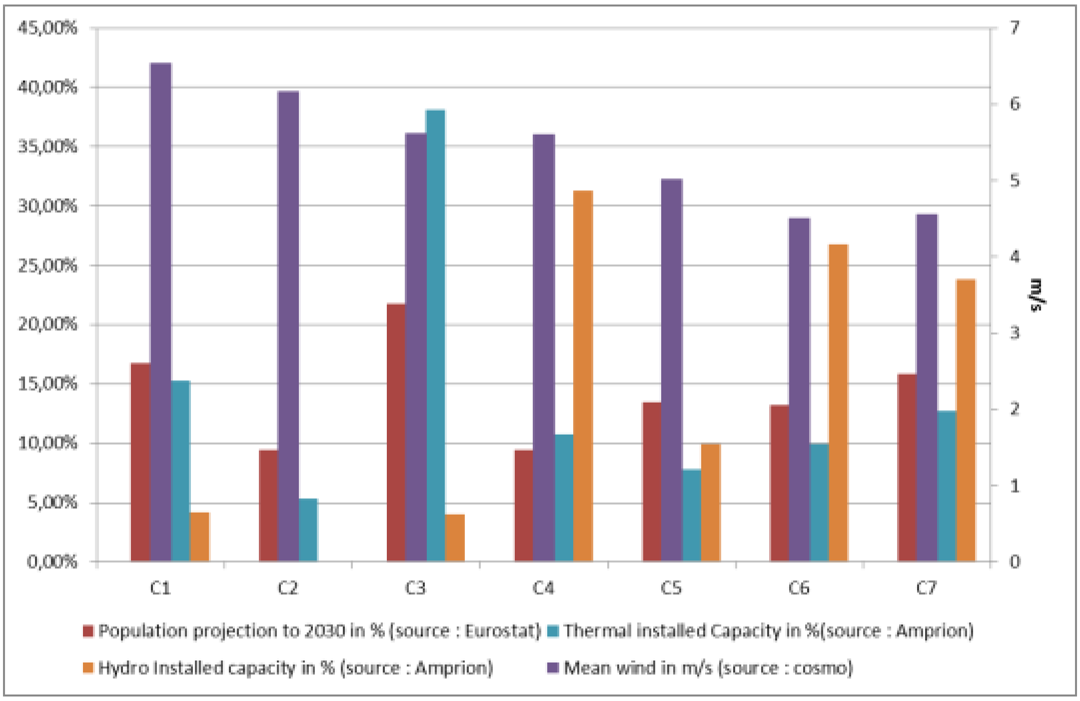

Figure 12: Main cluster data after consultation – Example Germany

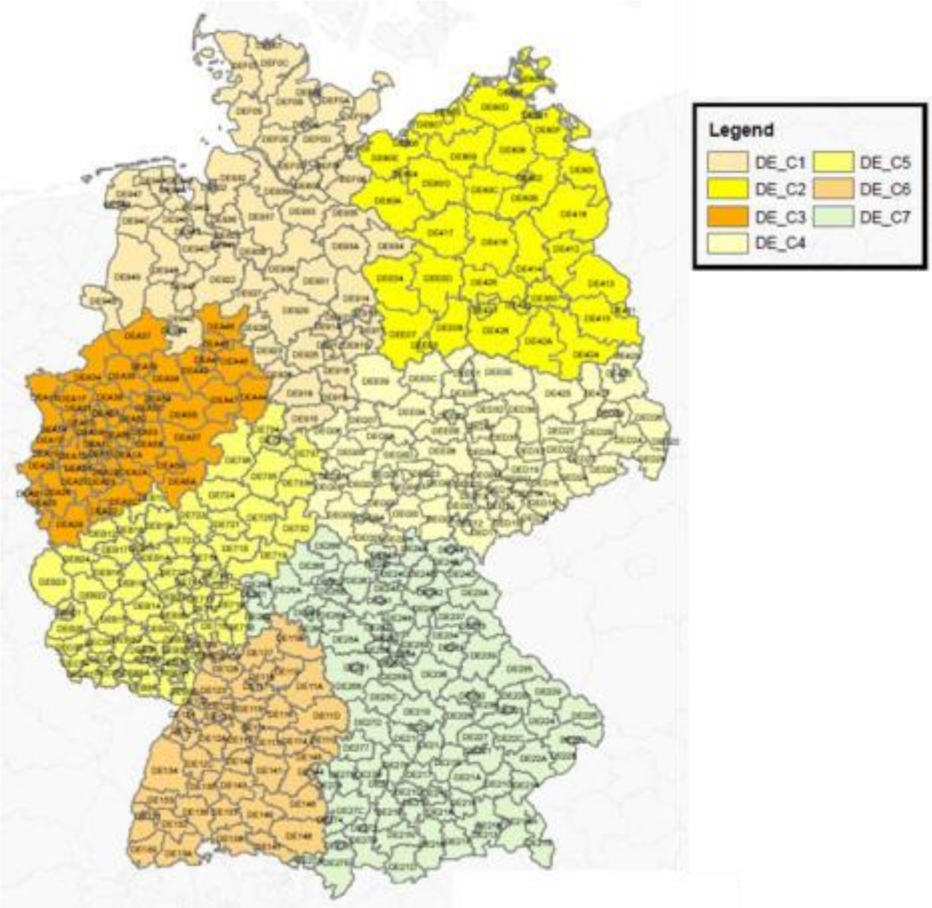

Figure 13: Graphical presentation cluster Germany – Results after consultation

4 Definition of distance between clusters

The identification of the clusters is the first step towards a European grid model. One additional step, that is relevant for later transmission system planning is to define the geographical distance between the selected clusters. The distance or length between two points determines the length of necessary reinforcements, which is one main driver for their investment costs. Thus in the strategic cost-benefit assessment length (and therefore costs) are an inevitable input parameter.

For the clustering one assumption was the cluster-internal copperplate, which leads the conclusion, that all generation and consumption is aggregated within one virtual node. This node is assumed to be in the geographical centre of the cluster. The distances are noe calculated as follows:

At first, the geographic centroids of each cluster are determined and expressed with their geographical coordinates (longitude and latitude). Secondly, the distances between all cluster centroids are identified by calculating the shortest linear distance between the centroids – air-line distance. This leads to a list of all possible connections between clusters and there distances. The shortest distance observed between two clusters is about 84 km while the maximum distance between two clusters is about 4,102 km. The distribution of all links is shown Figure 14.

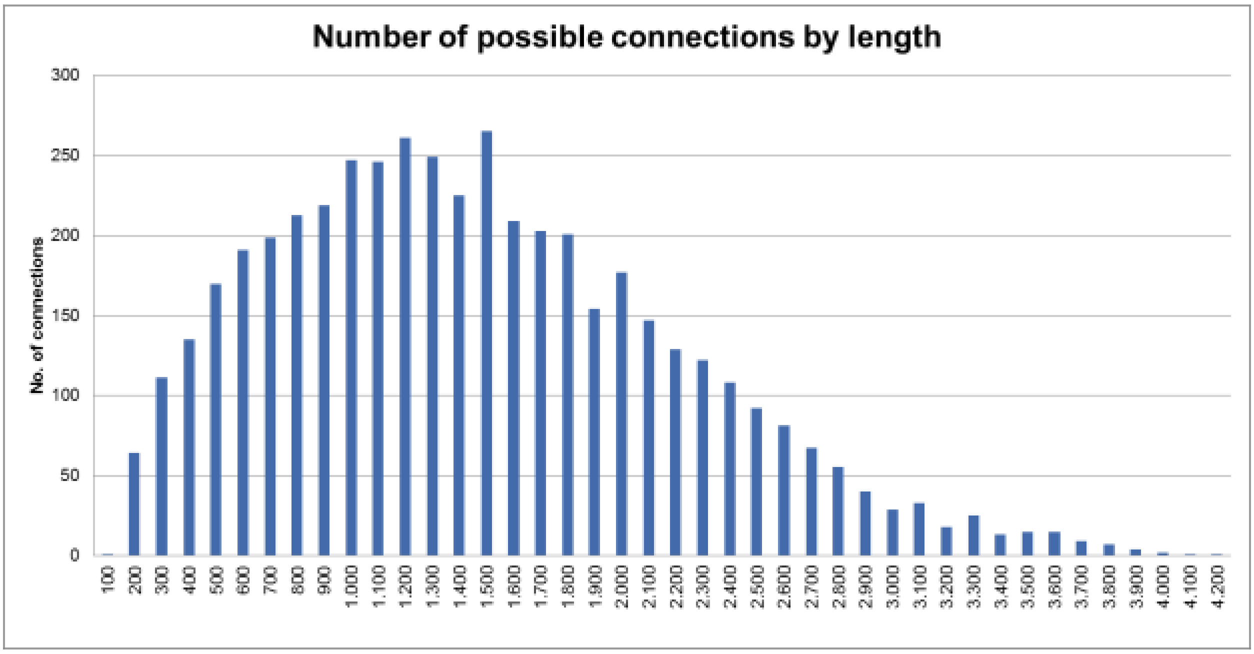

Figure 14: Possible connections between clusters by length (in km)

The identified 106 clusters lead to a (theoretical) amount of $\frac{(n*(n-1))}{2}$ or more than 5500 connections. Of course not all of these connections are relevant for grid expansion planning. For lines with a distance beyond e.g. 1.000km it seems unrealistic, to include them in the European system. In later analyses of System Simulation and grid development planning the maximum distance of transmission lines will be determined. This is also done by considering data on transmission technologies, since all connections cannot be exploited whose length is longer than the technical limit of the available transmission technologies.

What also needs to be considered is the “detour-factor”. When building transmission lines in reality it is not possible to go straight line between the points to be connected. The usual additional length, required to avoid obstacles, is considered as detour factor[7].

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[7] For European Grid Planning detour factors between 1.2 and 1.4 are realistic.

5 Grid reduction

Based on the completed cluster definition, which has been described above, a grid simplification process is conducted. The purpose is to reduce the European grid from several thousands of nodes to just one per cluster, which represent the main flows between clusters. Basically, the grid reduction process consists of the calculation of the grid transfer structure and the calculation of transfer capacities.

In the following, two methodologies to calculate the distribution of power flows in the grid are described and compared with respect to the purpose of the e-Highway 2050 project. Afterwards, an overview of the data which were used for the grid simplification is provided. This is followed by the conduction of the grid reduction. As a final step, the transfer capacities were calculated and the results consulted. The progress and results of this consultation can be found in the last part of this chapter.

5.1 *Modelling strategies for estimation of physical flows*

In a meshed grid, the distribution of power flows depends on the impedances of the different lines. Assuming the transportation of 1 megawatt (MW) from a fictional point A to fictional point C, not only the direct line between A and C, but also the lines between A and fictional point B and between B and C are loaded (compare Figure 15). Therefore, a grid simplification has to find a way to estimate the flows on the different lines.

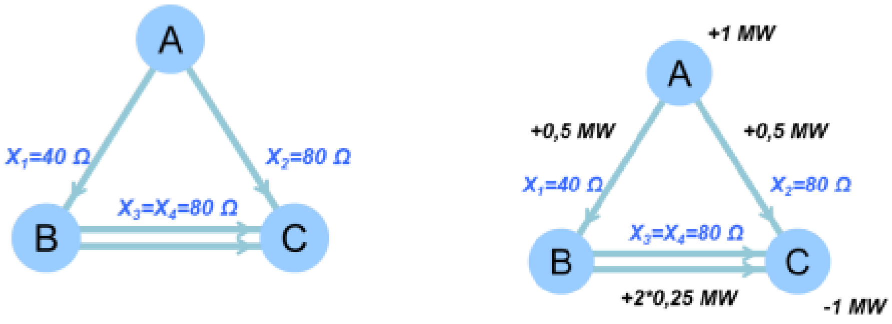

Figure 15: Example of distribution of power flows

In the case of the project, A, B and C are no longer substations, but a set of substations resulting from the clustering. To reduce the problem size and respect the uncertainties involved with the long time perspective, several grid nodes have been summarized in one virtual ling. ("copper-plate" inside the cluster)

This process leads to a simplified network illustrated in Figure 16 below, where all substations of a given cluster are unified in an equivalent node, and all links between two clusters are unified in an equivalent link. Therefore, one of the main challenges is to find a method to estimate the flows in this simplified grid, thus the sum of flows that in detailed grid consideration would be exchanged between two clusters.

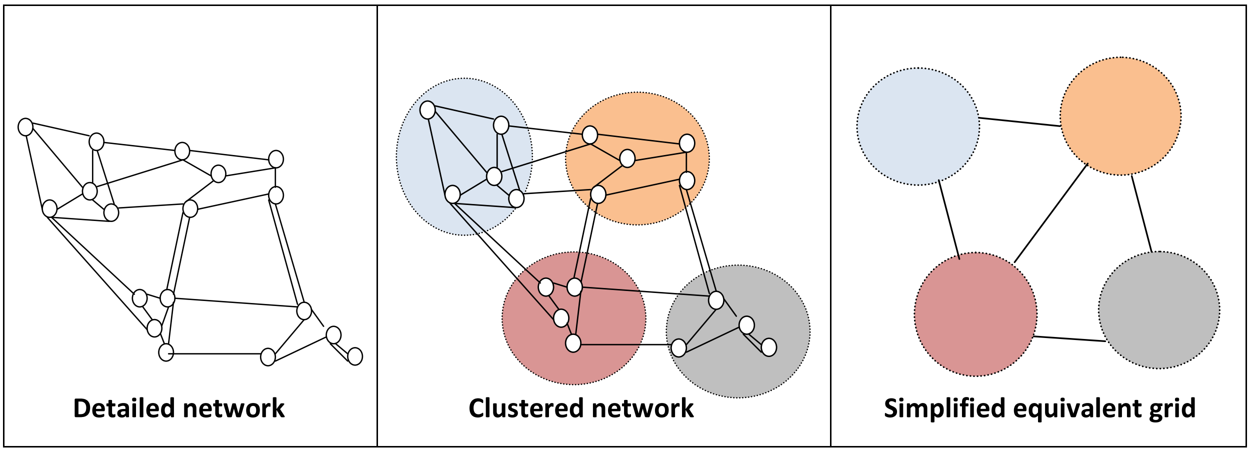

Figure 16: Illustration of steps in grid reduction

In general, there are several approaches to estimate the power flow distribution between the clusters in electricity grids. For the project, two methods, namely the equivalent impedances approach and the Power Transfer Distribution Factor (PTDF) approach, were examined in depth to find a method for calculating the distribution. The equivalent impedances method, which has been chosen, presents accurate methods for describing the load flow across borders, but to model completely the network, maximum flow limitations need to be added. This implies to determine the n-1 safe physical transmission capacity between clusters (Transfer Capacity, TC) in addition to the impedance calculations.

5.2 *Presentation and selection of method*

5.2.1 *PTDF-Method*

The Power Transfer Distribution Factor method (“PTDF method”) is a well-known approach[8]. With the PTDF method you can calculate the percentage impact on all lines of an exchange between two clusters. Starting from an arbitrary base case and the respective reference flow, the influence of an exchange of 1 MW between two clusters are calculated and the PTDF matrix can be determined. The flows on each line can then be calculated as follows:

$$[\boldsymbol{F}] = [\boldsymbol{F_{bc}}] + [\boldsymbol{PTDF}]\,[\Delta\boldsymbol{Balance}]$$

Where:

- ***[F]*** *is the vector of flows to calculate (n interconnections)*
- ***ΔBalance*** *= Balance – Balance$_{bc}$*
- ***Balance$_{bc}$:*** *is the vector of the balances in the base case*
- ***F$_{bc}$*** *is the vector of cross-border flows in the base case*

The equation above can be moved into an equation of flows by expressing the balance of each node.

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[8] For a detailed description of the use of PTDF factors on the UCTE transmission system, see Duthaler, Emery, Andersson, Kurzidem et al. (http://infoscience.epfl.ch/record/153995/files/0807_PSCC_PTDF-Duthaler.pdf).

This modified equation takes the following form:

$$\forall l \; F_l = \sum PTDF(l, node) \; Balance_{node}$$

Hence, for each interconnection between clusters there is one equation.
The method is preferably conducted in short term processes. However, it is not necessarily simple to implement this method in market tools especially regarding tap changing for Phase Shift Transformers (PST). Every change in parameters of the network structure requires a recalculation of the PTDF.

5.2.2 *Equivalent Impedances*

The equivalent impedance method leads to the assumption that the equivalent grid behaves like a detailed network and, thus, the equivalent line has equivalent impedance. However, on top of that equivalent impedance, at the same time the method proposes to define an initial loop flow to account for the asymmetries generated by the clustering between load and generation within the different substations composing the cluster.
In order to evaluate both equivalent impedances and these loop flows, the method uses a large sample (several thousands) of snapshots with a wide range of load and generation. Furthermore, the resulting flow needs to be calculated. In a next step, a reduced network of clusters with only one link between the clusters is modelled. The goal of the equivalent impedance method is to find the admittance matrix for the system and the referring flow, so that estimated flows best match the sample flows using a least squares approach.
The underlying optimisation problem of the impedance method can be expressed as follows: Given a sample of s=1, S snapshots of flows $\mathrm{F_{ij,s}}$ on each equivalent link i, j the optimal admittance matrix Y and the optimal set of initial loop flows T_0 can be determined such that:

$$Min\{\mathrm{Y}|\mathrm{T_0}\} \sum_{s,i,j} \left(\mathrm{F_{ij,s}} - \mathrm{T_{ij,s}}\right)^2$$

$$under\ constraints:$$

$$\forall s\colon Y.\theta_s = I_s$$

$$\forall s, \forall i, \forall j \;\; \mathrm{T_{ij,s}} = Y_{ij.}\left(\theta_{is} - \theta_{js}\right) + T_{oij}$$

Where:

- ***T_{ijs}*** *is the estimated Flow i, j for snapshot s when applying Y matrix and T_0 vector*
- ***F_{ijs}*** *is the real flow (full grid dc load flow calculation) between i, j for snapshot s*
- ***I_s*** *is the cluster Injection vector for snapshot s*
- ***ϑ_{is}*** *is the angle for cluster i for snapshot s*
- ***ϑ_s*** *is the angle vector for snapshot s*
- ***T_{0ij}*** *is the initial loop flow between clusters i, j*

In a nutshell, the method determines the Y and T_0 minimising the error on the sample between estimated flows and target flows (coming from a full grid direct current (DC) load flow calculation).

In order to solve this problem, a specific algorithm has been developed which provided convincing results. The quality of the results of the equivalent impedance method is implied by its design. The method includes an error estimator, which enables users to have a critical view on the equivalent network and thereby also on the clustering previously conducted.

It is concluded that the method provides the estimated flow for each interconnector and each snapshot which enables all kinds of error analyses on a local and a global scale.[9]

5.2.3 *Comparison of methods*

The two methods differ in their theoretical depiction of the grid. The PTDF method depicts each interconnection in a separate equation. However, the equivalent impedances method summarises one mesh with one equation. Figure 17illustrates the results of the two methods.

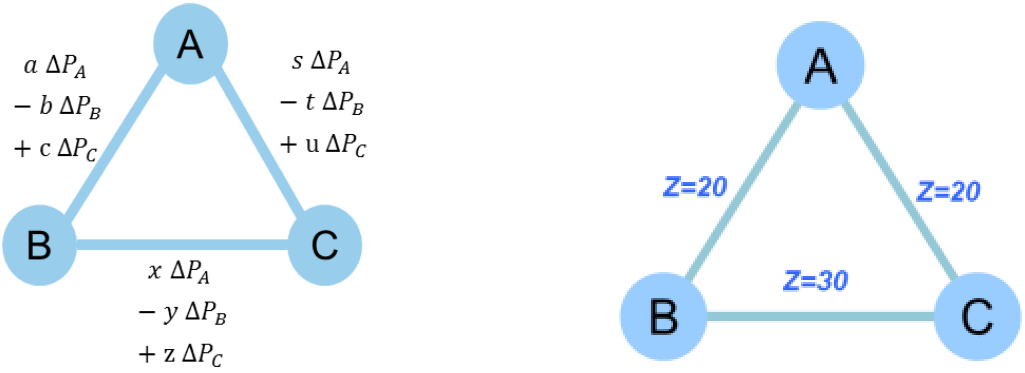

Figure 17: Illustration results PTDF (left) and Equivalent Impedance (right)-Method

5.2.4 *Update of the network after reinforcements*

For the implementation in the system simulator it is important to assess the methods with respect to the specific task of updating the initial characteristics of the zonal network after reinforcement. This is also important for the grid studies in Task 2.3. Four different kinds of reinforcements in the zonal network need to be considered:

1) ***A new DC line between two clusters,***
2) ***A change of conductors on an existing AC line between two clusters,***
3) ***A new AC line between two clusters reinforcing an existing interconnection,***
4) ***A new AC line between two clusters which were not connected before.***

1) Regarding the first case, i.e. adding a new DC line between two clusters, the equivalent impedances method does not require a recalculation after such reinforcement. It is sufficient to recalculate the capacity of the new DC line. There is no need to recalculate the equivalent network parameters since this DC line is only submitted to a transmission limit.

Since the PTDF method calculates each interconnection in a separate equation, an extra DC line added to the model requires one additional load flow. This additional load flow has to include a

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[9] A detailed analyses of quality of the approach can be found in Annex D

flow on the high voltage direct current (HVDC) link in order to assess the PTDF of this additional DC link taking into account the exact connection points in the grid.

2) The second case, i.e. changing conductors on an existing AC line between two clusters, generally requires an assessment of the new capacity. If the impedance of the respective line remains unchanged, no recalculation of either method is necessary. If, however, the impedance changes, a new equivalent impedance Z for the interconnection or a new PTDF matrix has to be calculated. Details about the possible modification and technological change of conductors are provided in WP3.

3) If a new AC line between two clusters is added, the need for a recalculation depends on the respective change in capacity of the interconnection. For the equivalent impedances model, three options are available. The best results are obtained by the first option, which is the full recalculation of equivalent impedances. However, it is also possible to manually estimate a new Z for the reinforced line and keep the other impedances as they are (option 2). The initially calculated loop flows can be kept constant. Option 2 usually is accurate, given that the new line is in parallel to already existing lines. In some cases, when existing interconnection is already significantly rich, the effect of one extra line on the Z equivalent is insignificant. Therefore, it is possible that in the end the Z equivalent and the initial loop flows can be kept unchanged (option 3).
In the case of a PTDF zonal network, it is possible to either recalculate the entire PTDF matrix or to decide that the effect on the PTDF matrix is insignificant and does not require a change in the matrix and the initial loop flows. However, there is no possibility to partly check the PTDF model through manual calculations.

4) The fourth case describes a new AC line, which connects two previously disconnected clusters. In this case, most probably a full recalculation becomes necessary. The PTDF method always needs a full recalculation to consider a new interconnection. With the equivalent impedances method, a manual calculation may be feasible if there is a similar grid pattern available within the zonal network which can be used as a sample for the new line.

In all cases of reinforcement, a possible solution would be provided by a full recalculation of the models. However, a full calculation is very time consuming. Deciding to undertake the calculation manually (which is only possible in the equivalent impedances method) may already provide a rough estimation about the impacts of reinforcements and respective capacity changes. This may allow researchers to conduct system simulations more rapidly, taking into account different scenarios of new reinforcements. This is helpful to define a selection of reinforcements which are of interest and should be subject to a full recalculation of the model more narrowly. Conducting a manual recalculation may especially be feasible in cases of new AC lines which are parallel or close to parallel to existing lines. A simple example is the modelling of a new line similar to the existing corridor. In such a case, the impedance of the interconnection would be divided by two.

In order to test and compare the level of accuracy, the two methods have been applied on a smaller scale. I.e., both methods were used to simplify parts of the grid. Figure 18 illustrates the grid used for this comparison. To test the methodology, analyses were focused on the central European grid, namely France (14 clusters), Germany (10), Belgium, Netherlands, Luxembourg, Switzerland, Austria and Italy North (each represented by one cluster). The grid is an excerpt of the Common Information Model (CIM) used in the final calculations of task 2.2.

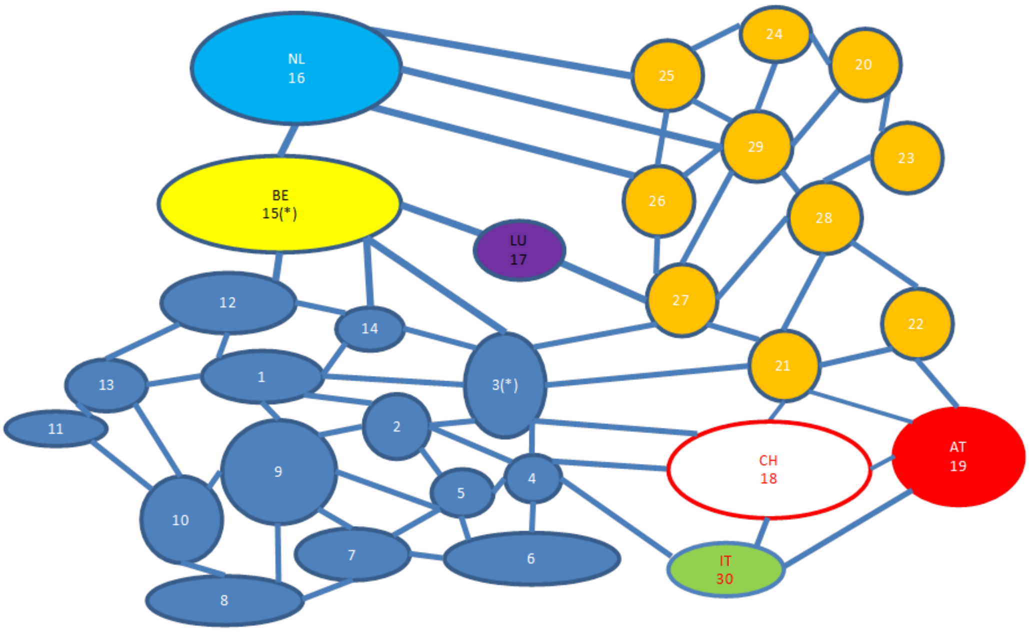

Figure 18: Illustration of the grid which is used for comparison of the methods

The comparison revealed that both methods lead to results of similar quality with an error range of a few 100 MW. The errors on estimation of flows (Root Mean Square Error, RMSE) are shown in Figure 19.

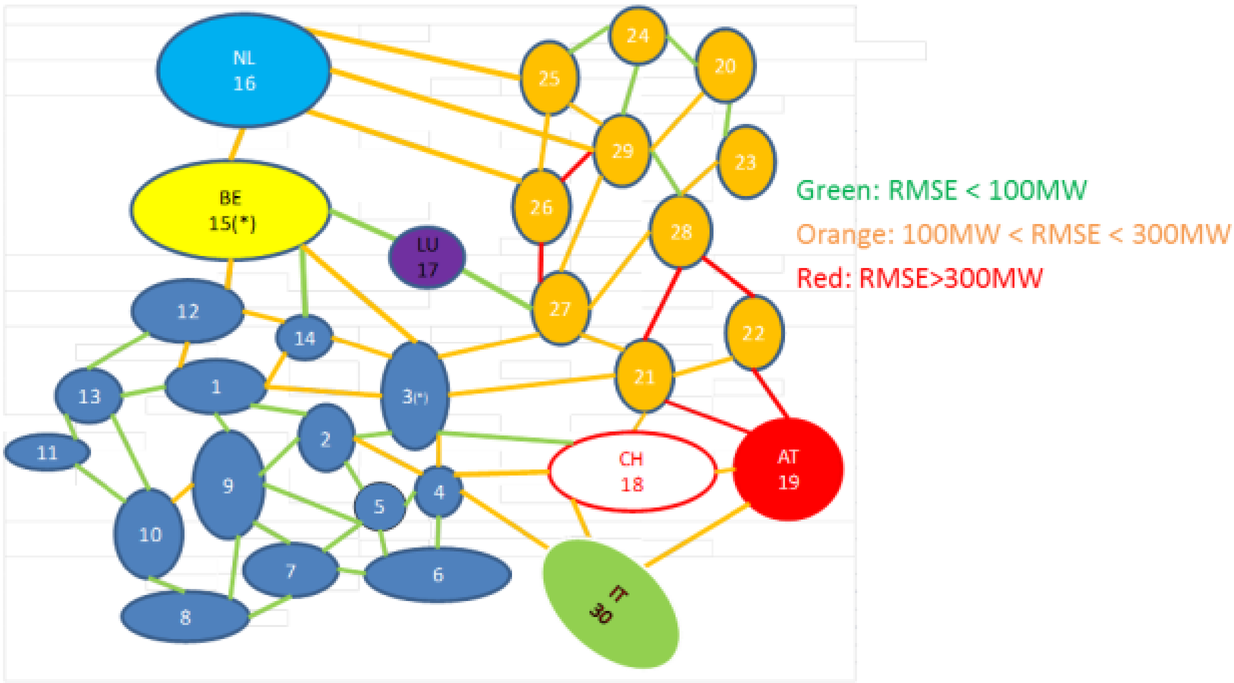

Figure 19: Errors on estimation of flows (RMSE) for both methods

Furthermore, it was shown that, in general, the quality mainly depends on the level of clustering and the quality of clusters. Overall, however, both methods provided good results with very similar levels of accuracy.

5.2.5 *Selection of methodology for grid calculation*

The project partners agreed on the equivalent impedances method as the method for grid simplification in this project. It is found that the reliability of results is similar to the PTDF method and sufficient for the purposes of this project. Besides that, as already described, the equivalent impedances model is advantageous as it allows for rough estimations of the impacts of updates in the zonal network. This reduces the time and the efforts necessary to provide sound research results as in some cases full recalculations of the model can be avoided. Another advantage is that partners are more experienced applying this method to the system simulator which is chosen for the analysis of this project.

5.2.6 *Input and Results*

As described above, the method reduces the full network model of initially thousands of nodes to less than a hundred nodes. The basis for the analysis is provided by the geographic clustering conducted before the grid simplification, which has been described above. I.e., the method is applied to the synchronous continental AC clustered grid as depicted below (Figure 20), based on a CIM network (version exchanged by TSOs on 26th April 2013) and modelling a 2030 network.

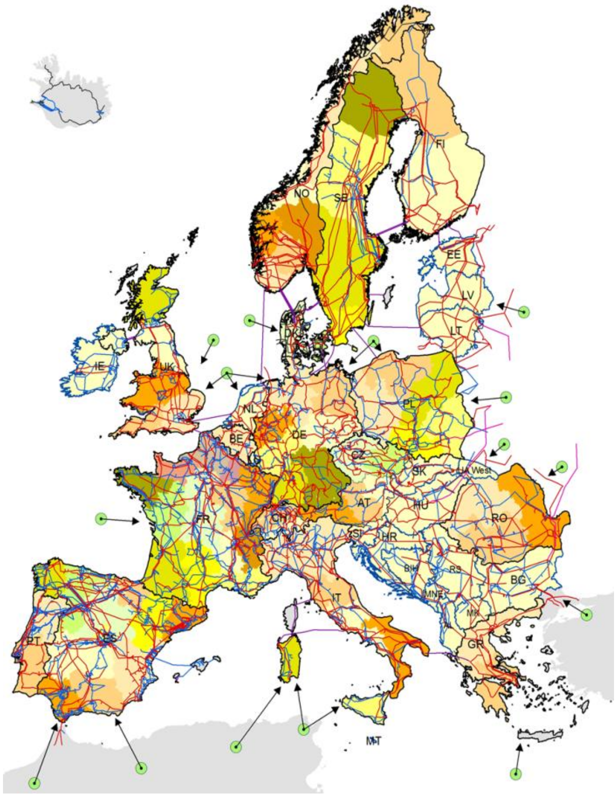

Figure 20: Geographic clustering

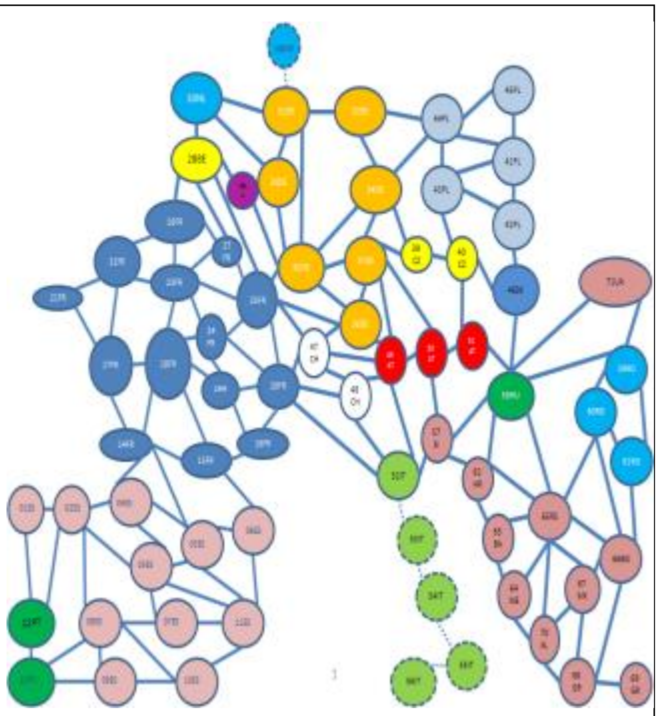

Figure 21: Cluster model for continental Europe

The method aims at evaluating the impedances and loop flows of all AC links of Figure 21, except antennas (38DW, 53IT, 54IT, 55IT, 56IT, 69GR and Luxembourg antenna with France, Belgium and Germany).

As Albania and West Ukraine are not modelled in the CIM, a simplified representation has been implemented. All X-Nodes[10] in Albania have been linked to a single Albanian node. The same was applied to Ukraine.
The following settings have been applied in the base case:

- Loads on all XNODE with the rest of the world have been set to 0MW,
- All DC lines are set to 0,
- All Phase Shift Transformers have been set to an angle of 0.

The sampling of situations has been done with the RTE probabilistic platform and was based on the CIM base case. The variables used for the sampling are:

- The loads,
- the generation from renewable, i.e. wind power, PV power and hydro power and
- the thermal generation unit outages

Results equivalent impedances

Figure 22 illustrates the results of the calculated impedances. These impedances are relative and they have been normalised so that the minimum value is equal to 1. As expected, minimum and maximum impedances can be found in locations where the network is highly meshed and where it is weakly meshed, respectively.

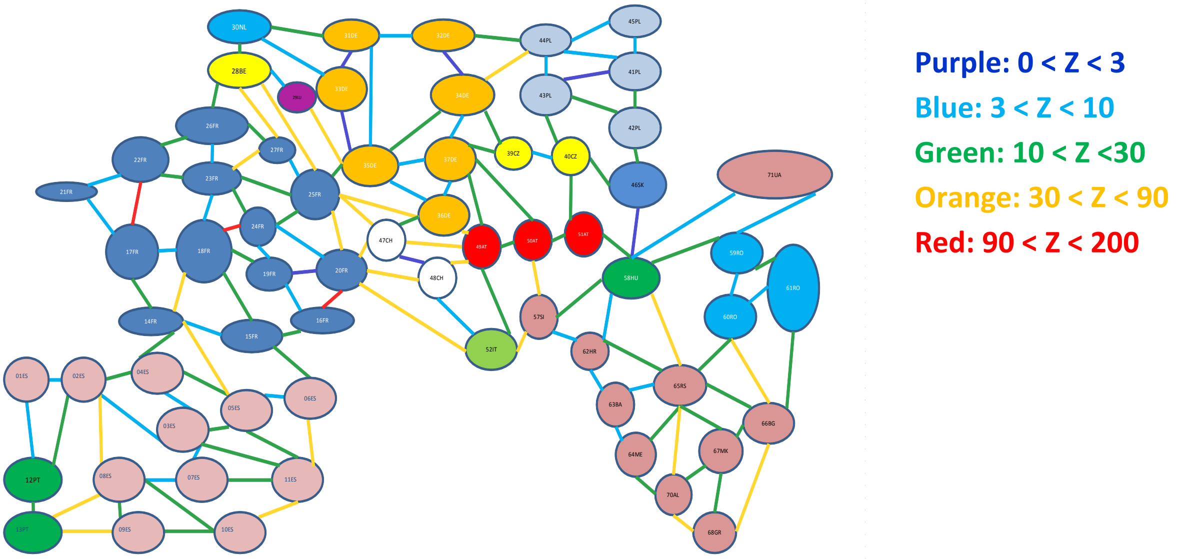

Figure 22: Equivalent impedances

The interconnection with the biggest impedance is located in France (18FR-24FR). This interconnection consists of only one geographical 225 kilovolt (kV) long line, which explains its great electric length. The two following electrically longest interconnections are also located in France (17FR-22FR and 16FR-20FR) and are composed of a 225kV line and three 225kV lines.

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[10] The CIM-model used in the analyses of task 2.2 is merged from the grid models of the European TSOs. To define the connection-points between neighboring countries X-Nodes are defined. They represent the real exiting connections between the countries.

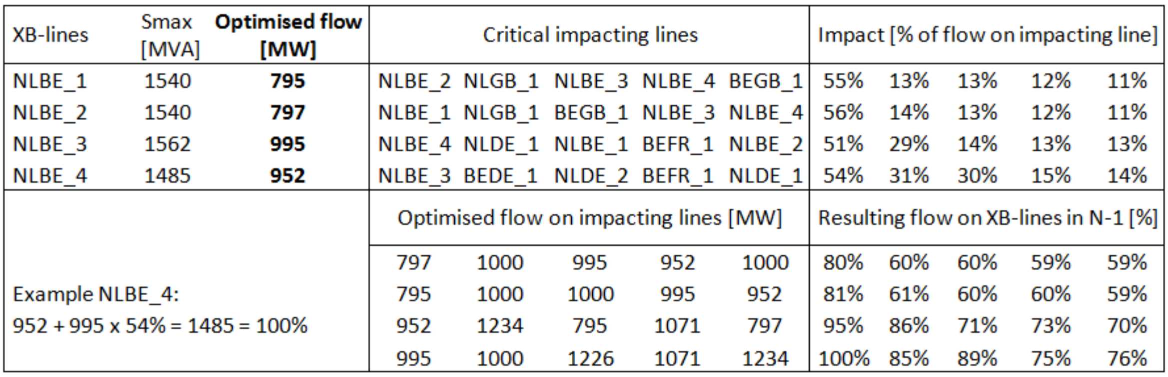
The shortest interconnection is located in Germany (33DE-35DE). This interconnection consists of 15x380kV lines and 6x110kV lines, which explains its low electric length. Detailed results also on the accuracy of the results are described in Annex D.

5.2.7 *Results transfer capacities*

The equivalent impedances method presents accurate methods for describing the load flow across borders, but to model completely the network, maximum flow limitations need to be added. This implies to determine the n-1 safe physical transmission capacity between clusters (Transfer Capacity, TC) in addition to the impedance calculations. Therefore, a method for calculating allowed flows between clusters is imperative. The method ultimately used is called “Mutual n-1 impact”. The impact of outages between cross-border lines is calculated and for each cross-border line the five most critical outages are determined. These are then used in a solver to optimise the flow on all border lines. I.e., the individual flows on cross-border lines are “chosen” by the solver, in order to obtain the highest possible overall flow across borders while maintaining the utilization of each individual line within its safe limits.

E.g., consider the 4 lines on the border NL-BE, Figure 23. Line NLBE_4 is most heavily impacted by the loss of lines NLBE_3, BEDE_1, NLDE_2, BEFR_1 and NLDE_1. At the loss of line NLBE_3, 54% of the flow on this line is transferred to line NLBE_4. For the other 4 outages, only some 14-31% is transferred to NLBE_4. The solver optimised all flows (also on other borders such as NL-DE or BE-FR). Line NLBE_4 has an optimal flow of 952 MW, and line NLBE_3 a flow of 995 MW. At the loss of line NLBE_3, the flow on NLBE_4 becomes 952 + 54% x 995 = 1485 MW, or full capacity for this line. Flows on lines NLBE_3 or 4 cannot both be increased; increasing one requires a reduction on the other one.

As can be seen, the other lines are not at their individual maximum in this result. It must be considered, that the flow on e.g. NLBE_1 could be limited by the impact of the loss of NLBE_1 on another border. This means the flow on NLDE_1 does not lead to overloads on NLBE_3 (86% loading), but could be limited by its own critical impacting lines.



XB-lines	Smax [MVA]	**Optimised flow [MW]**	Critical impacting lines					Impact [% of flow on impacting line]				
NLBE_1	1540	**795**	NLBE_2	NLGB_1	NLBE_3	NLBE_4	BEGB_1	55%	13%	13%	12%	11%
NLBE_2	1540	**797**	NLBE_1	NLGB_1	BEGB_1	NLBE_3	NLBE_4	56%	14%	13%	12%	11%
NLBE_3	1562	**995**	NLBE_4	NLDE_1	NLBE_1	BEFR_1	NLBE_2	51%	29%	14%	13%	13%
NLBE_4	1485	**952**	NLBE_3	BEDE_1	NLDE_2	BEFR_1	NLDE_1	54%	31%	30%	15%	14%
			Optimised flow on impacting lines [MW]					Resulting flow on XB-lines in N-1 [%]				
			797	1000	995	952	1000	80%	60%	60%	59%	59%
Example NLBE_4:			795	1000	1000	995	952	81%	61%	60%	60%	59%
952 + 995 x 54% = 1485 = 100%			952	1234	795	1071	797	95%	86%	71%	73%	70%
			995	1000	1226	1071	1234	100%	85%	89%	75%	76%

Figure 23: Example of mutual flow impact between lines – I

The impact of the outage of one line on another line determines the allowed flow on a line under n-1 condition. This means the optimal use of a line is the thermal capacity of the line, reduced by the maximum possible additional flow which on this line, caused from an outage on an impacting line. It has to be mentioned that the resulting flows cannot be seen as a load flow situation that could actually occur in reality. This is not possible in the cluster approximation.

The direction of flow is not considered. Each line is a separate entity, only linked through the percentage of its capacity which impacts other lines. Furthermore, the estimation only considers cross-border lines. Internal bottlenecks are not considered. The performed optimisation process was split into seven areas (south-east Europe, north-east Europe, BENELUX, DE+CH, FR, ES+PT, IT) with iterations between the seven areas, due to limitations mentioned in chapter 5.2.

The resulting TC between clusters show significant variation when expressed as a percentage of the sum of thermal capacities of all lines at the border. Values range from 32% to 75%, with an average of 60-65%. A value of less than 40% only occurs at borders, with less than six real lines, and often with mixtures of 380 and 220 kV lines.

65% of the installed capacity of the lines was used as typical value, for borders with unavailable data for the described method to be applied. This value has been proven to be “good practice”.

The method was finally tested by Elia on the Belgian system, in comparison with their more detailed Transmission Capacity calculations. This comparison shows a good match at the higher end of the range:

- FR-BE: 4650 MW, cf. detailed calculation 4300 +/- 650 MW (avg. +/- 1σ)
- NL-BE: 3500 MW, cf. detailed calculation 3300 +/- 100 MW
- LU-BE: 720 MW, cf. detailed calculation 770 +/- 40 MW

This is in accordance with the expectations, since the method looks for an optimum, whereas detailed calculations use more realistic flow distributions.

Table 4 in Annex E gives an overview of all results of the TC calculations.

5.3 *Exceptions*

CIM grid data for Great Britain, Ireland, the Scandinavian countries as well as the Baltics were not available or not accessible for the e-Highway 2050 project. Therefore, data for these countries had to be obtained differently than for continental Europe and the data collection was focused on TC data. This means that the full approach of the project could not be applied to these countries. For those countries, a NTC model is used (no impedance, no thermal capacity), in which network limitations are directly embedded.

Due to confidentiality considerations, data were not available for Scandinavian and Baltic states. For alternative estimations, definitions of regions in Scandinavia and the Baltic countries were adopted from NORD POOL market zones expected for 2015. In mutual discussions, the TSOs Statnett, Svenska Kraftnät and Fingrid confirmed that these definitions are accurate. Furthermore, the official market capacities, which are published by NORD POOL for 2015, are used as an estimate for transfer capacities. This is less accurate than the capacities for continental Europe since market capacities refer to mere commercial capacities, which can differ from actual physical capacities.

For Great Britain, detailed grid data could not be obtained, because the TSO(s) are not involved in the project and no other party could allocate the nodes of the system to the cluster. Therefore, the amount of connection lines depicted in the ENTSO-E map, multiplied by a security factor, was used to make an approximation of the TC. These values were then sent to the British TSO National Grid, who made some adjustments. Hence, similar to the Scandinavian and Baltic States cases, it can be concluded that the values are less accurate than for continental Europe, but are still sufficiently solid.

5.4 *Consultation*

The consultation process was conducted to validate the TC values. The obtained impedances can only be assessed for the whole system. It is not beneficial to adjust individual values of impedances. Hence, consulting TSOs to validate values of impedances is not applicable. I.e. TSOs cannot contribute any country specific knowledge to the obtained impedances.[11]

Consultation of TSOs involved in e-Highway 2050

First of all, the TSOs involved in the e-Highway 2050 project were consulted. The methodology of the TC calculation was explained to them and they had access to the calculated values with the obtained results of TC values. The TSOs were asked to adjust the proposed values according to their specific knowledge about the grid in their countries/regions. This led to several adjustments on cluster connections. Adjustments were made by Amprion, APG, CEPS, Energinet, PSE, REN, RTE and Terna.
Table 5 in Annex E lists the connections for which TC values have been adjusted.

Consultation within entire ENTSO-E

In order to further improve and validate the results of the TC calculation, additional TSOs, which are not involved in the project, were also consulted. Therefore, a document describing the method used and results received were distributed to the SDC of ENTSO-E. This included a call for feedback and an inquiry for their estimation of the adequacy of the calculated capacities a further need for considerations of seasonal effects. In cases were no answer was provided, these were considered as agreement with the proposed values.
Due to the consultation, additional feedback of Fingrid and AST was received, which made some minor changes on their borders. Figure 24 shows the final results.

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[11] There has been a qualitative assessment of the resulting impedances by selected TSOs which have concluded that the proportion between the impedances is suitable for assessing flows in the system.

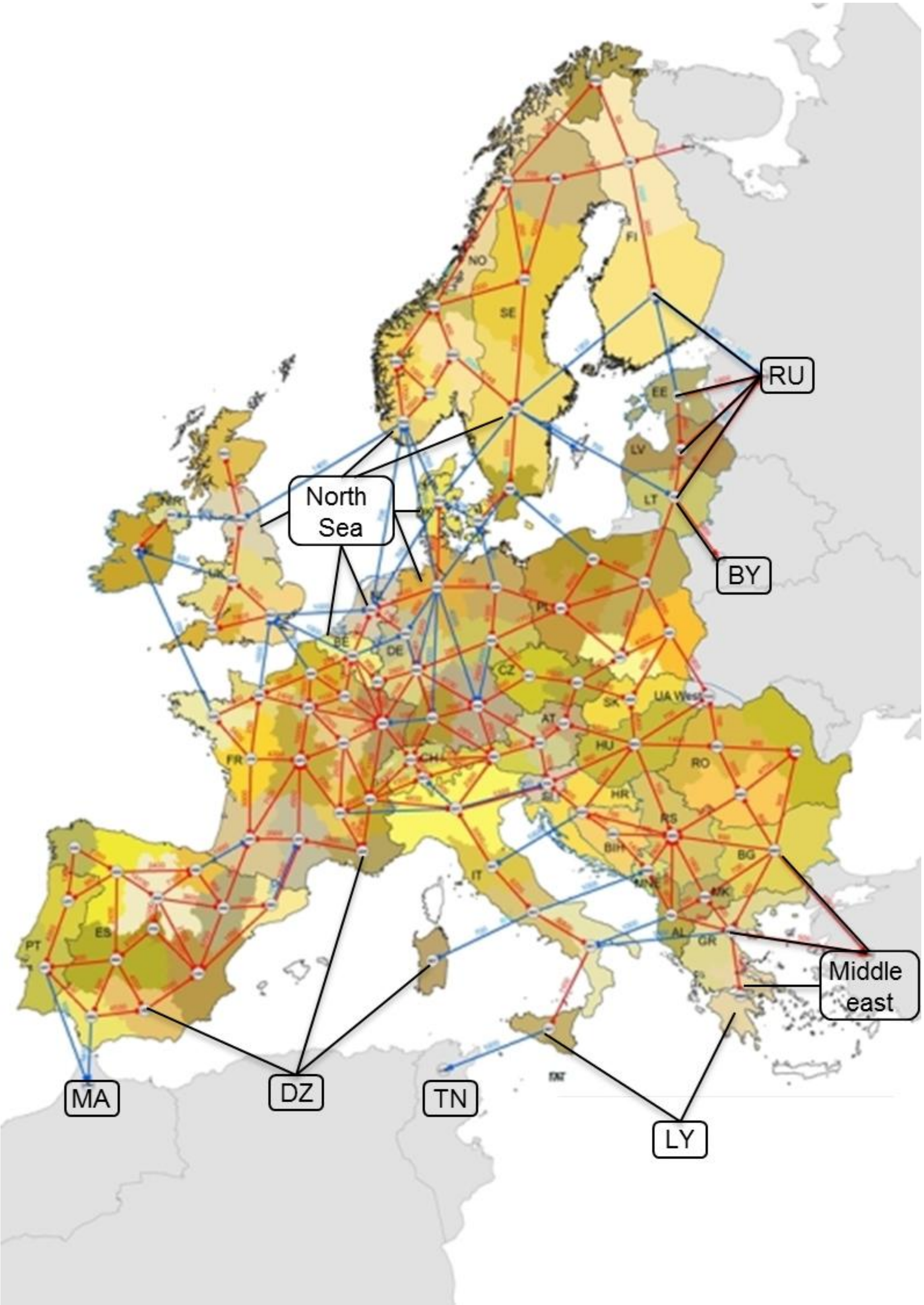


Figure 24: Map of European cluster with TCs

6 Conclusion and outlook

Throughout this report, a simplified model of the European transmission grid has been developed.

As a first step, geographical clusters were proposed. Technical criteria were defined to be used in an algorithm to calculate geographical clusters. Based on the application of this mathematical algorithm 105 clusters in 31 countries were defined.

In a second step, a consultation with TSOs was conducted to validate/cross check these clusters. After this step 95 clusters remained.

Grid simplification was undertaken by assessing the characteristics of the equivalent grid remaining after clusterisation. This method, indeed, summarises the detailed network (thousands of lines) into a reduced amount of equivalent inter-cluster line (a few hundreds). These connections represent the starting transmission system between the different clusters. Maximum capacities are calculated using the “mutual n-1 impact” method. The resulting transmission capacities were subject to a consultation with TSOs in order to include specific qualitative knowledge into the technically developed model. As shown, some adjustments regarding the transfer capacities on connections between clusters were made. Due to the involvement of all TSOs within ENTSO-E (either direct involvement in the task or with the assistance of consultations), appropriate and validated results could be achieved. The resulting model builds the basis for further research of the e-Highway 2050 project especially for the work in Task 2.3.

The cluster model of the Pan-European transmission grid will serve as the basis for system simulations to be performed in Task 2.3, thus defining the initial transportation capacities between regions / clusters. With the aim to develop an overlay grid for 2050, generation scheduling should be defined. The 2050 hourly generation scheduling is defined on the basis of system simulations, balancing the generation, consumption and exchange with third countries, while respecting simplified grid constraints. The system simulation will use the clusters defined in Task 2.2 as market regions and the simplified grid to consider the grid constraints. The results are used as **indicators to suggest required grid reinforcement**.

Annex A – Calculation number of clusters per country

Basis for initial estimation of clusters per country:

Guideline for initial estimation of the number of clusters per country (assuming each country is represented by at least 1 cluster)												
Country Base Data					Number of clusters per country based on				Suggested range			
Country	Short	Peak LOAD [GW]	Area km²	Population	LOAD	Area	Pop.	AVG	Min	Avg	Max	Final value
Albania	AL		28748	3 011 405								1
Austria	AT	10,90	83 894,70	8 414 638	1,9	1,5	1,5	1,6	1	**2**	2	3
Bosnia & Herzegovina	BA	2,53	52 238,71	4 048 500	0,5	0,9	0,7	0,7	1	**1**	1	1
Belgium	BE	15,91	32 681,18	11 007 020	2,8	0,6	1,9	1,8	1	**2**	3	2
Bulgaria	BG	7,40	110 936,49	7 621 337	1,3	1,9	1,3	1,5	1	**2**	2	2
Switzerland	CH	11,00	44 032,81	7 785 000	2,0	0,8	1,4	1,4	1	**1**	2	2
Cyprus	CY	1,04	10 158,32	863 457	0,2	0,2	0,1	0,2	1	**1**	1	not connected
Czech Republic	CZ	11,70	80 982,41	10 535 811	2,1	1,4	1,8	1,8	1	**2**	3	3
Germany	DE	75,10	350 590,05	81 757 600	13,4	6,1	14,2	11,2	6	**11**	15	10
Denmark	DK	6,16	44 693,85	5 568 854	1,1	0,8	1,0	0,9	1	**1**	2	2
Estonia	EE	1,50	42 034,54	1 315 681	0,3	0,7	0,2	0,4	1	**1**	1	1
Spain	ES	49,00	528 004,48	47 150 800	8,7	9,2	8,2	8,7	8	**9**	10	9
Finland	FI	15,70	350 165,82	5 357 537	2,8	6,1	0,9	3,3	1	**3**	7	3
France	FR	76,40	551 826,09	63 460 000	13,6	9,6	11,0	11,4	9	**11**	14	12
Great Britain (without Northern Ireland)	GB	57,40	254 061,05	62 041 708	10,2	4,4	10,8	8,5	4	**8**	11	8
Greece	GR	9,15	144 304,13	11 645 343	1,6	2,5	2,0	2,1	1	**2**	3	2
Croatia	HR	3,50	59 684,17	4 637 460	0,6	1,0	0,8	0,8	1	**1**	2	2
Hungary	HU	6,51	92 142,20	9 979 000	1,2	1,6	1,7	1,5	1	**1**	2	2
Ireland	IE	5,24	73 547,68	4 434 925	0,9	1,3	0,8	1,0	1	**1**	2	1
Northern Ireland	NI	1,72	13 843,00	1 710 300	0,3	0,2	0,3	0,3	1	**1**	1	1

Italy	IT	64,20	315 337,74	60 418 711		11,4	5,5	10,5	9,1		5	**9**	12	10
Iceland	IS	2,37	112 689,26	304 261		0,4	2,0	0,1	0,8		1	**1**	2	not connected
Lithuania	LT	1,90	61 614,82	3 401 138		0,3	1,1	0,6	0,7		1	**1**	2	1
Luxemburg	LU	0,96	2 723,74	472 569		0,2	0,0	0,1	0,1		1	**1**	1	1
Latvia	LV	1,49	64 658,88	2 366 515		0,3	1,1	0,4	0,6		1	**1**	2	1
Montenegro	ME	0,75	1 507,13	67 218		0,13	0,026	0,012	0,0		1	**1**	1	1
Macedonia	MK	1,90	25 336,62	2 054 800		0,3	0,4	0,4	0,4		1	**1**	1	1
Netherlands	NL	17,90	42 485,24	16 696 700		3,2	0,7	2,9	2,3		1	**2**	4	2
Norway	NO	20,80	352 151,14	4 930 116		3,7	6,1	0,9	3,6		1	**4**	7	4
Poland	PL	23,82	309 246,96	38 192 000		4,2	5,4	6,6	5,4		4	**5**	7	5
Portugal	PT	10,23	96 348,73	10 607 995		1,8	1,7	1,8	1,8		1	**2**	2	2
Romania	RO	9,20	238 036,70	19 042 936		1,6	4,1	3,3	3,0		1	**3**	5	3
Serbia	RS	7,92	77 478,90	7 345 000		1,4	1,3	1,3	1,3		1	**1**	2	1
Slovenia	SI	2,36	21 121,90	2 012 917		0,4	0,4	0,3	0,4		1	**1**	1	1
Sweden	SE	23,20	475 132,64	9 360 113		4,1	8,3	1,6	4,7		1	**5**	9	5
Slovakia	SK	4,31	48 850,14	5 422 366		0,8	0,8	0,9	0,9		1	**1**	1	1
	Sum:	561,58	5 755 170,51	576 259 846		100	90	92	94		65	**100**	143	105
	Source:	ENTSO-E	Wikipedia	Wikipedia		Target:	100	clusters						

Table 1: Basis for initial estimation of clusters per country

Annex B – Clustering results per country

The proposed clusters as well as changes made by the respective TSOs are listed for each country in the graphics below (if available with comments and explanations by the respective TSO). Countries that are not listed here consist of one cluster before and after the consultation.

Austria

Results of algorithm:

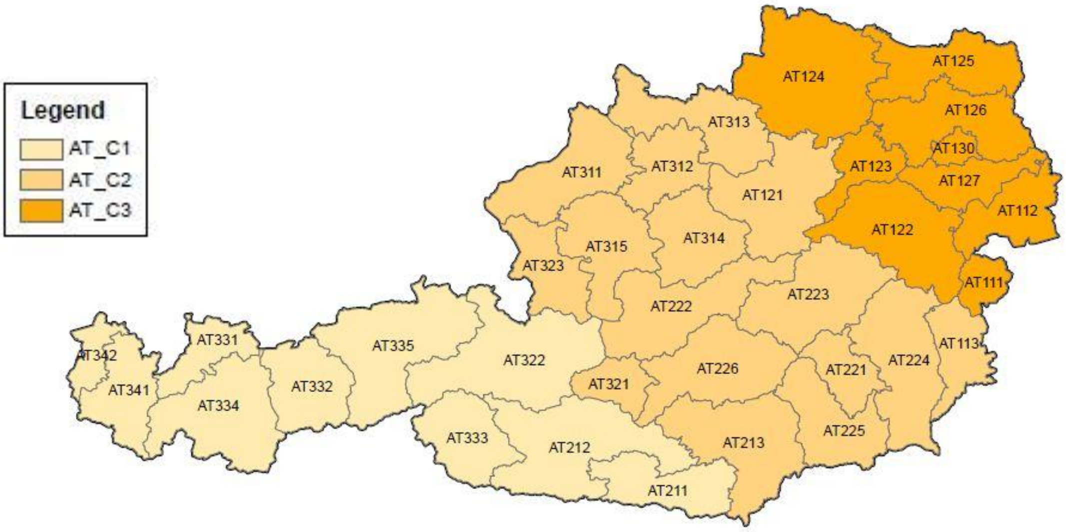


Figure 25: Austria: Results of the algorithm

Results after consultation:

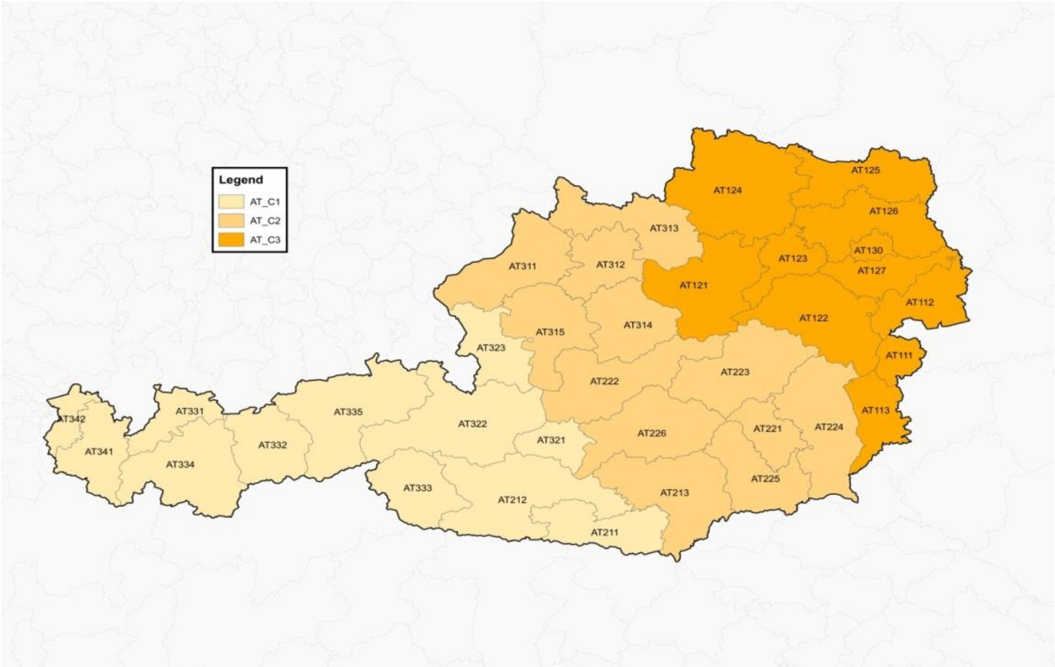


Figure 26: Austria: Results after consultation

Belgium

Results of algorithm:

Figure 27: Belgium: Results of the algorithm

Results after consultation:

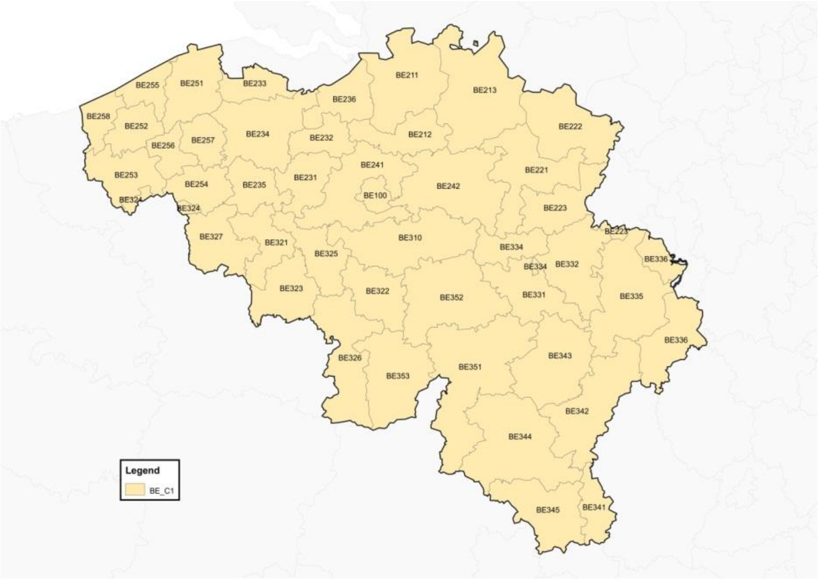


Figure 28: Belgium: Results after consultation

Bulgaria

Results of algorithm:

Figure 29: Bulgaria: Results of the algorithm

Results after consultation:

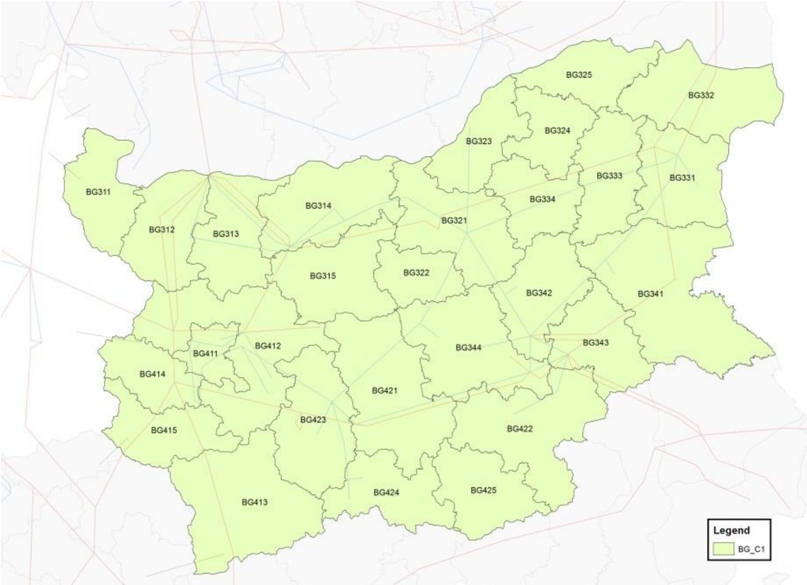


Figure 30: Bulgaria: Results after consultation

Switzerland

Results of algorithm:

Figure 31: Switzerland: Results of the algorithm

Results after consultation:

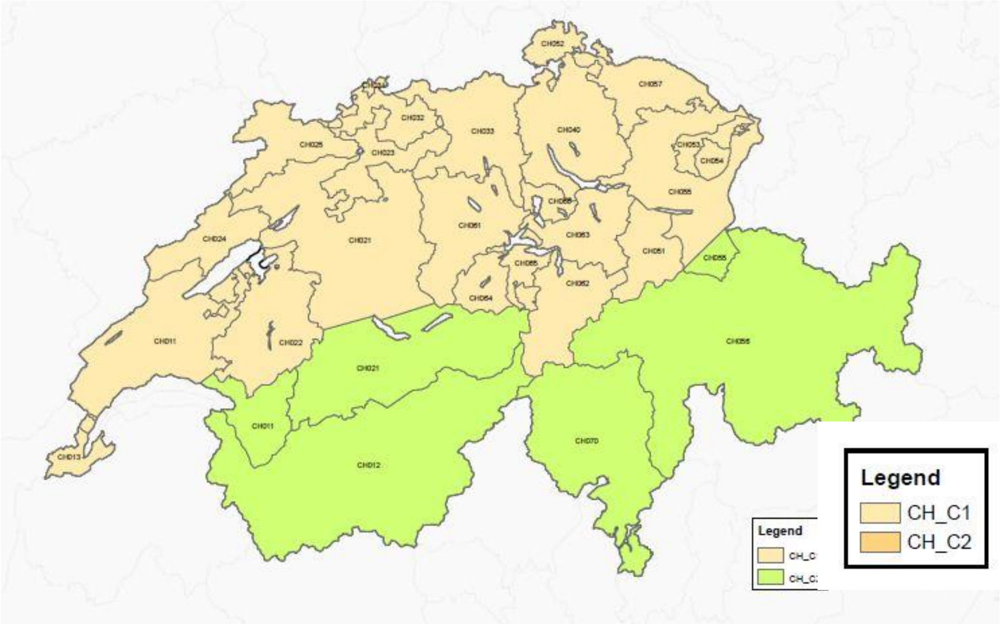


Figure 32: Switzerland: Results after consultation

Czech Republic

Results of algorithm:

Figure 33: Czech Republic: Results of the algorithm

Results after consultation:

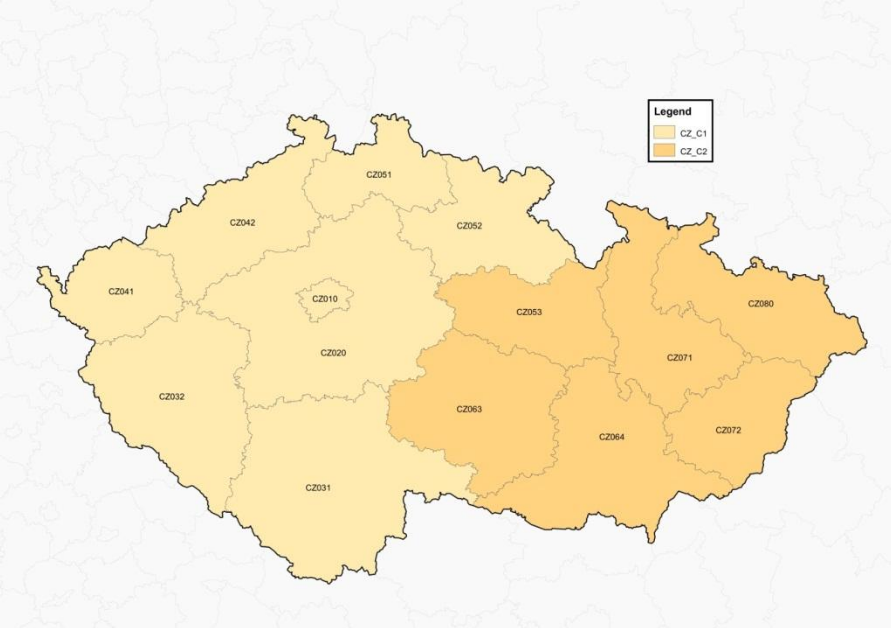


Figure 34: Czech Republic: Results after consultation

Germany

Results of algorithm:

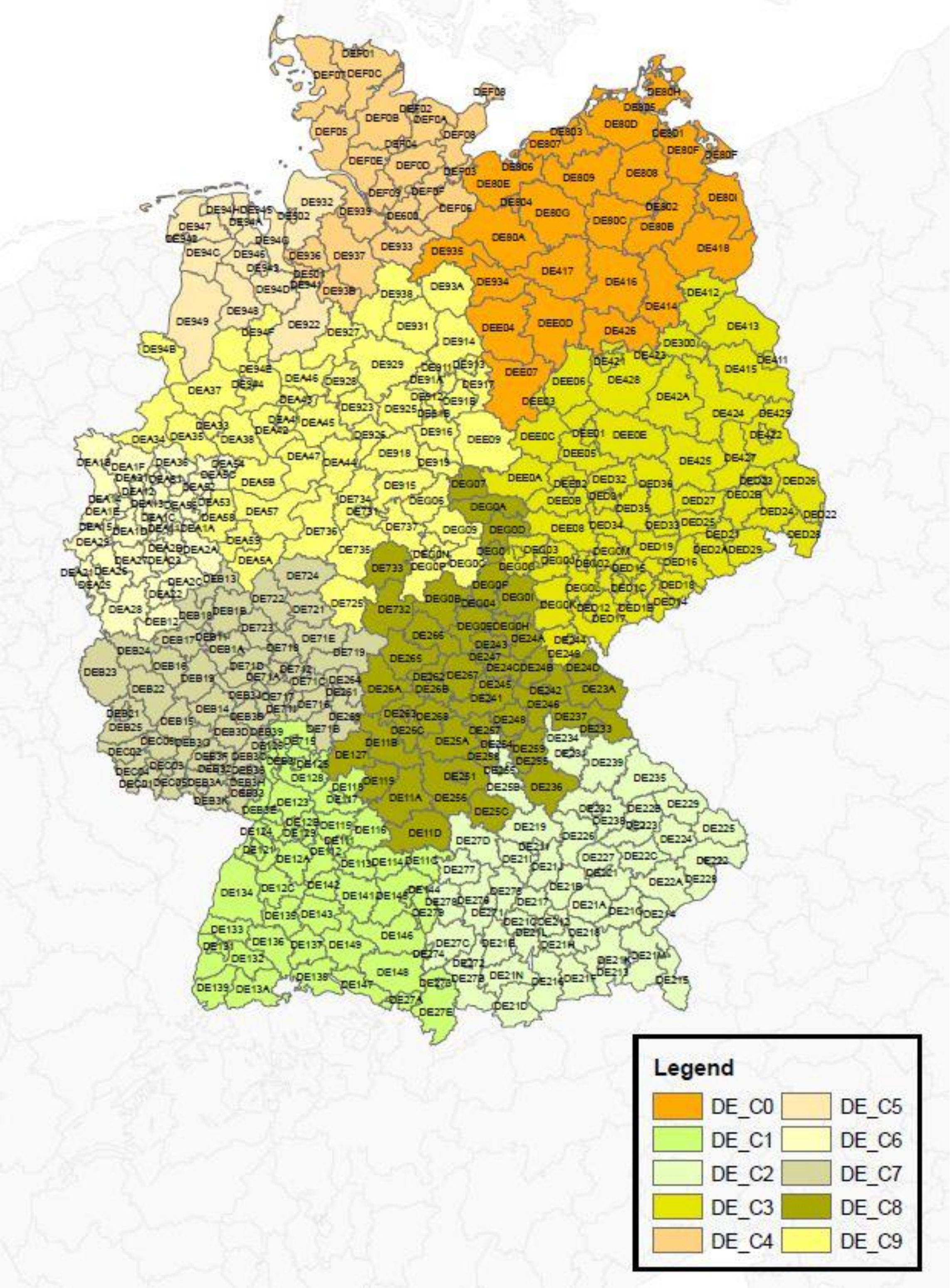


Figure 35: Germany: Results of the algorithm

Results after consultation:

Figure 36: Germany: Results after consultation

Spain

Results of algorithm:

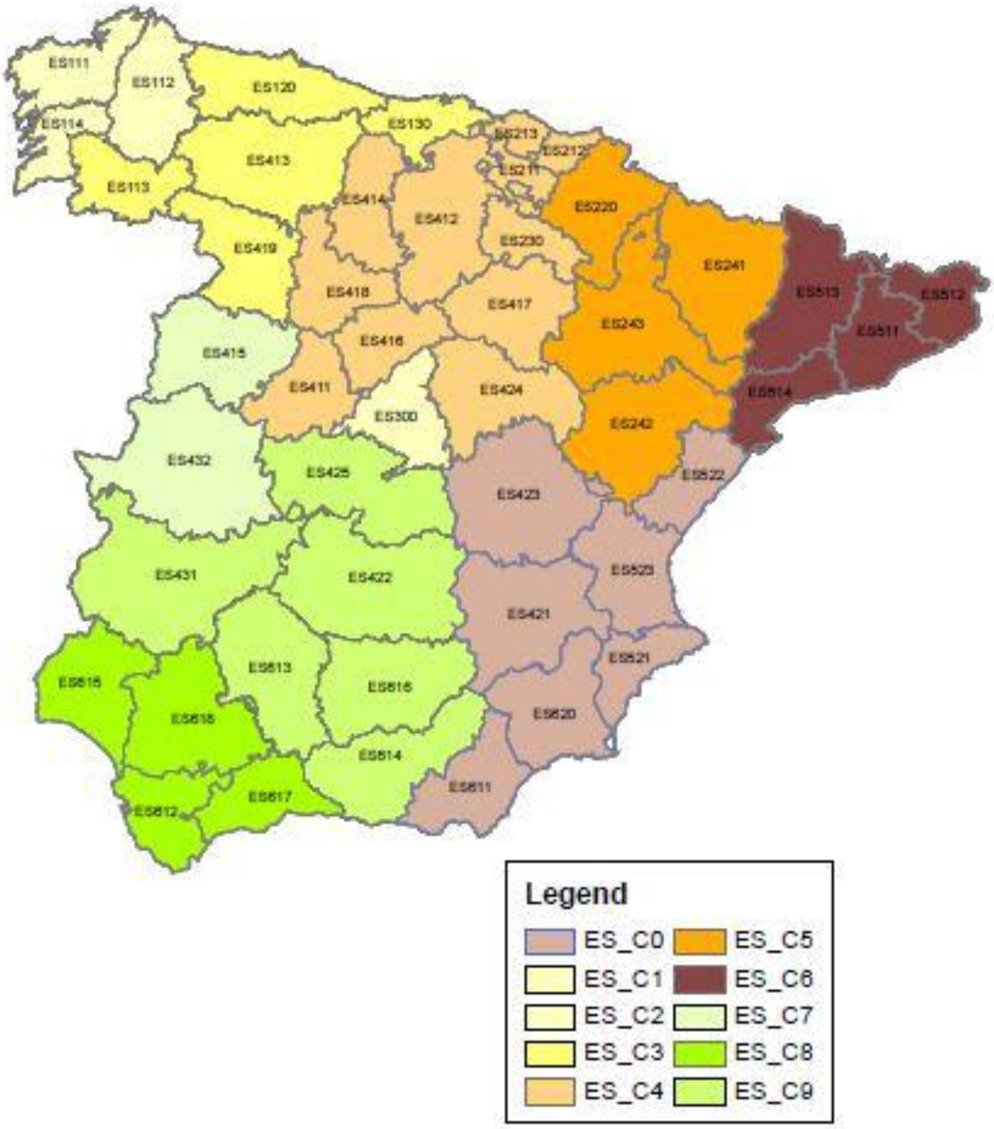


Figure 37: Spain: Results of the algorithm

Results after consultation:

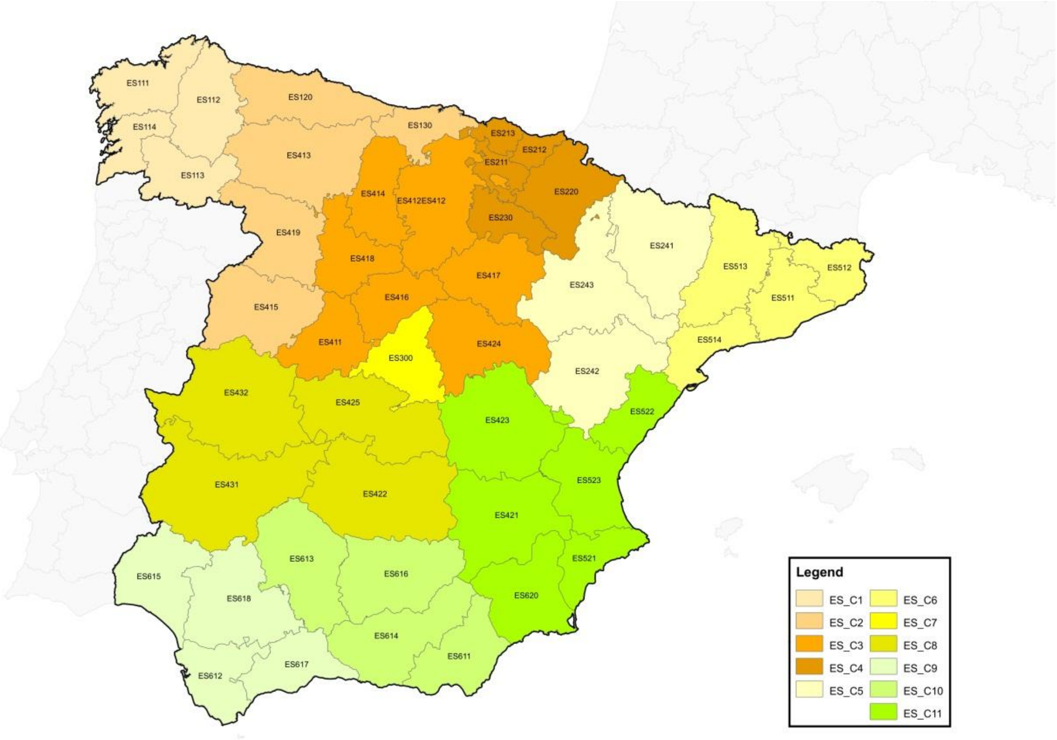


Figure 38: Spain: Results after consultation

France

Results of algorithm:

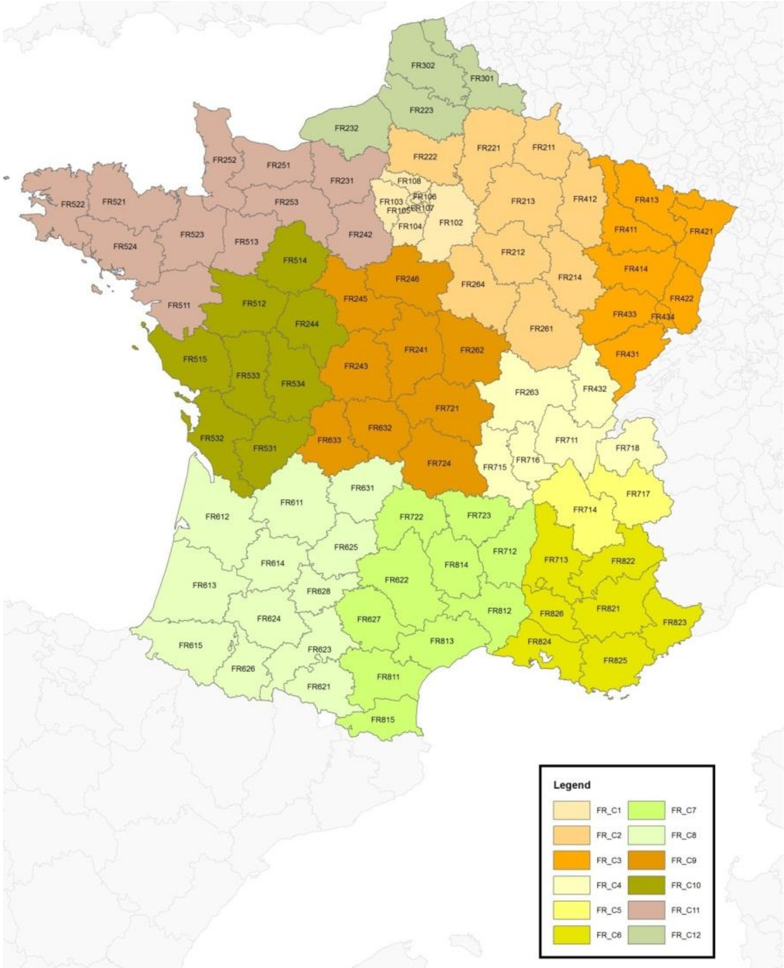


Figure 39: France: Results of the algorithm

Results after consultation:

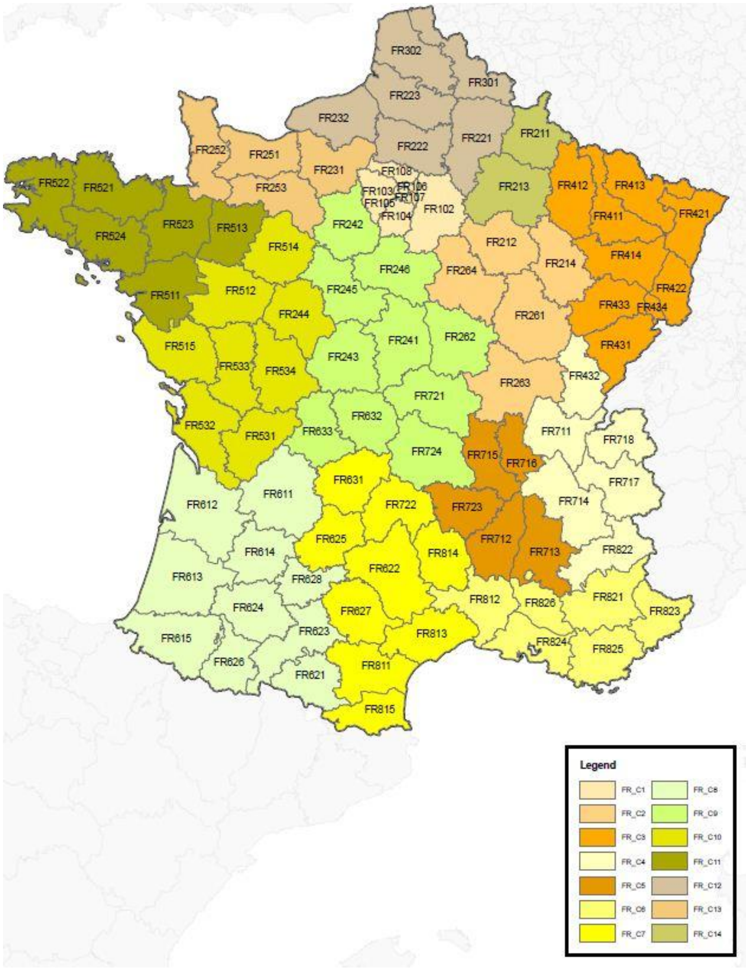


Figure 40: France: Results after consultation

Finland

Results of algorithm:

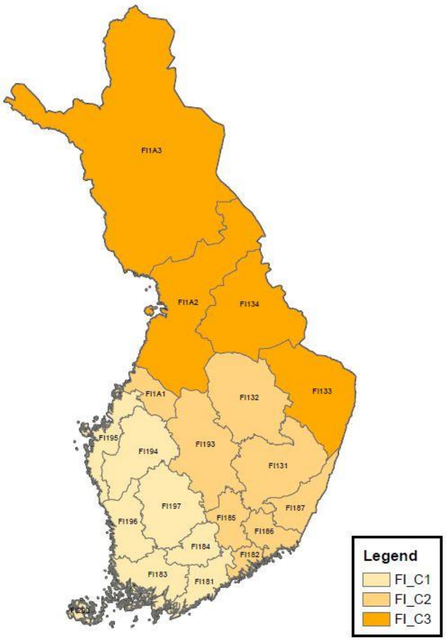


Figure 41: Finland: Results of the algorithm

Results after consultation:

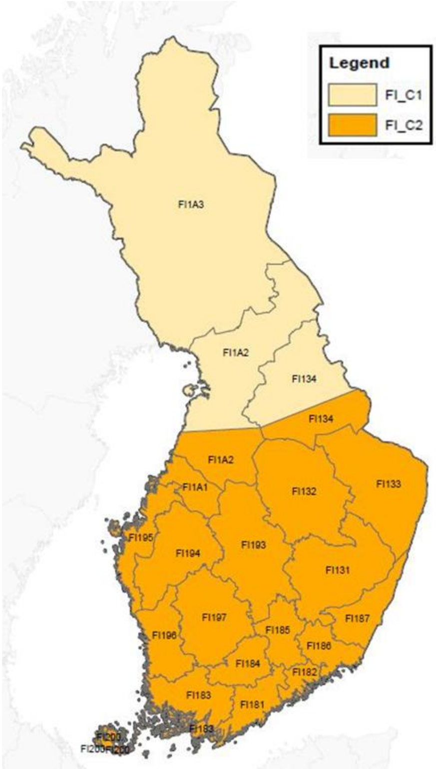


Figure 42: Finland: Results after consultation

Great Britain

Results of algorithm:

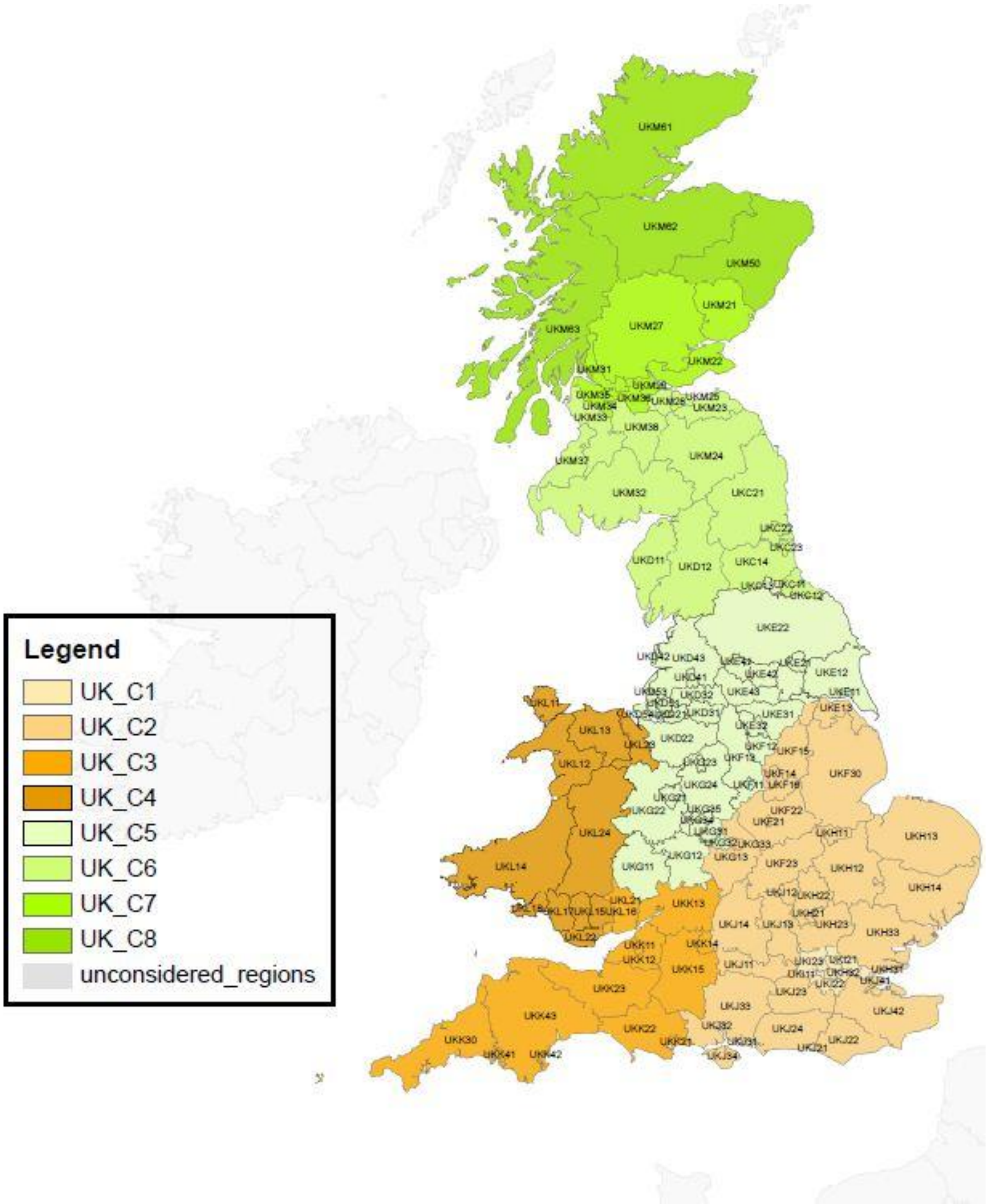


Figure 43: Great Britain: Results of the algorithm

Results after consultation:

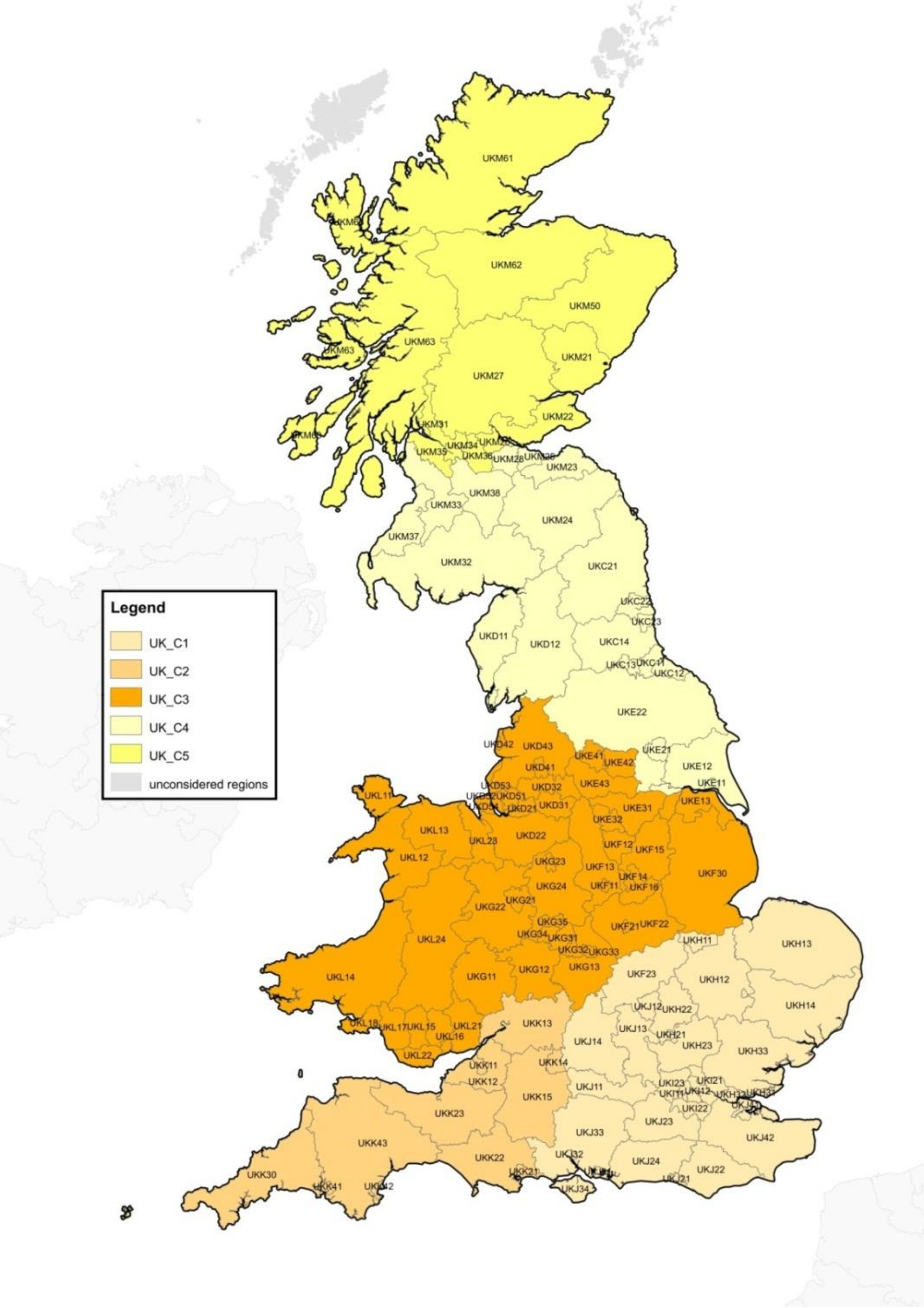


Figure 44: Great Britain: Results after consultation

Greece

Results of algorithm:

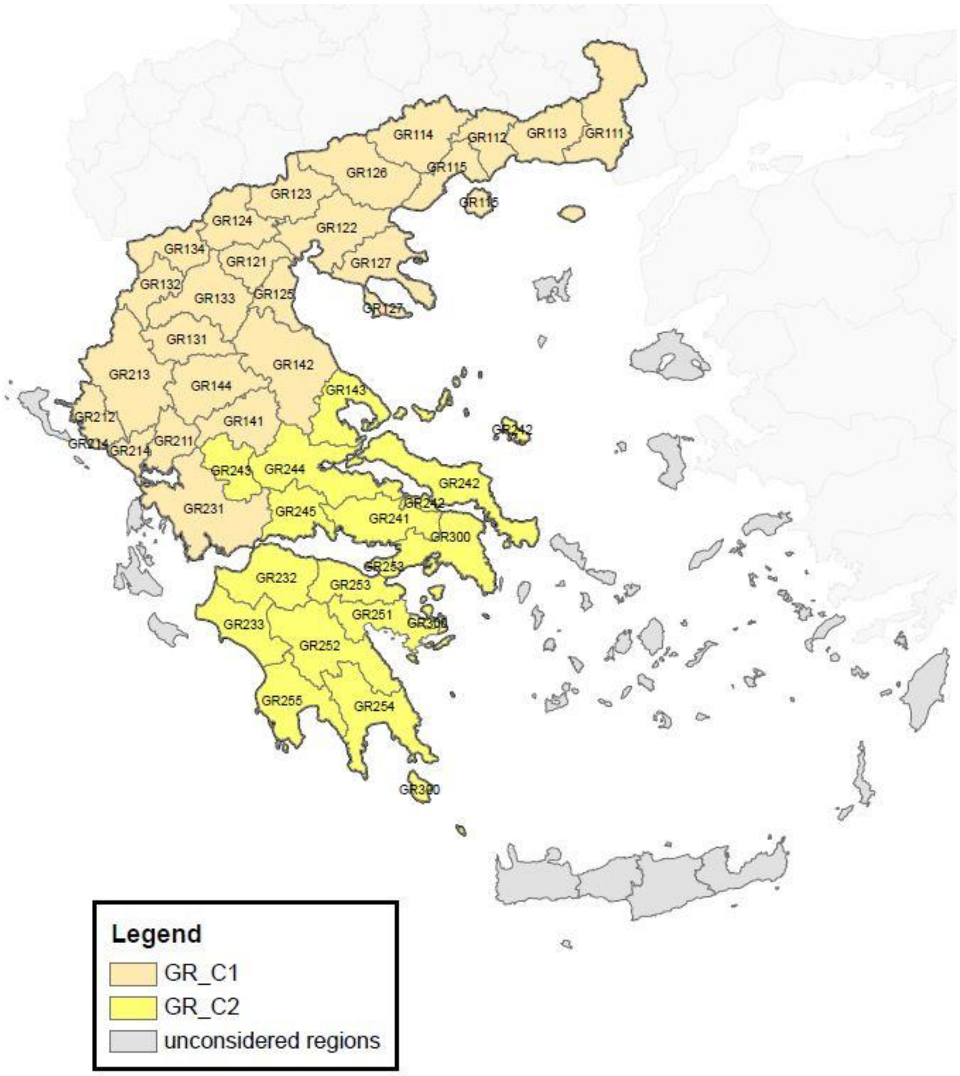


Figure 45: Greece: Results of the algorithm

Results after consultation: Cluster remains the same

Hungary

Results of algorithm:

Figure 46: Hungary: Results of the algorithm

Results after consultation:

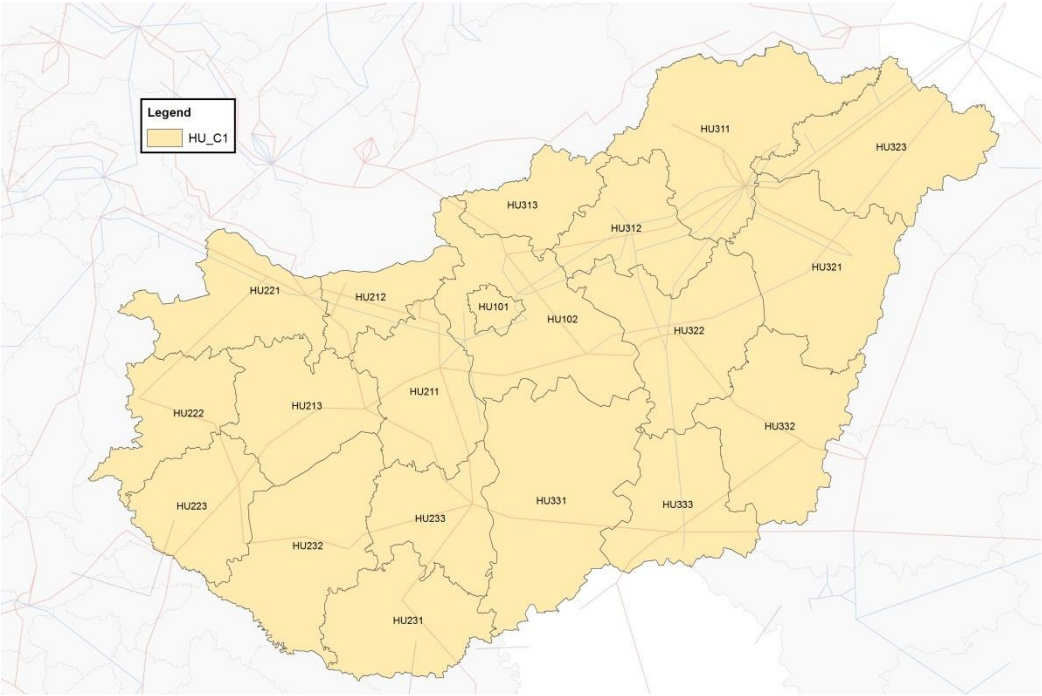


Figure 47: Hungary: Results after consultation

Italy

Results of algorithm:

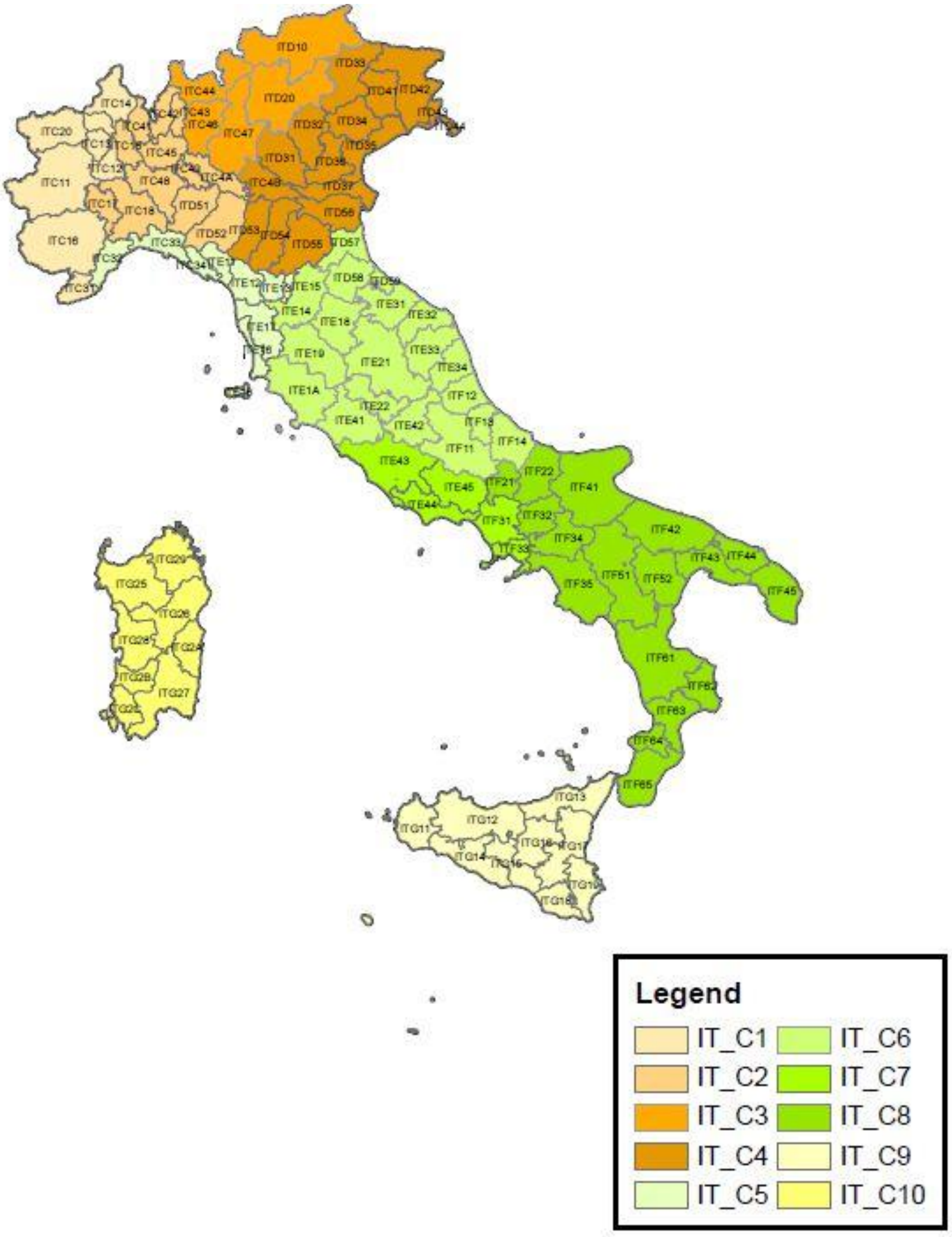


Figure 48: Italy: Results of the algorithm

Results after consultation:

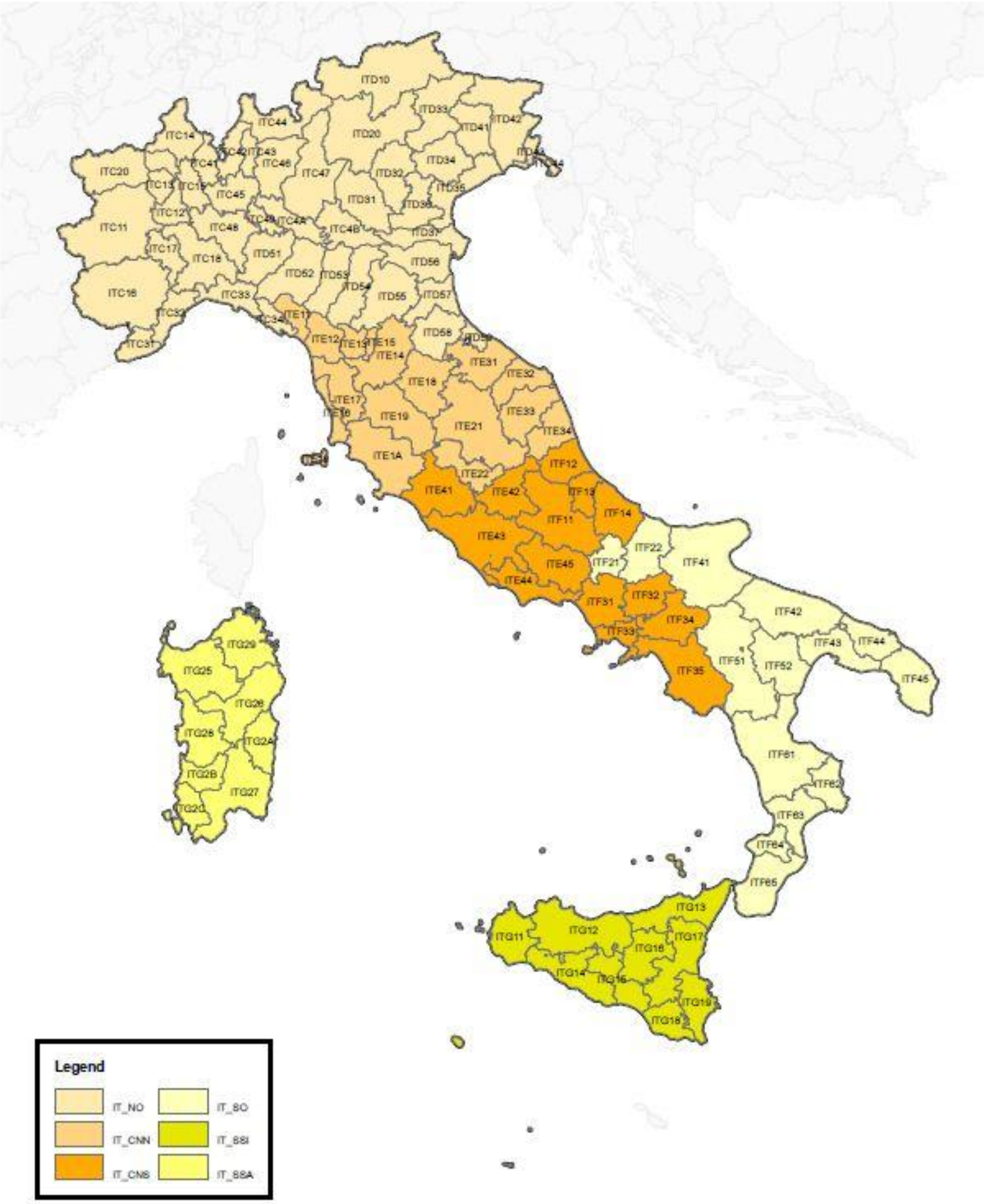


Figure 49: Italy: Results after consultation

Netherlands

Results of algorithm:

Figure 50: Netherland: Results of the algorithm

Results after consultation:

Figure 51: Netherland: Results after consultation

Norway

Results of algorithm:

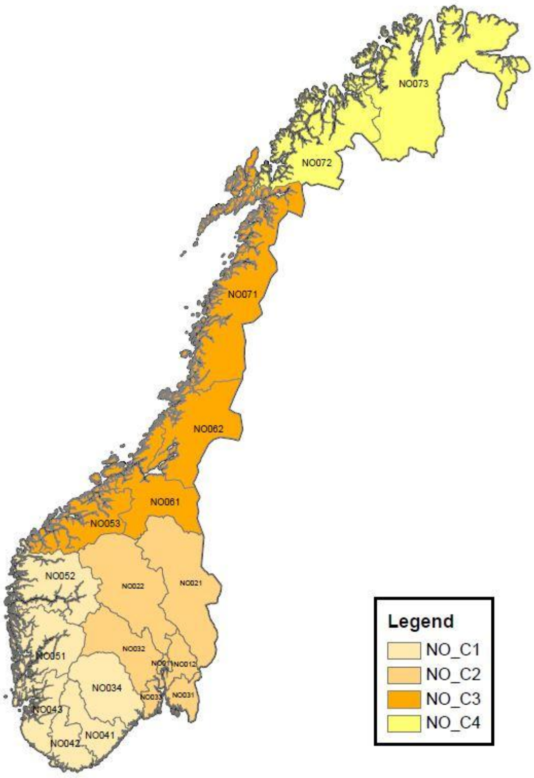


Figure 52: Norway: Results of the algorithm

Results after consultation:

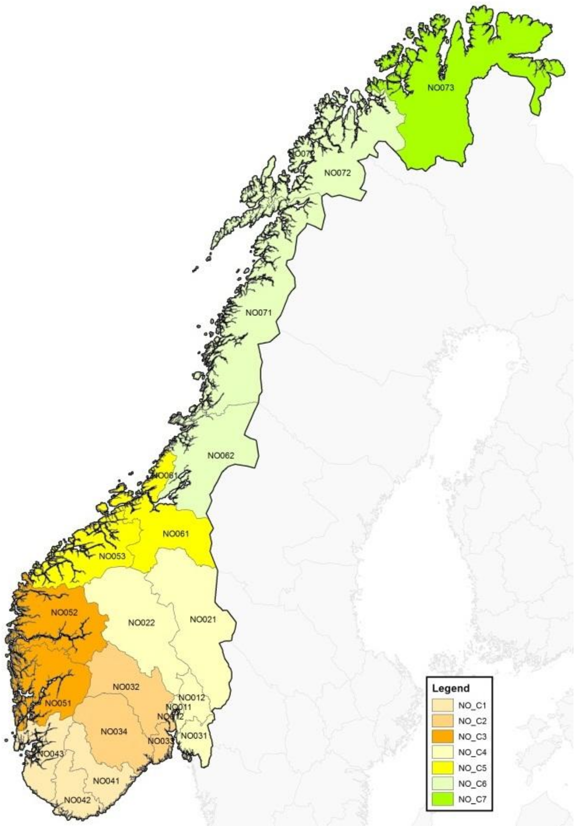


Figure 53: Norway: Results of the algorithm

Poland

Results of algorithm:

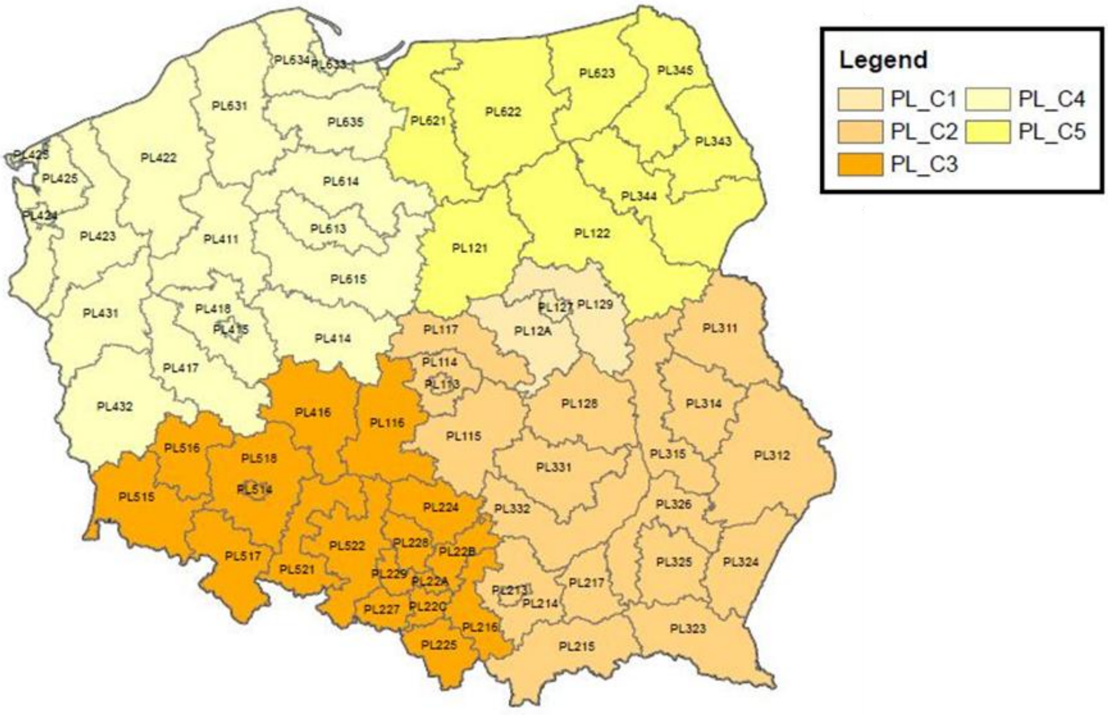


Figure 54: Poland: Results of the algorithm

Results after consultation:

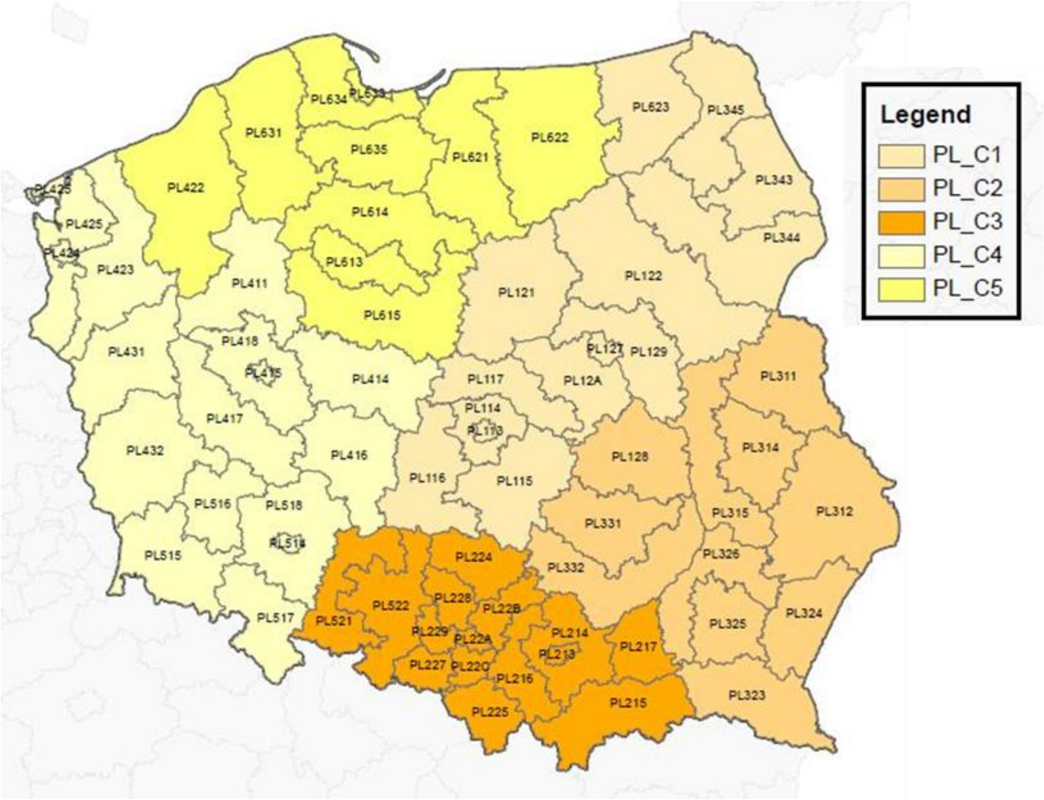


Figure 55: Poland: Results after consultation

Portugal

Results of algorithm:

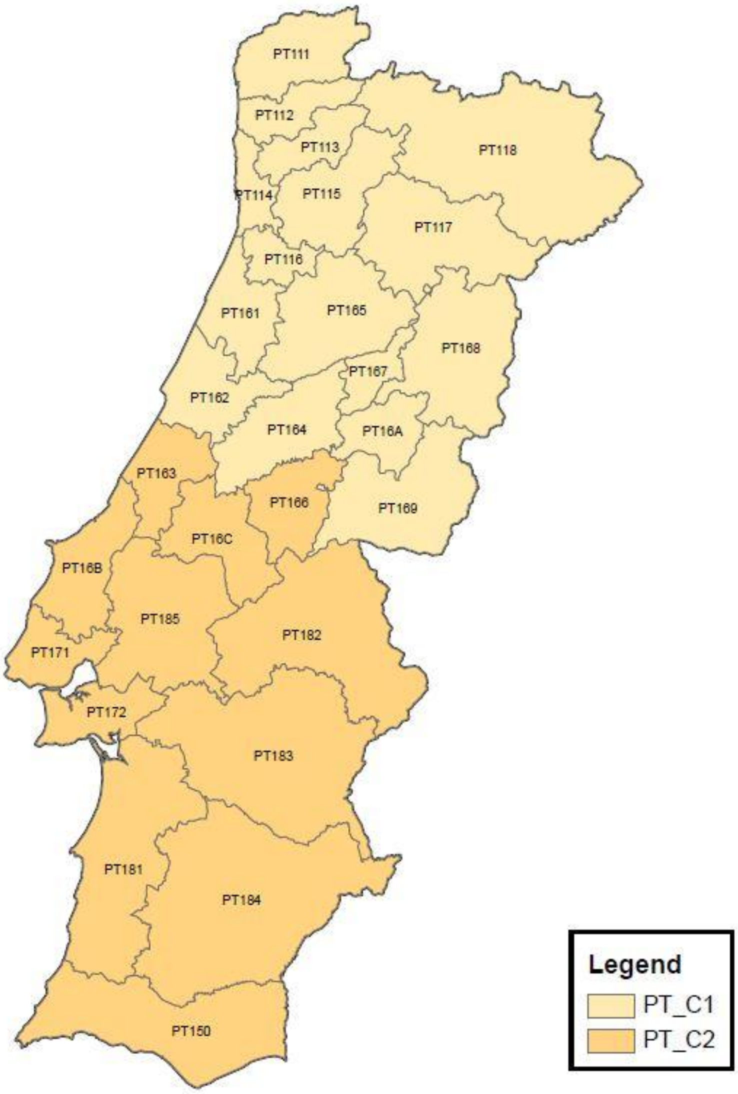


Figure 56: Portugal: Results of the algorithm

Results after consultation: Cluster remains the same.

Romania

Results of algorithm:

Figure 57: Romania: Results of the algorithm

Results after consultation: Cluster remains the same.

Sweden

Results of algorithm:

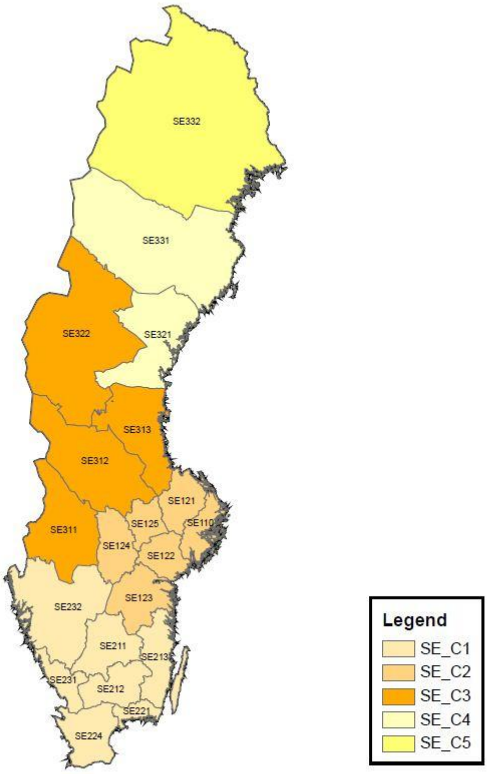


Figure 58: Sweden: Results of the algorithm

Results after consultation:

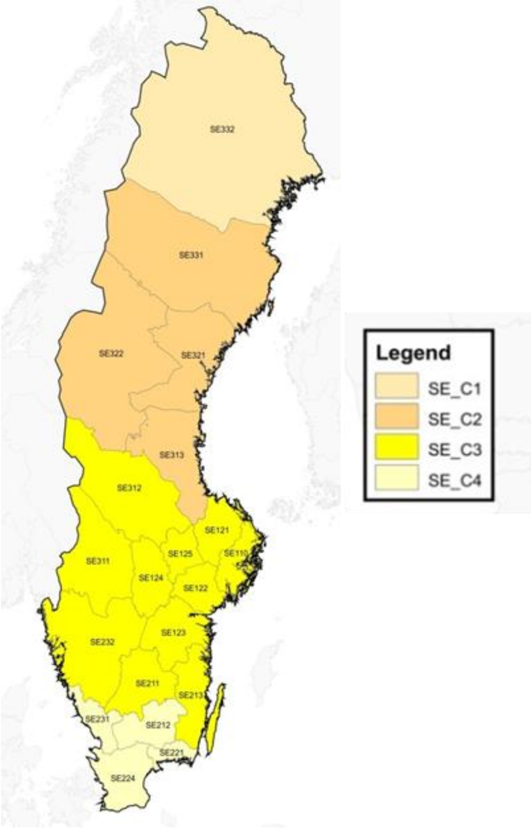


Figure 59: Sweden: Results after consultation

Annex D – Results grid reduction

Estimation of precision

One of the results of the method are the flows calculated with the equivalent network for each interconnection between clusters and each snapshot.

It allows calculating indicators that measure the precision of the equivalent on the whole sample.

Among these indicators, the Root Mean Square Error (RMSE) on the difference between initial flows and calculated flows is calculated for each interconnection; a global RMSE is also calculated (see Figure 60).

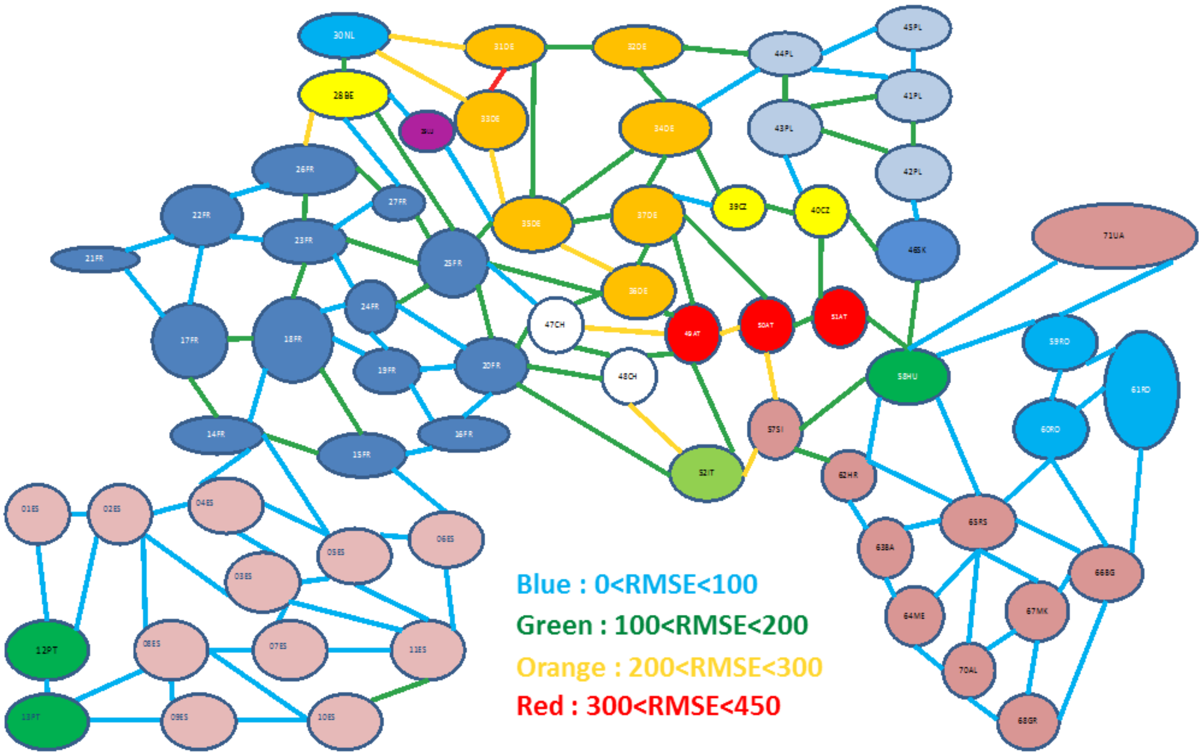


Figure 60: Error on estimation of flows : local RMSE (MW) ; global RMSE = 123MW

The precision is satisfying, with an average of 120 MW (=global RMSE), and local variations of RMSE from a few MW to around 400 MW.

All links have a RMSE below 300 MW, except for the link 31DE-33DE with a RMSE of 400 MW.

This value of RMSE has to be analysed relatively to the flow circulating on this link:

It is an important corridor, with an average of 5400 MW for the absolute values of the flows circulating on it. And in 87% of the samples, the difference on this link between the initial flow and the calculated flow is less than 600 MW.

The clustering of countries is very satisfying, as clustered countries (Portugal, Spain France, Poland, Romania, Czech Republic, Switzerland, Germany, Austria) all of them, except for a few ones, have inner links with a very low RMSE (below 200 MW),

Spain and Portugal

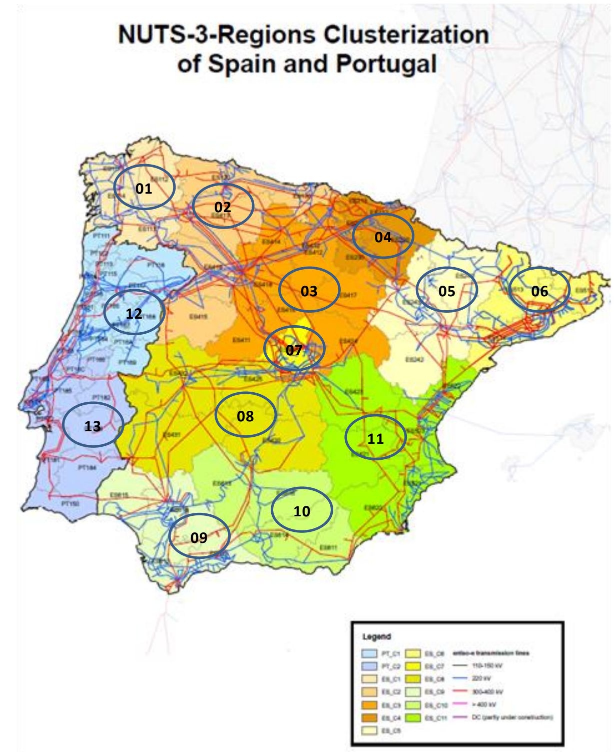
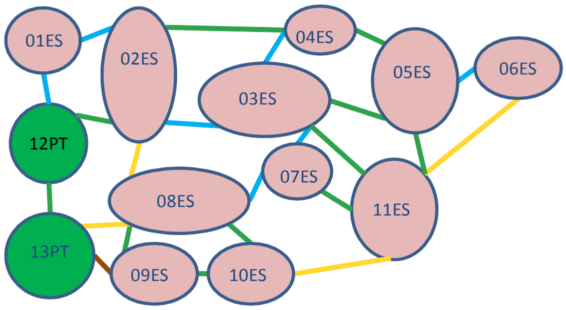


Figure 61: Regional clusters of Spain and Portugal



Purple: 0<Z<3

Blue: 3<Z<10

Green: 10<Z<30

Orange: 30<Z<50

Dark orange: 50<Z<90

Red: 90<Z<200

Figure 62: Equivalent impedances for Spain and Portugal

The electrically shortest interconnection between Spain and Portugal is 05ES-06E. This interconnection consists of 6x380kV lines and 6x225kV lines. Furthermore, the geographical distances between the two clusters are among the shortest ones in Spain, which also is an indicator for the relatively low electric length. Table 2 lists all the remaining links of Spain and Portugal, which have a relatively short geographic distance combined with a high amount of high voltage links.

Interconnection	Number of lines 380kV	Number of lines 225kV
ES03-ES04	5	11
ES01-ES02	6	6
ES07-ES08	5	7
ES02-ES03	17	16
ES03-ES07	8	2

Table 2: Shortest links of Spain and Portugal

By far the longest link within the Spain-Portugal region is the interconnection 09ES-13PTE. This link consists of a 1x380kV line, which is covering an important geographical distance.

Other especially long links are ES06-ES11 and ES02-ES08, with a distance of 1x380kV (ES06-ES11) and 3x280kV (ES02-ES08).

Germany

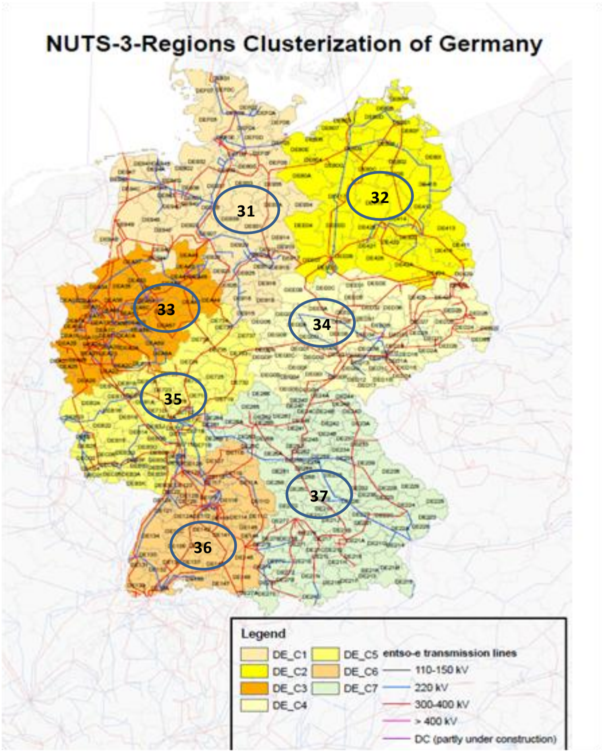


Figure 63: Regional clusters of Germany

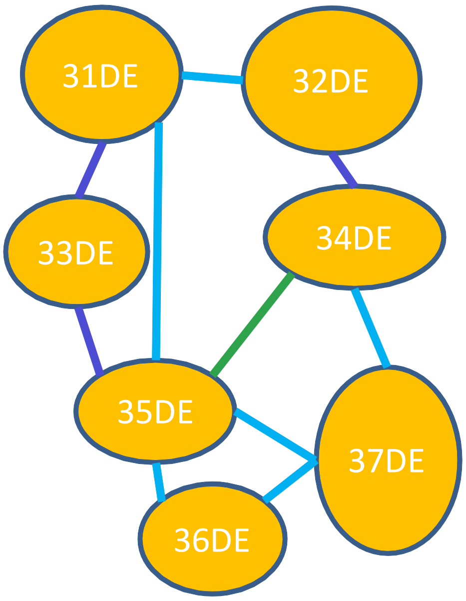


Figure 64: Calculated impedances for Germany

Purple: 0<Z<3
Blue : 3<Z<10
Green : 10<Z<30
Orange : 30<Z<90
Red : 90<Z<200

The electrically shortest interconnection in Germany and the whole continental grid is the link 33DE-35DE. This interconnection is made of 15x380kV lines and 6x110kV lines. Furthermore, the geographical distances between the two clusters are among the shortest ones in Germany, which also explains the low electric length.

Other comparatively short links are the links 31DE-33DE and 32DE-34DE, which also have a high number of high voltage links (15x380kV lines and 8x110kV lines for 31DE-33DE and 8x380kV lines for 32DE-34DE).

The longest link within the region of Germany is 34DE-35DE. This interconnection consists of 2x380kV lines, which cover a more important geographical distance than the shortest links listed above.

France

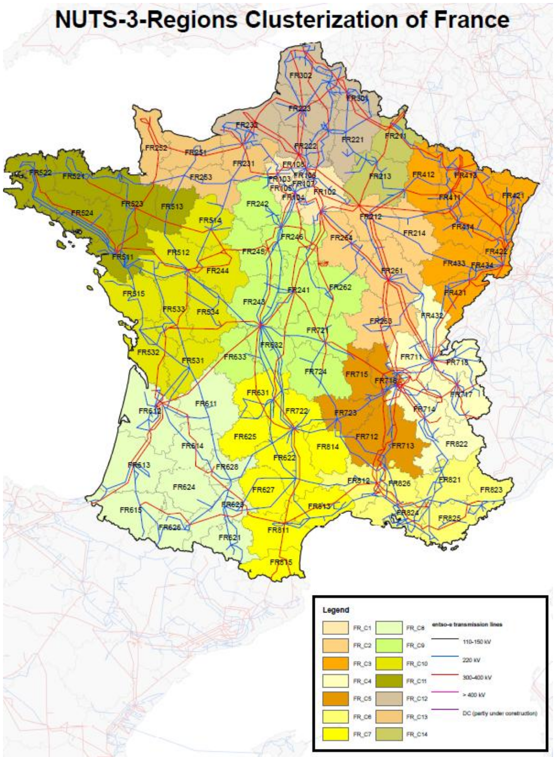
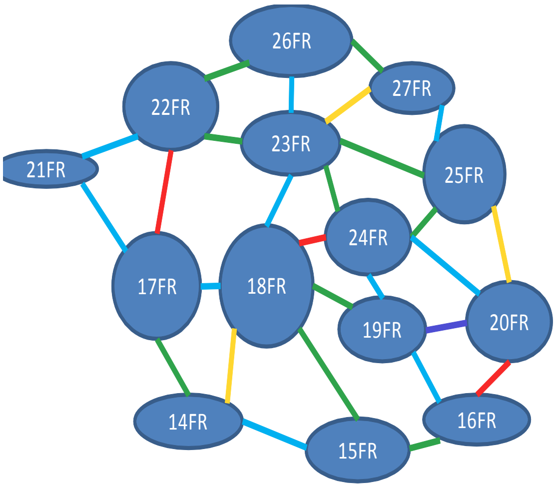


Figure 65: Regional clusters of France



Purple: $0<Z<3$

Blue: $3<Z<10$

Green: $10<Z<30$

Orange: $30<Z<90$

Red: $90<Z<200$

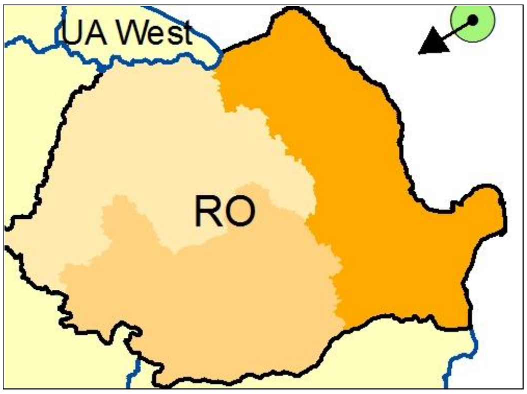
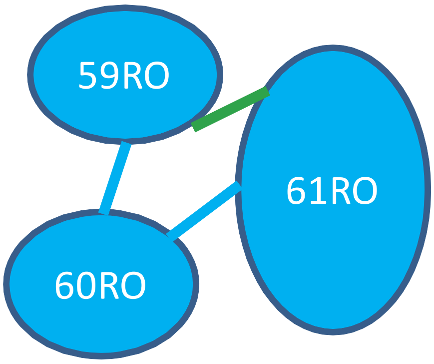
Figure 66: Calculated impedances for France

The electrically shortest link in France is 19FR-20FR, with a high number of high voltage links (5x380kV lines and 15x225kV lines) to connect the Lyon region to the Alps.

Next in the list of shortest links is the connection 23FR-26FR, which connects the Parisian region to the north of France and is highly meshed with 11x380kV lines and 4x225kV lines.

The interconnection with the biggest impedance considering the whole continental grid is located in France (18FR-24FR). This link is made of only one geographically long 225kV line, which explains its great electric length. The two following electrically longest interconnections are also located in France (17FR-22FR and 16FR-20FR) and are made respectively of one 225kV line and three 225kV lines.

Romania

 **Figure 67: Regional clusters of Romania**	 **Purple: 0<Z<3** **Blue: 3<Z<10** **Green: 10<Z<30** **Orange: 30<Z<90** **Red: 90<Z<200** **Figure 68: Calculated impedances for Romania**

The electrically longest link inside Romania is the interconnection 59RO-61RO. In comparison to the other two links of Romania this link consists of fewer lines but covers longer distances.

Interconnection	Number of lines 380kV	Number of lines 225kV	Number of lines 110kV
59RO-61RO	1	1	0
59RO-60RO	3	2	12
60RO-61RO	5	2	3

Table 3: Interconnections of Romania

Annex E – Results of the TC estimation

Table 4 shows the complete results of the GTC estimation. The names of the borders contain the two cluster names as well as the nature of the link (DC or AC). Also given is the number of links as well as the sum of installed capacities (∑ MVA), the GTC estimation and the percentage of installed capacity which is available. Since the GTC values for DC borders are based on TYNDP (ten year network development plan) market values, they can be lower than the ∑ MVA value.

Link	# of links	∑ MVA	GTC	%
01ES-02ES_(AC)	12	12530	7200	57
01ES-12PT_(AC)	3	4478	2700	60
02ES-03ES_(AC)	27	28146	19100	68
02ES-04ES_(AC)	4	4280	2400	56
02ES-08ES_(AC)	2	3250	2400	74
02ES-12PT_(AC)	4	3006	2100	70
03ES-04ES_(AC)	16	12699	7100	56
03ES-05ES_(AC)	5	5614	3900	69
03ES-07ES_(AC)	10	14236	10200	72
03ES-11ES_(AC)	2	3980	2700	68
04ES-05ES_(AC)	3	2421	950	39
04ES-14FR_(AC)	2	2081	1000	48
04ES-14FR_(DC)	1	1000	1000	100
05ES-06ES_(AC)	12	11790	7000	59
05ES-11ES_(AC)	5	9110	5700	63
05ES-14FR_(AC)	1	329	175	53
06ES-11ES_(AC)	1	1570	1150	73
06ES-15FR_(AC)	1	1710	800	47
06ES-15FR_(DC)	1	1000	1000	100
07ES-08ES_(AC)	13	12959	8700	67
07ES-11ES_(AC)	3	4070	2100	52
08ES-09ES_(AC)	6	8310	6100	73
08ES-10ES_(AC)	6	5609	4000	71
08ES-13PT_(AC)	2	3026	2000	66
09ES-10ES_(AC)	13	12600	8100	64
09ES-13PT_(AC)	1	1700	1100	65
09ES-102MA_(AC)	2	1430	1400	98
10ES-11ES_(AC)	3	4340	3200	74
12PT-13PT_(AC)	19	13073	7000	54
14FR-18FR_(AC)	1	1560	1050	67
14FR-15FR_(AC)	6	4514	1900	42
15FR-18FR_(AC)	8	7381	5100	69
15FR-16FR_(AC)	4	6465	2400	37
19FR-52IT_(DC)	1	1000	600	60
14FR-17FR_(AC)	5	6032	1900	31

17FR-18FR_(AC)	5	8607	4200	49
17FR-21FR_(AC)	10	11098	7200	65
17FR-22FR_(AC)	1	406	250	62
16FR-19FR_(AC)	13	9366	6300	67
18FR-19FR_(AC)	2	3159	2200	70
19FR-52IT_(DC)	1	1000	1000	100
16FR-20FR_(AC)	3	1219	425	35
19FR-20FR_(AC)	25	16672	7000	42
20FR-47CH_(AC)	3	6025	4300	71
20FR-48CH_(AC)	2	2101	1300	62
20FR-52IT_(AC)	3	6292	4600	73
21FR-22FR_(AC)	6	10650	6800	64
21FR-96IE_(DC)	1	1000	700	70
22FR-23FR_(AC)	3	3522	2400	68
22FR-90UK_(DC)	1	1000	1000	100
18FR-23FR_(AC)	9	14689	8900	61
23FR-24FR_(AC)	4	5616	3000	53
23FR-25FR_(AC)	4	5460	3500	64
18FR-24FR_(AC)	1	298	125	42
19FR-24FR_(AC)	6	5784	2400	41
20FR-24FR_(AC)	4	5618	3900	69
24FR-25FR_(AC)	6	7482	4500	60
20FR-25FR_(AC)	3	1933	1150	59
25FR-47CH_(AC)	4	5900	3900	66
22FR-26FR_(AC)	6	6802	4600	68
23FR-26FR_(AC)	16	27491	17600	64
26FR-27FR_(AC)	6	8174	5600	69
26FR-28BE_(AC)	2	5200	2900	56
26FR-90UK_(DC)	2	2000	2000	100
23FR-27FR_(AC)	1	1580	1100	70
25FR-27FR_(AC)	4	6008	4300	72
27FR-28BE_(AC)	2	1893	1350	71
25FR-28BE_(AC)	2	937	400	43
28BE-29LU_(AC)	3	1440	700	49
28BE-30NL_(AC)	4	6127	3500	57
28BE-33DE_(DC)	1	1000	1000	100
28BE-90UK_(DC)	1	1000	1000	100
28BE-29LU_(AC)	1	440	275	63
30NL-79NO_(DC)	2	2633	2000	76
30NL-31DE_(AC)	2	2764	1400	51
31DE-32DE_(AC)	4	8319	5500	66
31DE-33DE_(AC)	25	34291	23000	67
31DE-35DE_(AC)	3	5738	4200	73
31DE-38DK_(AC)	6	5680	3200	56
31DE-79NO_(DC)	1	2494	1400	56
31DE-89SE_(DC)	1	693	1200	173
32DE-34DE_(AC)	8	13308	9400	71

32DE-44PL_(AC)	4	7261	5000	69
32DE-72DK_(DC)	1	575	325	57
32DE-72DK_(DC)	3	5314	2500	47
30NL-33DE_(AC)	6	11518	7100	62
33DE-35DE_(AC)	21	30451	20000	66
34DE-35DE_(AC)	2	3633	2600	72
34DE-37DE_(AC)	15	22013	15200	69
34DE-44PL_(AC)	2	3492	1900	54
25FR-35DE_(AC)	3	3441	2100	61
29LU-35DE_(AC)	8	4413	2900	66
35DE-36DE_(AC)	9	13345	8300	62
35DE-37DE_(AC)	6	8356	6000	72
25FR-36DE_(AC)	2	2043	850	42
25FR-36DE_(DC)	1	1000	1000	100
36DE-37DE_(AC)	6	10719	7100	66
36DE-47CH_(AC)	12	12739	6000	47
36DE-49AT_(AC)	13	12100	7300	60
37DE-49AT_(AC)	6	6155	3300	54
37DE-50AT_(AC)	4	6055	2500	41
30NL-38Dk_(AC)	1	987	700	71
38DK-79NO_(DC)	4	1889	1800	95
38DK-88SE_(DC)	2	1221	1200	98
34DE-39CZ_(AC)	2	2772	1100	40
37DE-39CZ_(AC)	2	2955	2000	68
39CZ-40CZ_(AC)	10	12017	8300	69
40CZ-43PL_(AC)	4	3572	2200	62
40CZ-46SK_(AC)	3	3706	2000	54
40CZ-51AT_(AC)	4	3621	2400	66
41PL-42PL_(AC)	10	8258	4700	57
41PL-43PL_(AC)	10	7691	4900	64
41PL-44PL_(AC)	8	5099	3400	67
41PL-45PL_(AC)	5	6585	4400	67
42PL-43PL_(AC)	11	6883	4300	62
42PL-46SK_(AC)	2	1621	600	37
43PL-44PL_(AC)	5	6165	4000	65
44PL-45PL_(AC)	12	14727	8900	60
45PL-89SE_(DC)	1	1000	600	60
47CH-48CH_(AC)	26	29153	19700	68
47CH-49AT_(AC)	2	1580	750	47
48CH-49AT_(AC)	2	2527	1050	42
49AT-50AT_(AC)	10	14949	9000	60
50AT-51AT_(AC)	8	8825	5000	57
50AT-57SI_(AC)	3	2945	1250	42
48CH-52IT_(AC)	11	11261	7200	64
49AT-52IT_(AC)	2	3868	2800	72
52IT-57SI_(AC)	4	5710	2600	46
52IT-57SI_(DC)	1	1000	1000	100

52IT-53IT_(AC)	8	10337	4800	46
53IT-54IT_(AC)	10	12545	6000	48
54IT-55IT_(AC)	9	13206	8900	67
54IT-64ME_(DC)	1	1732	1000	58
54IT-98IT_(DC)	1	1738	1250	72
55IT-56IT_(AC)	3	3245	1000	31
56IT-104TN_(DC)	1	1732	1000	58
46SK-58HU_(AC)	7	9422	5400	57
51AT-58HU_(AC)	4	2951	1700	58
57SI-58HU_(AC)	1	1386	950	69
58HU-59RO_(AC)	2	2494	1400	56
58HU-65RS_(AC)	1	1109	750	68
58HU-100EA_(AC)	3	1181	700	59
59RO-60RO_(AC)	16	5378	3500	65
59RO-61RO_(AC)	2	1687	950	56
59RO-100EA_(AC)	1	1204	700	58
60RO-61RO_(AC)	10	7328	4700	64
60RO-65RS_(AC)	3	3712	2500	67
53IT-62HR_(DC)	1	1732	1000	58
57SI-62HR_(AC)	9	5713	3400	60
58HU-62HR_(AC)	3	4157	2300	55
62HR-65RS_(AC)	2	1405	800	57
62HR-63BA_(AC)	20	8086	4400	54
63BA-64ME_(AC)	4	2779	1450	52
63BA-65RS_(AC)	5	5908	3200	54
64ME-65RS_(AC)	5	4658	3100	67
60RO-66BG_(AC)	2	2553	1600	63
61RO-66BG_(AC)	2	2149	950	44
65RS-66BG_(AC)	3	1460	950	65
66BG-67MK_(AC)	3	1404	725	52
66BG-68GR_(AC)	2	3308	1700	51
66BG-101MI_(AC)	2	2551	1500	59
65RS-67MK_(AC)	3	3654	1900	52
55IT-68GR_(DC)	1	700	1000	143
67MK-68GR_(AC)	2	1720	600	35
68GR-69GR_(AC)	47	18584	11400	61
68GR-101MI_(AC)	1	2000	1200	60
55IT-70AL_(DC)	2	1732	1000	58
64ME-70AL_(AC)	2	1660	950	57
65RS-70AL_(AC)	2	1605	950	59
67MK-70AL_(AC)	1	1218	725	60
68GR-70AL_(AC)	1	1400	800	57
38DK-72DK_(DC)	1	831	800	96
30NL-90UK_(DC)	1	1000	1000	100
28BE-29LU_(AC)	1	400	225	56
41PL-77LT_(DC)	2	3554	2100	59

Table 4: Results of the GTC estimation

	DC/AC/Rest of the world	GTC	GTC direct winter	GTC indirect winter	GTC direct summer	GTC indirect summer
01es - 02es	AC	7200				
01es - 12pt	AC	1200				
02es - 03es	AC	19100				
02es - 04es	AC	2400				
02es - 08es	AC	2400				
02es - 12pt	AC	950				
03es - 04es	AC	7100				
03es - 05es	AC	3900				
03es - 07es	AC	10200				
03es - 11es	AC	2700				
04es - 05es	AC	900				
04es - 14fr	AC	1000				
04es - 14fr	DC	1000				
05es - 06es	AC	7000				
05es - 11es	AC	5700				
05es - 14fr	AC	100				
06es - 11es	AC	1100				
06es - 15fr	AC	1000				
06es - 15fr	DC	800				
07es - 08es	AC	8700				
07es - 11es	AC	2100				
08es - 09es	AC	6100				
08es - 10es	AC	4000				
08es - 13pt	AC	900				
09es - 10es	AC	8100				
09es - 13pt	AC	500				
10es - 11es	AC	3200				
100ea - 42pl	RoW		1000	0	1000	0
100ea - 58hu	RoW		700	0	700	0
100ea - 59ro	RoW		700	0	700	0
100ea - 73ee	RoW		1000	0	1000	0
100ea - 74fi	RoW		70	0	70	0
100ea - 75fi	RoW		1400	0	1400	0
100ea - 77lt	RoW		1900	0	1900	0
100ea - 78lv	RoW		400	0	400	0
12pt - 13pt	AC	4000				
14fr - 15fr	AC	2000				
14fr - 17fr	AC	3000				
14fr - 18fr	AC	1100				
15fr - 16fr	AC	3500				
15fr - 18fr	AC	4500				
16fr - 19fr	AC	5200				
16fr - 20fr	AC	450				
17fr - 18fr	AC	4200				

17fr - 21fr	AC	5400				
17fr - 22fr	AC	250				
18fr - 19fr	AC	2200				
18fr - 23fr	AC	10000				
18fr - 24fr	AC	125				
19fr - 20fr	AC	6000				
19fr - 24fr	AC	2500				
19fr - 52it	DC	1000				
20fr - 24fr	AC	3000				
20fr - 25fr	AC	1150				
20fr - 47ch	AC	4300				
20fr - 48ch	AC	1300				
20fr - 52it	AC	4800				
21fr - 22fr	AC	7000				
21fr - 96ie	DC	700				
22fr - 23fr	AC	2400				
22fr - 26fr	AC	3200				
22fr - 90uk	DC	1000				
23fr - 24fr	AC	3500				
23fr - 25fr	AC	4000				
23fr - 26fr	AC	17900				
23fr - 27fr	AC	1100				
24fr - 25fr	AC	4200				
25fr - 27fr	AC	3500				
25fr - 28be	AC	400				
25fr - 35de	AC	2100				
25fr - 36de	AC	800				
25fr - 36de	DC	1000				
25fr - 47ch	AC	3900				
26fr - 27fr	AC	4900				
26fr - 28be	AC	2900				
26fr - 90uk	DC	2000				
27fr - 28be	AC	1300				
28be - 29lu	AC	700				
28be - 30nl	AC	3500				
28be - 33de	DC	1000				
28be - 90uk	DC	1000				
29lu - 35de	AC	2900				
30nl - 31de	AC	1400				
30nl - 33de	AC	7100				
30nl - 38dk	DC	700				
30nl - 79no	DC	700				
30nl - 90uk	DC	1000				
31de - 32de	AC	5400				
31de - 33de	AC	15330				
31de - 33de	DC	2000				
31de - 35de	AC	4300				

31de - 35de	DC	2000				
31de - 36de	DC	2000				
31de - 37de	DC	4000				
31de - 38dk	AC	3000				
31de - 79no	DC	1400				
31de - 89se	DC	1200				
32de - 34de	AC	9300				
32de - 44pl	AC	3400				
32de - 72dk	DC	600				
33de - 35de	AC	19050				
33de - 36de	DC	2000				
34de - 35de	AC	2600				
34de - 37de	AC	12840				
34de - 37de	DC	2000				
34de - 39cz	AC	1700				
34de - 44pl	AC	1700				
35de - 36de	AC	7700				
35de - 37de	AC	6130				
36de - 37de	AC	7500				
36de - 47ch	AC	6000				
36de - 49at	AC	2800				
37de - 39cz	AC	2000				
37de - 49at	AC	2500				
37de - 50at	AC	5500				
38dk - 72dk	DC	600				
38dk - 79no	DC	1700				
38dk - 88se	DC	740				
39cz - 40cz	AC	7600				
40cz - 43pl	AC	2100				
40cz - 46sk	AC	2700				
40cz - 51at	AC	2100				
41pl - 42pl	AC		4700	4700	3290	3290
41pl - 43pl	AC		4900	4900	3430	3430
41pl - 44pl	AC		3400	3400	2380	2380
41pl - 45pl	AC		4400	4400	3080	3080
41pl - 77lt	AC	1000				
42pl - 43pl	AC		4300	4300	3010	3010
42pl - 46sk	AC	600				
43pl - 44pl	AC		4000	4000	2800	2800
44pl - 45pl	AC		8900	8900	6230	6230
45pl - 89se	DC	600				
46sk - 58hu	AC	5400				
47ch - 48ch	AC	19800				
47ch - 49at	AC	900				
48ch - 49at	AC	1500				
48ch - 52it	AC	7500				
48ch - 52it	DC	1000				

49at - 50at	AC	6300				
49at - 52it	AC	2300				
50at - 51at	AC	6100				
50at - 57si	AC	1600				
51at - 58hu	AC	1600				
52it - 53it	AC		2200	4000	2200	4000
52it - 57si	AC	2600				
52it - 57si	DC	1000				
53it - 54it	AC		2000	3400	2000	3400
53it - 62hr	DC	1000				
53it - 99fr	DC	300				
54it - 55it	AC		10000	6000	10000	6000
54it - 64me	DC	1000				
54it - 98it	DC		700	900	700	900
55it - 56it	AC	1100				
55it - 68gr	DC	1000				
55it - 70al	DC	1000				
57si - 58hu	AC	900				
57si - 62hr	AC	3400				
58hu - 59ro	AC	1400				
58hu - 62hr	AC	2300				
58hu - 65rs	AC	700				
59ro - 60ro	AC	3500				
59ro - 61ro	AC	900				
60ro - 61ro	AC	4700				
60ro - 65rs	AC	2500				
60ro - 66bg	AC	800				
61ro - 66bg	AC	900				
62hr - 63ba	AC	4000				
62hr - 65rs	AC	700				
63ba - 64me	AC	1400				
63ba - 65rs	AC	3100				
64me - 65rs	AC	2900				
64me - 70al	AC	900				
65rs - 66bg	AC	900				
65rs - 67mk	AC	1900				
65rs - 70al	AC	900				
66bg - 67mk	AC	700				
66bg - 68gr	AC	500				
67mk - 68gr	AC	600				
67mk - 70al	AC	700				
68gr - 69gr	AC	11600				
68gr - 70al	AC	800				
72dk - 89se	AC		1700	1300	1700	1300
73ee - 75fi	DC	1000				
73ee - 78lv	AC		950	1250	950	1250
74fi - 75fi	AC		3500	2500	3500	2500

74fi - 85no	AC	50				
74fi - 86se	AC	1800				
75fi - 88se	AC	1350				
77lt - 78lv	AC		1500	1300	1500	1300
77lt - 88se	DC	700				
79no - 80no	AC		1500	1300	1500	1300
79no - 81no	AC		1700	1600	1700	1600
79no - 93uk	DC	1400				
80no - 81no	AC		1500	3500	1500	3500
80no - 82no	AC		5300	2000	5300	2000
81no - 83no	AC	800				
82no - 83no	AC	400				
82no - 88se	AC		2148	2095	2148	2095
83no - 84no	AC		200	1000	200	1000
83no - 87se	AC	1000				
84no - 85no	AC	700				
84no - 86se	AC		700	600	700	600
84no - 87se	AC		250	300	250	300
86se - 87se	AC		4200	3300	4200	3300
87se - 88se	AC	7300				
88se - 89se	AC		6500	3200	6500	3200
90uk - 91uk	AC	7600				
90uk - 92uk	AC	8000				
91uk - 92uk	AC	5000				
92uk - 93uk	AC	7900				
92uk - 96ie	DC	500				
93uk - 94uk	AC	4500				
93uk - 95uk	DC	500				
95uk - 96ie	AC	1100				
98it - 99fr	DC	400				

Table 5: Adjusted TC values after consultation, including non-synchronous areas with continental Europe

Annex F – Modelling of North Sea

This document describes the starting point adopted in E-Highway for development of a 2050 North Sea Grid for offshore wind power production.

Paragraph 1 gives the distribution of the off-shore capacities among countries. Paragraph 2 gives the off-shore clusters modelled and the distribution of the off-shore capacities among off-shore clusters.

Distribution of the off-shore capacities among countries

Seven countries are concerned by offshore North Sea wind potential: United Kingdom (UK), Netherlands (NL), Germany (DE), Denmark (DK), Belgium (BE), Norway (NO) and Sweden (SE).

The distribution among countries of the total capacities for the 5 scenarios are given in the following table :

	NSCOGI	TYNDP 2020 (EU2020) (source : SOAF2012)	TYNDP 2020 Scenario B (source : SOAF2012)	TYNDP 2020 Scenario A (source : SOAF2012)	Potential (0-20m) (source : figure 6.6 of document EEA 2009)	X5	X7	X10	X13	X16
UK	17.7	17.0	26.9	3.0	180.0	40.2	37.2	29.0	17.0	3.0
NL	6.0	5.2	4.0	0.2	40.0	8.9	15.9	7.0	5.2	0.2
DE	16.7	13.5	17.5	7.6	90.0	20.1	27.2	18.0	13.5	7.6
DK	1.2	1.3	2.5	1.7	140.0	31.2	25.6	19.0	4.0	1.7
BE	3.1	2.0	2.2	2.2	5.7	2.0	3.0	2.0	2.0	2.2
NO	0.7	0.0	0.0	0.0	3.0	0.7	3.0	0.5	0.0	0.0
SE	0.7	0.3	0.2	0.2	3.0	0.7	3.0	0.5	0.3	0.2
total	46.1	39.3	53.3	14.9	461.7	103.0	114.9	76.0	42.0	14.9

Table 6: wind off-shore capacities for the 5 scenarios and in reference studies

- X5 distribution is based on the wind energy potential at 0-20 m water depth (source : Environmental Agency, Europe's onshore and offshore wind energy potential No 6/2009).
- X7 distribution is based on the wind energy potential at 0-20 m water depth, but with a levelling relying on the fact that, in X7 there is :
    - more than in X5 the aim of producing near the demand
    - less than in X5 the "respect" of potential :
    - ➔ countries with the biggest capacities (UK, DK) have had their capacity reduced, while the other countries have had their capacity raised.
- X10 distribution is based on the wind energy potential at 0-20m, except the huge capacity of DK which has been reduced slightly and DE capacity which has been a bit raised in order to be consistent with respective country demand level; Netherlands capacity stays around its TYNDP 2012 EU2020 capacity.
- X13 distribution is based on the TYNDP 2012 EU2020 except for DK which is 2,7GW higher in X13 ; this distribution is very close to the distribution which would be based on the wind energy potential at 0-20m water depth, except for DK where the wind

potential would lead to 8,4GW more than in X13. The distribution in X13 is also relatively close to the NSCOGI distribution.

- X16 distribution is based on the TYNDP 2012 scenario A for 2020; the initial total capacity of 10GW in E-Highway has been updated to the total of scenario A (14GW). In the TYNDP 2012, scenario A ("Conservative") derived from scenario B ("Best Estimate" based on the expectations of TSOs) with the secure generating capacity only.
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Offshore clusters and distribution of the capacities among them

Among the 7 countries having North Sea offshore capacity, eleven clusters were identified by the TSOs as having an offshore wind potential. So North Sea is modelled with 11 clusters (106_NS to 116_NS), linked to the 11 on-shore clusters. The table below gives the correspondences between on- and off-shore clusters and the distribution of country capacities among clusters for UK and DK, based on geography:

On-shore cluster on-shore	corresponding off-shore cluster	distribution of country capacity among clusters
90_UK	106_NS	60%
92_UK	107_NS	30%
93_UK	108_NS	5%
94_UK	109_NS	5%
30_NL	111_NS	100%
31_DE	112_NS	100%
38_DK	113_NS	75%
72_DK	114_NS	25%
28_BE	110_NS	100%
79_NO	115_NS	100%
88_SE	116_NS	100%

Table 7: Off-shore clusters

Initial North Sea grid

The initial North Sea grid, considered in the system simulation, is made of radial links between off clusters and on-shore clusters (Figure 70), with a capacity in both directions equal in the starting grid to:

- *max (half the installed wind capacity of the offshore cluster, 8GW) in X5 and X7*
- *max (half the installed wind capacity of the offshore cluster, 5GW) in X10 and X13,*
- *half the installed wind capacity of the offshore cluster in X16*

In order to see the interest of the development of an additional non radial North Sea offshore network, "circular" links between offshore clusters (of 1MW capacity for starting grid) have been added (black links in graph 1 below).

All these radial and circular links have an infinite capacity in the case of the copperplate simulation.

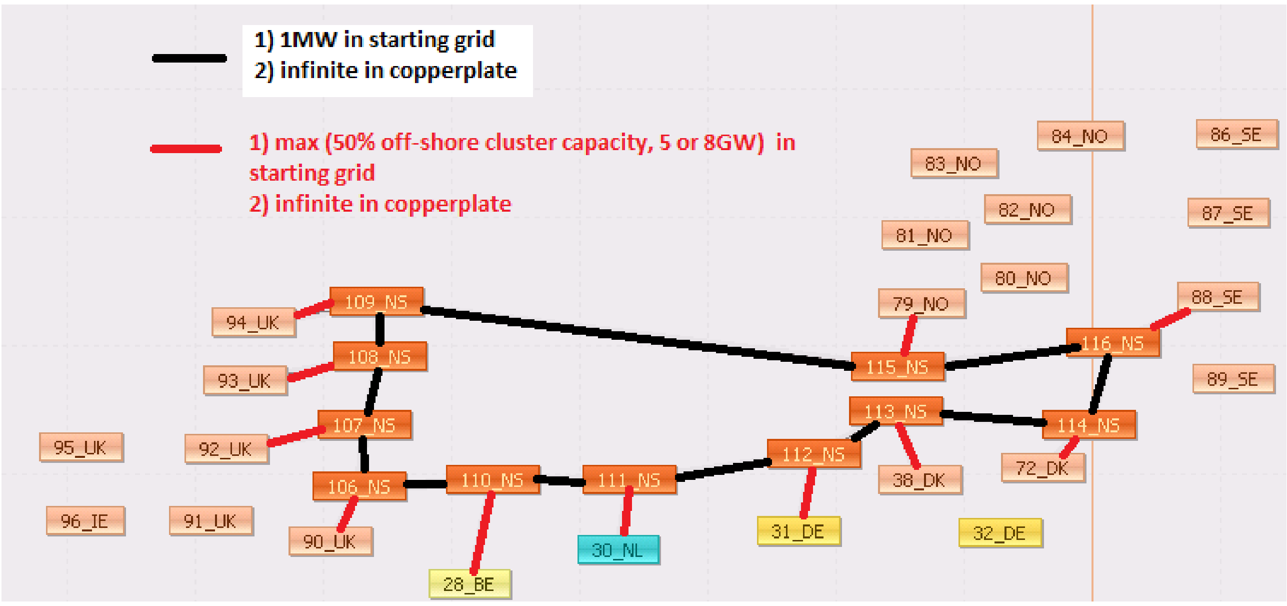

Figure 69: view of the initial North Sea grid[12]

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[12] For better visualization other existing links of the grid model have been removed from the graph.