Methodology:
Flow-based market modelling

entsoe

Reliable Sustainable Connected

1.2

Identification of system needs using a flow-based market model approach

While the generation mix throughout Europe is changing very fast, the development of the European integrated market, together with the interconnection reinforcements, significantly enlarge the playing field to be tackled in long-term grid planning studies. This also poses new challenges to identify and assess network reinforcements in long-term studies such as the ones performed by European Transmission System Operators for the TYNDP. Therefore ENTSO-E did a new and innovative study in parallel with the classical approach for the assessment of system needs for the 2040 scenarios. This additional study was based on a flow-based approach, similar to the one used within the E-Highway 2050 project. ENTSO-E will consider the approach and results of this study further and it will be investigated, whether it is appropriate and how this can be implemented in future TYNDPs.

1.2.1 Conventional methods for grid planning: a two-step approach

The conventional methods used by ENTSO-E teams to assess power flows, congestions and needed reinforcements on the grid are based on a two-step approach made up of a "market" study, followed by a detailed network study.

Market Studies consist currently in market simulations of a single representative node at country[2] level of the European system, interconnected with market Net Transfer Capacities (NTC). Calculations to determine market and system outputs are made for each hour of the year and for different climatic conditions and time horizons.

Results of market studies are then transposed from national single node into a more detailed network (down to the substation level), to enable Network Studies. These are realised through two complementary approaches:

- Deterministic approach, which aims to detect voltage constraints and overloads, through an analysis of a reduced number of load/generation configurations (so-called "snapshots").
- Probabilistic approach, which aims to assess benefits provided by an interconnection reinforcement (mainly increase of NTC on one or several boundaries and losses). Those benefits are estimated based on a high number of plausible load/generation configurations at nodal level, derived from a reference situation (seasonal base-case).

1.2.2 A new methodology at an experimental stage

ENTSO-E experiments with a new method for the assessment of system needs in 2040 scenarios, based on a flow-based approach, similar to the one used within the E-Highway 2050 project.

Indeed, the scenarios in "European Power System 2040: Completing the map" report aim to detect the major electric energy transportation issues and the most valuable cross-border reinforcements. It does not intend to design precisely each reinforcement and define the optimal portfolio of new projects, which would be unrealistic for such a horizon.

Therefore, given the time horizon, the size of the geographic scope and the granularity of the expected results of such a study, a flow-based market model seems to be particularly appropriate and efficient as:

- it includes network model constraints directly in the market model
- it removes the need to allocate the generation from country level to nodal level
- it enables a balanced description of the network that goes beyond the interconnectors, without modelling the whole grid (all voltage levels and substations), while procuring a good estimate of actual flows along the transmission corridors of the European grid; more refinements in the spatial description seems illusive
- the computation time is acceptable.

[2] Except for the countries currently divided into several bidding zones such as Italy, Denmark Sweden and Norway.

1.2.3 Main principles of a flow-based market model

The tested method relies on the integration of a simplified model of the physical grid directly into the market model. The "physical" equivalent impedances of the different links are calculated and used by the model to constrain the flows to comply with Kirchhoff's mesh rule.

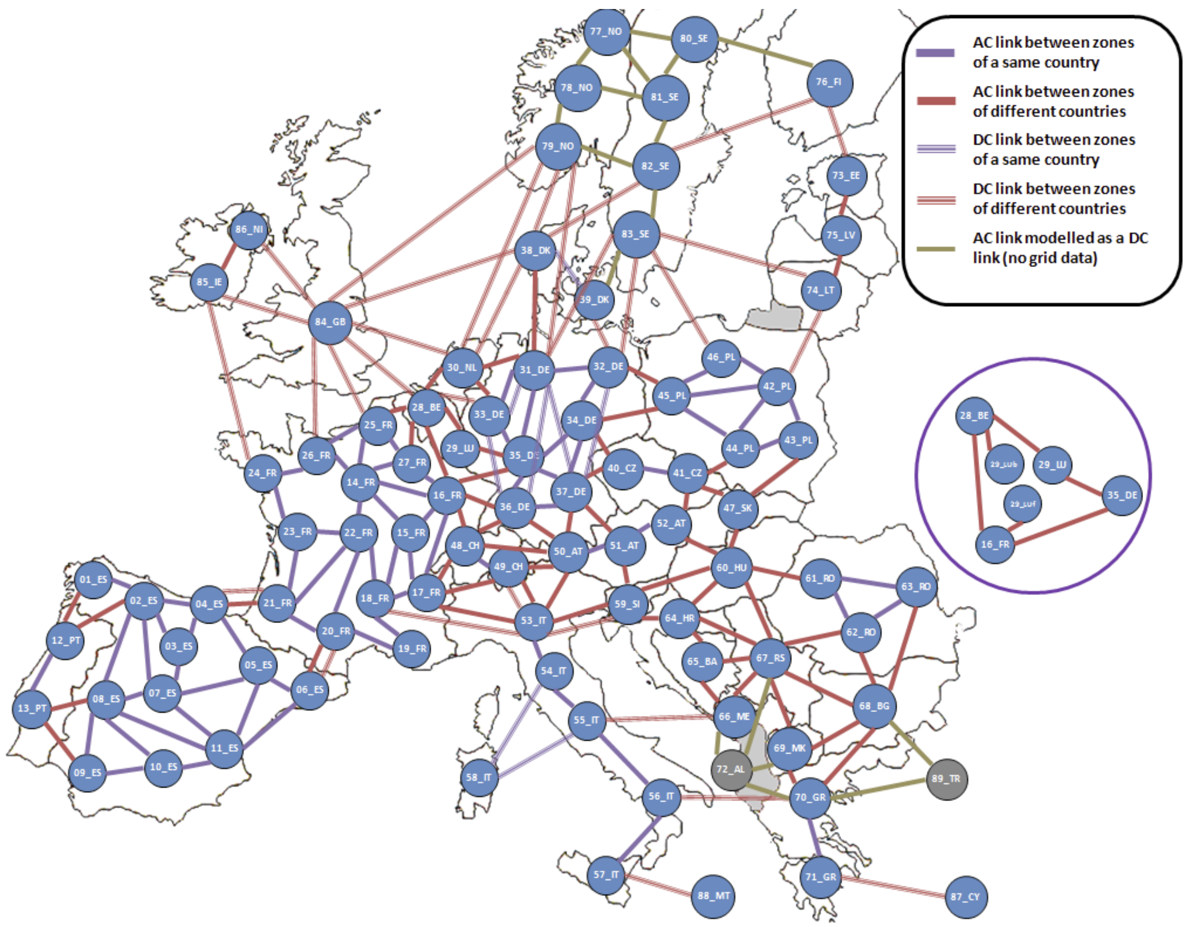
Key drivers of the methodology:

1. The physical model included in the simplified grid removes some of the limits related to commercial exchange capacities and better assess physical flows, on both internal grid and interconnections, in a coherent way.
2. The simplification of the grid allows tackling a large scope of plausible futures, and measuring the impact of various energy mixes on macroscopic corridors of the network; a macro analysis of major overloads and bottlenecks can be conducted for several scenarios.
3. The approach creates an intermediary level between "Market studies", performed at country/ bidding zone level, and "Network Studies", carried out at a nodal level, making the downscaling and the link between different processes easier.

To reach a sufficient level of accuracy in the reduced grid, large countries have to be modelled as smaller zones. Generation and consumption hypothesis have then to be built at this new zonal level, which allows accounting for the location of the different types of generators within large countries (wind in the north and solar in the south have not the same impact on the grid, for instance).

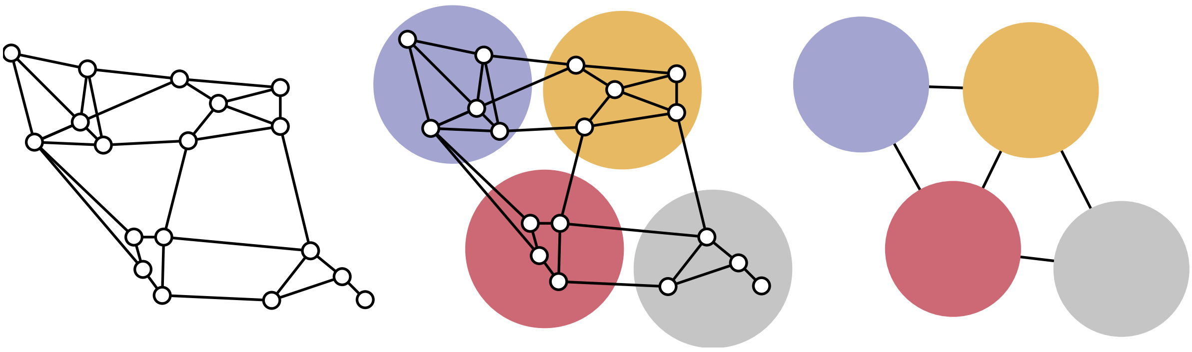
For the first experiment described in this Appendix, the definition of zones was based on the one elaborated during the E-Highway 2050 project. It is characterised by a high degree of consultation of results and inclusion of feedback by TSOs and ENTSO-E. The definition of zones is depicted in Figure 1.

Figure 1: Zones used for the experiment and based on E-Highway 2050



The process leads to a simplified network illustrated in Figure 2, where all substations of a given area are merged in an equivalent node – a "zone" – and all links between two areas are unified in an equivalent link – an "inter-zone".

Figure 2: From detailed to reduced network

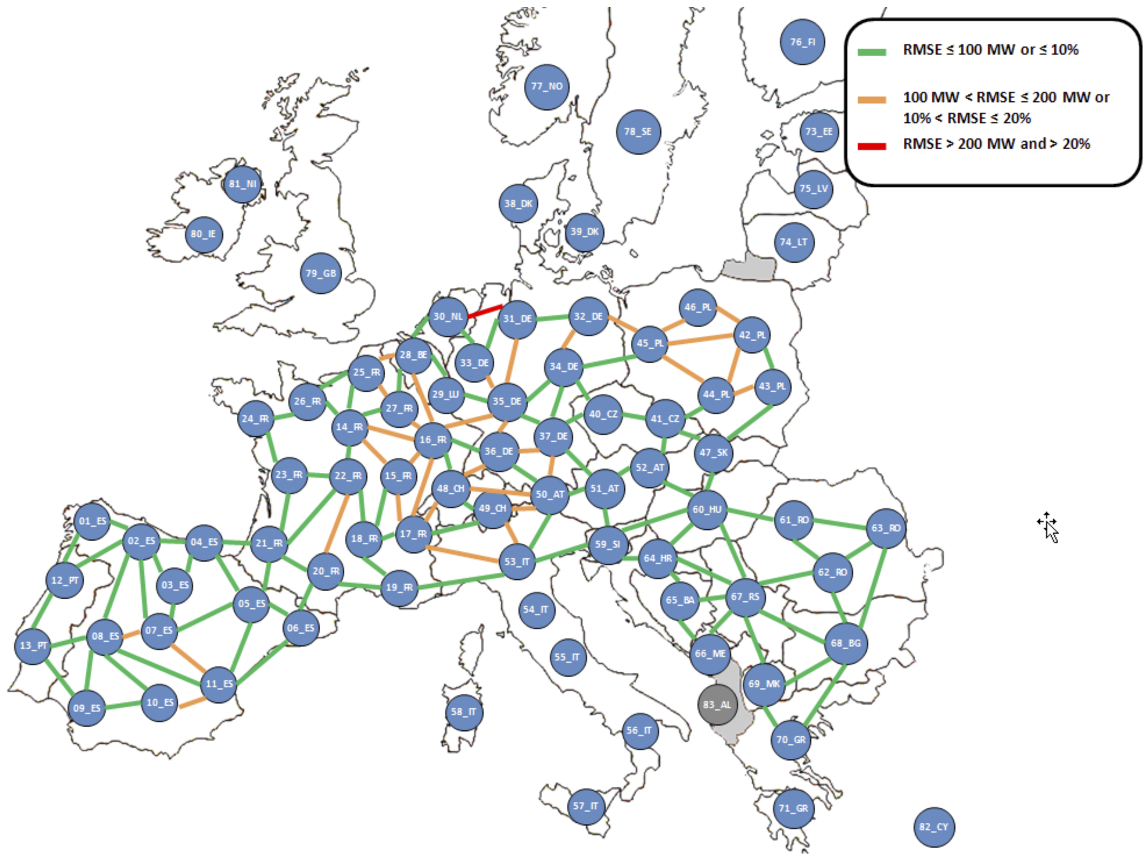


The simplified AC network thus obtained is assumed to follow Kirchhoff's laws:
— The first law is scrupulously respected.
— The second law, the mesh law, requires allocating an impedance to each equivalent link.

An extra parameter is added to the modelling: each equivalent link hosts an initial/structural flow correction, accounting for the possible asymmetries between load and generation within each area.

The set of impedances and flow corrections can be assessed through an optimisation problem. In a nutshell, the method determines the optimal set of impedances and flow corrections minimising the error between estimated flows (with the simplified grid) and target flows (with the detailed grid) on all equivalent links. This optimisation is done on a sample[3] of flows. The method comes by construction with an error estimator, which offers a critical view on the quality of the equivalent network, and provides a first indication of where it is worth improving the definition of zones.

Figure 3: Root Mean Square Error (RMSE): an error estimator of the reduced grid



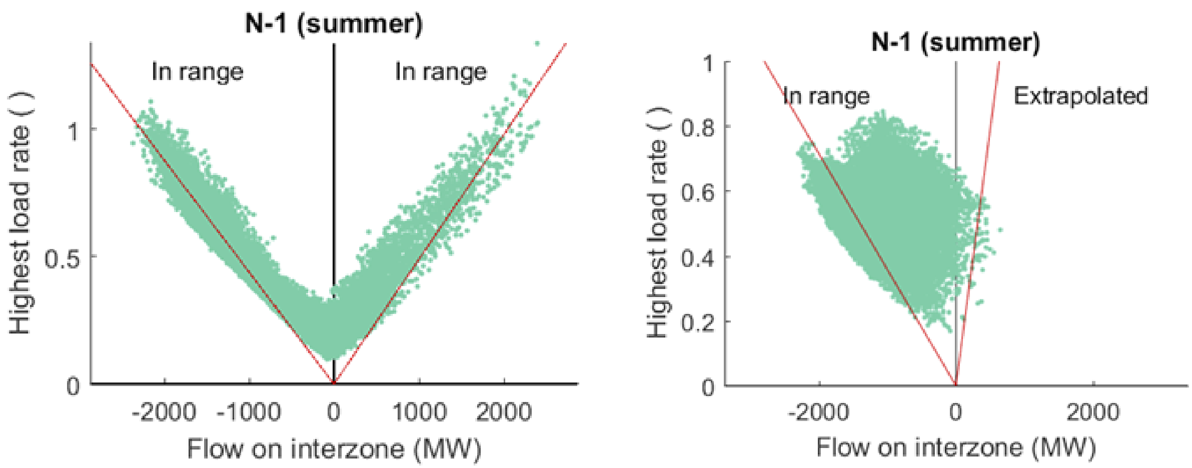
[3] The sample can come from actual measurements of flows, or flows generated from a CIM base case ENTSO-E (TYNDP) on which load flows are computed with different load and generation patterns.

Each equivalent link is assigned a transmission capacity N-1 robust (seasonal and directional). The sample of flows can be used to compute under normal condition and for any given contingency the maximum capacity that can flow on each equivalent link without generating the overload of a single component composing the "border". Indeed, the sample offers different base cases with different initial loading of actual lines composing the inter-zone. Thus, the transmission capacity of the equivalent link can be estimated over the whole sample, and the capacity value determined within a given risk level.

Depending on the correlation between the flows on the different critical branches and critical outages of each inter-zone, the quality of the resulting equivalent capacity may be variable, which is another indicator of where it is worth improving the definition of zones.

Controllable devices can also be included into the model:
— HVDC are modelled through additional links which have not to respect Kirchhoff's mesh rule.
— PSTs are modelled through an additional degree of freedom in Kirchhoff's equations of appropriate meshes, reflecting their phase shifting capability.

Figure 4: Assessment of equivalent capacities: good quality (left) or lower quality (right)



1.2.4 Identification of system needs using a flow-based market model

The identification of system needs for the 2040 horizon starts with a macro-analysis of bottlenecks and their impact on generation mix. The effects of network constraints on generation mix are measured by the difference between two simulations:
— "Copperplate" simulation, in which the transmission grid is assumed to be without constraints, i.e. where network capacities are set to infinite.
— Simulation with grid constraints, in which capacities are limited to the "starting grid" in a first step, and the "starting grid" plus the reinforcements tested during the identification of system needs process for the following steps.

The "copperplate" simulation gives the upper limit of what could be achieved by grid reinforcement to ensure system security and optimise operating costs. On the contrary, the "starting grid" simulation gives the lowest level of system security than can be achieved with the 2030[4] transmission network status after implementation of 2040 demand and generation development.

Several indicators can be inferred from the comparison of these simulations: delta energy not supplied, delta dumped energy, thermal redispatch (increase of more expensive generation and decrease of cheaper generation), etc. The main challenges of each scenario are thus pointed out.

The bottlenecks can be detected through the Marginal Value of the links: this indicator (marginal, €/MW, different for each hour) displays the potential benefits for the system for an extra MW available on a given inter-zone. It points out the first bottlenecks in the system. Not that the indicator only makes sense in a simulation with limited capacities (in a "copperplate" simulation, all the marginal values are equal to zero).

The methodology also builds on the definition by TSOs regarding standard costs for each boundary and for different sizes of reinforcement (as the conventional approach).

For each boundary, the use of indicators like mean marginal value of congestion divided by standard cost of reinforcement allows possible projects for which the benefits should exceed the costs to be identified. Such projects are then tested in the model to determine their benefits and their impact on the main challenges of the scenario. The different projects can be tested individually or by groups.

Step by step, the needs for 2040 are thus identified. The process ends when no new project can be found out that brings more benefits than costs.

This new methodology was tested on the scenario Sustainable Transition 2040 of the TYNDP 2018.

[4] The starting grid assumed in the analysis builds on a full realisation of the TYNDP 2016 projects for the horizon 2030.

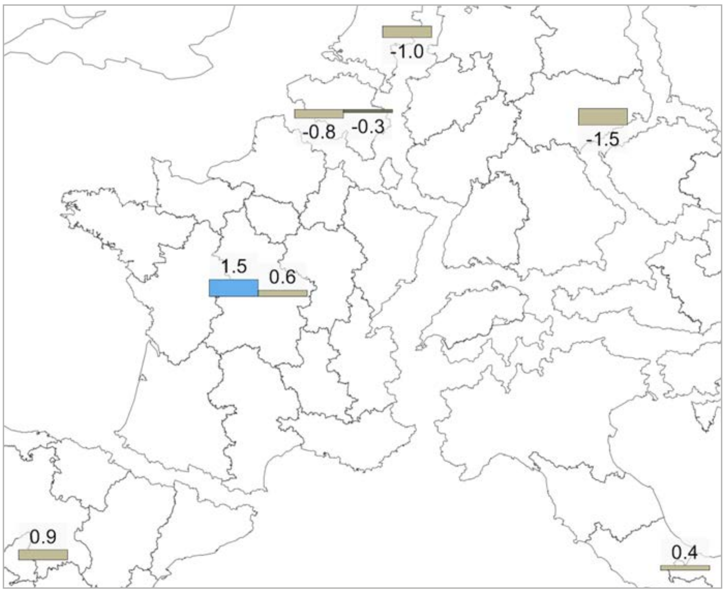
It points out the main challenges of this scenario: Renewable Energy Sources integration in Germany, Spain, Great Britain, Turkey, Ireland, Greece, the Netherlands, Italy and Denmark and nuclear decreases in France, Turkey and Great Britain.

The main bottlenecks are also identified through their mean marginal value (directional). Among them, the following congestions can be mentioned:

— from France to Belgium, Germany, Italy and Switzerland
— from Turkey to Bulgaria and Greece
— from Great Britain to Norway, Denmark, Netherlands, Belgium and France
— from Spain to Portugal
— from Germany to Austria, Czech Republic, Sweden and Poland
— from Greece to Macedonia and Albania
— from Sweden to Finland
— from Denmark, Netherlands and Germany to Norway.

The marginal value displays the potential benefits of the first additional MW of capacity on a given inter-zone but is not necessarily indicative for the following MW. The potential benefits have also to be set against the standard cost of a reinforcement. Therefore, each reinforcement is implemented in the model and thus tested individually. Reinforcements for which benefits exceed costs are then tested by groups. As an example, Figure 5 shows the effects on the system of 1 GW of reinforcement between France and Belgium, France and Germany and both of them. Note that there is almost no competition between these reinforcements.

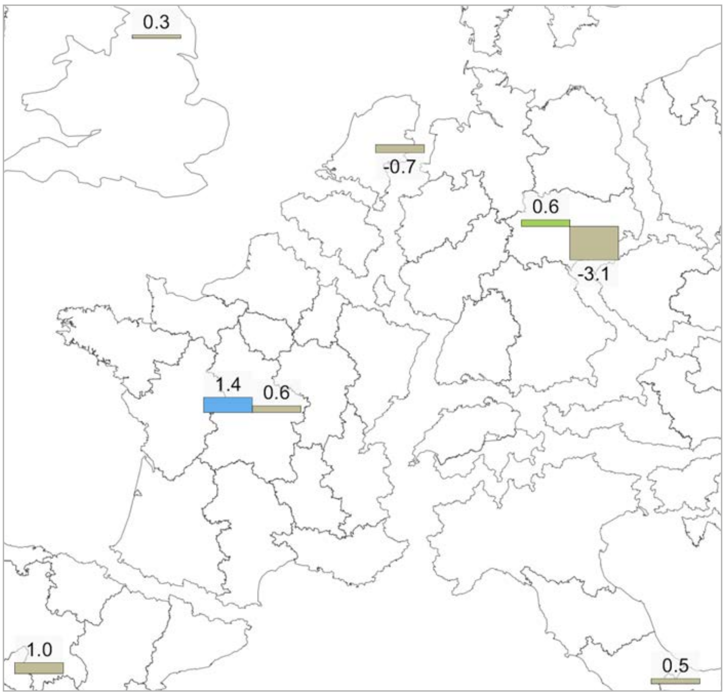
Figure 5: Impact on generation mix and benefits of reinforcements Belgium-France and France-Germany – scenario Sustainable Transition 2040



1 GW of additional capacity between Belgium and France:
Annuity: 6 M€
Generation cost savings: 98 M€/y
Reduction of CO_2 emission: 1.4 Mt/y
Avoided dumped energy: 0.6 TWh/y

Main drivers of benefits: French nuclear replacing thermal generation

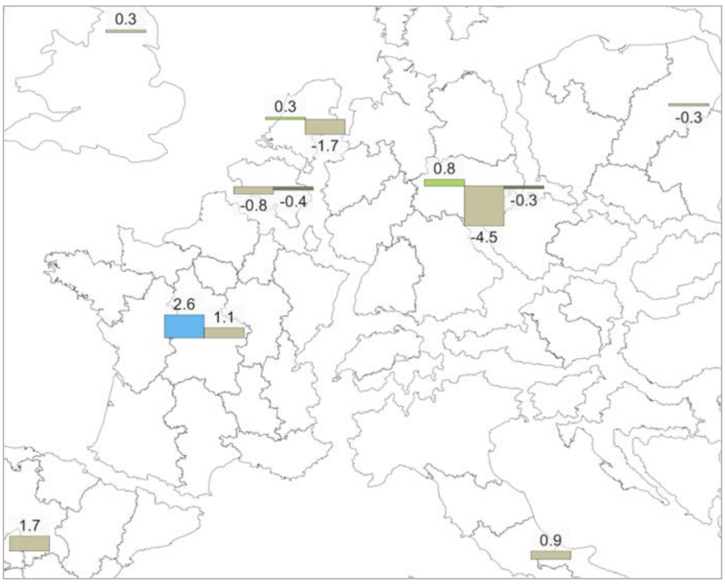
Generation shifts (TWh/y)
- 0 cost generation
- nuclear
- thermal 40 to 60 €/MWh
- thermal 60 to 80 €/MWh
- thermal > 80 €/MWh



1 GW of additional capacity between France and Germany:
Annuity: 19 M€
Generation cost savings: 116 M€/y
Reduction of CO_2 emission: 1.6 Mt/y
Avoided dumped energy: 0.9 TWh/y

Main drivers of benefits: French nuclear and avoided dumped energy in Germany replacing thermal generation

Generation shifts (TWh/y)
- 0 cost generation
- nuclear
- thermal 40 to 60 €/MWh
- thermal 60 to 80 €/MWh
- thermal > 80 €/MWh



1 GW of additional capacity between Belgium and France + 1 GW of additional capacity between France and Germany:
Annuity: 25 M€
Generation cost savings: 210 M€/y
Reduction of CO_2 emission: 2.8 Mt/y
Avoided dumped energy: 1.4 TWh/y

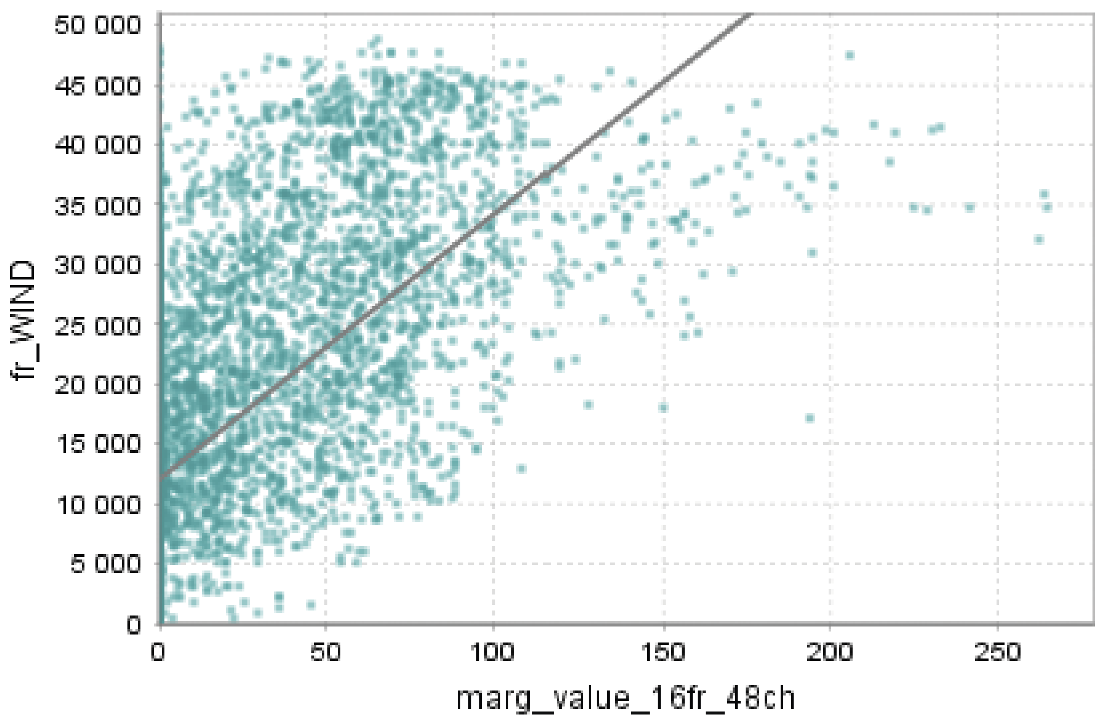
Main drivers of benefits: French nuclear and avoided dumped energy in Germany and the Netherlands replacing thermal generation

To be noted: no competition between both reinforcements (benefits of the group are almost equal to the sum of the benefits of each one) but slightly different arbitrages regarding the location of redispatch

1.2.5 Benefits and challenges of a flow-based market model

The simulation of the interconnected system gives access to a huge database, containing flows for each of the inter-zone links as well as load and generation data for each zone, for every hour of the year and every Monte Carlo scenario. As the transmission grid is AC and highly meshed, a lot of those variables (sometimes correlated) influence the flows, and it can be tricky to determine intuitively the load/generation configurations that cause a constraint. However, statistical analyses of the whole database help to understand what drives flows and constraints. Several methods can be deployed to facilitate the understanding of the electrical system (correlation, principal components analysis, k-means classification, decision tree, etc.). As an example, Figure 6 shows the correlation between the marginal value of congestion between France and Switzerland and wind generation in France.

Figure 6: Correlation between marginal value of a congestion between FR and CH and wind in FR (example)



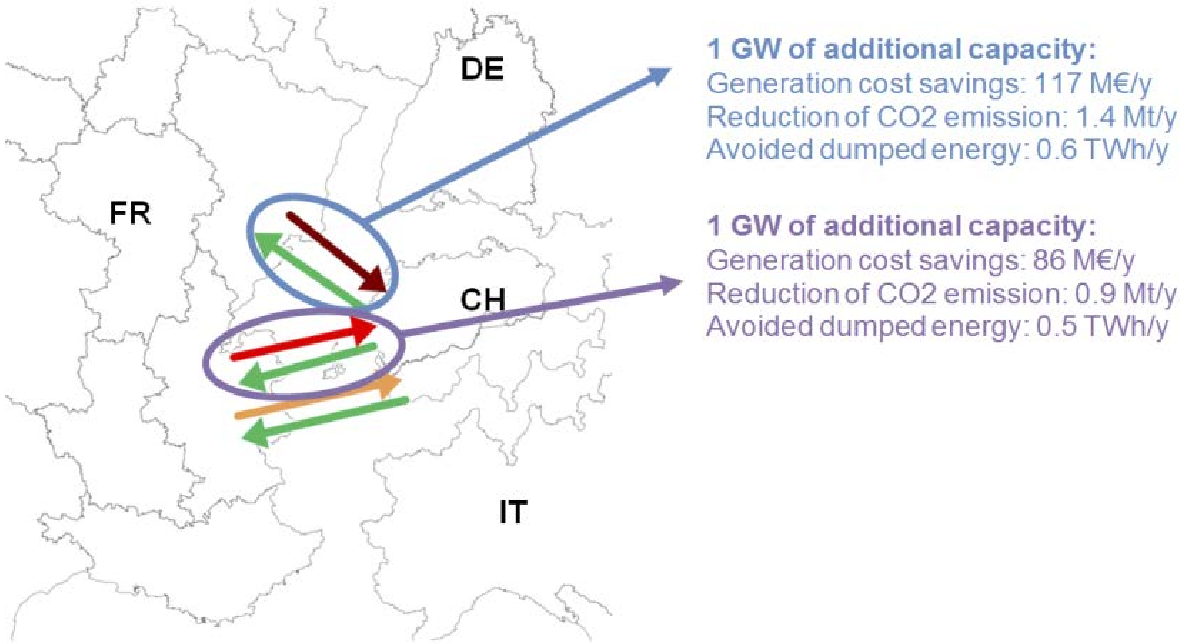
All results of load and generation available at zonal level can be downscaled (for instance via homothetic transformation) to substation level for more detailed network studies (both deterministic and probabilistic). This downscaling appears much more reliable than using a homothetic transformation from national to substation level, and allows to conserve the geographical and inter-modal correlation.

Moreover, the in-depth analysis of constraints presented in the previous paragraph allows study teams to identify and target the main load/generation/exchanges configurations (representative and constrained) to be analysed with tools that model the entire nodal grid.

The outcomes of a "flow-based" market model are more detailed than those of a "classical" NTC market model, which allows to focus on the relevant areas of the grid. Figure 7 below provides an example with the boundary between France and Switzerland – one of the main challenging boundary of the scenario Sustainable Transition 2040. This boundary is divided into three inter-zones of which two are highly congested.

The benefits and the impact on generation mix are not the same between both CH-FR inter-zones. The north of the boundary seems to be more challenging, which cannot be identified directly with a NTC market study.

Figure 7: Congestion and impact of reinforcement on the different inter-zones between France and Switzerland



1.2.6 Conclusion

ENTSO-E has, as part of the Identification of System Needs study, tested a new and innovative approach to assess future capacity needs in the European electrical system. The proposed approach to incorporate the network in market modelling is simplified yet respecting the fundamental laws of physics and is therefore closer to the actual physical grid. It provides a good quality of flow estimates on the macro corridors if the definition of zones is adapted to the structure and the weaknesses of the grid. The approach allows simulating even very large systems such as the European one, while producing detailed results using a sequential and probabilistic approach which is necessary to capture properly load and generation behaviours and dynamics.

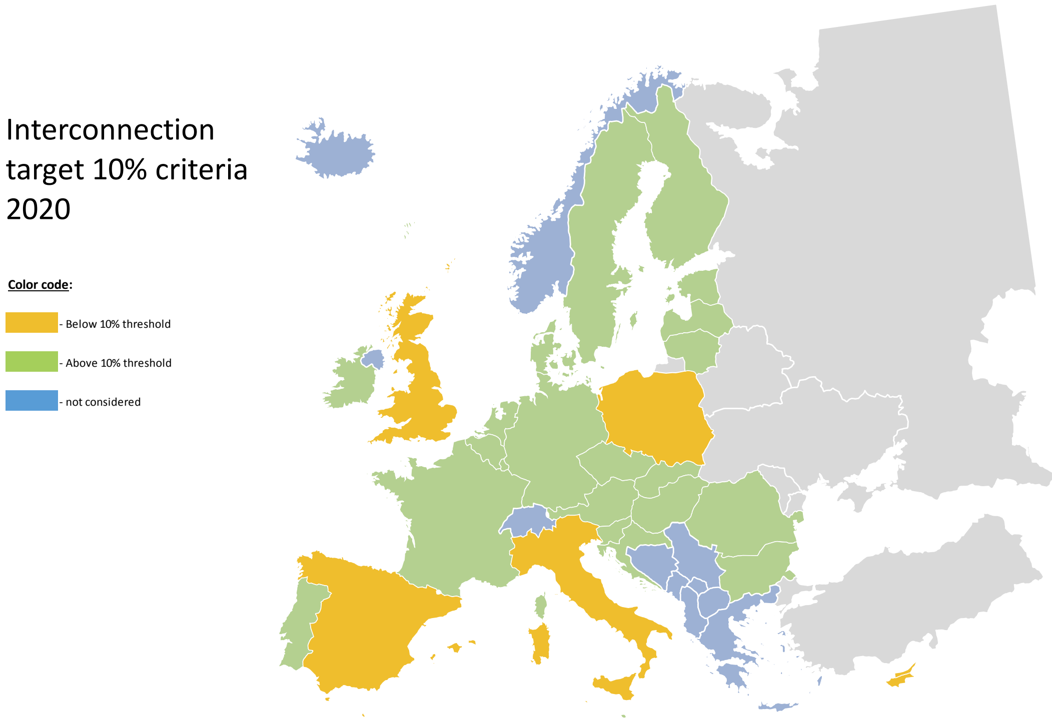
Flow-based market studies produce results on their own, but also help building representative and valuable snapshots and provide data constituting quality inputs for detailed grid studies, which remain essential to precisely analyse constraints on the entire network and design efficient and realistic reinforcements.

It can be concluded that the methodology is very promising for long-term studies where the level of generation and demand are completely different from the current ones, with high uncertainties regarding their specific location, and for which the granularity of the expected results is not too fine. It enables a real European approach as the whole system is simulated at once and reinforcements are identified while the relevant amount of detail is considered. Furthermore, the approach may developed further, e.g., towards a more appropriate definition of zones and the assessment of the needs inside the countries.

1.3
Interconnection targets

Figure 8 shows the previous 10% Interconnection Targets for 2020 as defined by EC.

Figure 8: Previous 10% Interconnection Targets for 2020 as defined by EC



In comparison to that, the new Interconnection Target for the three new 2040 scenarios of the ENTSOs are shown in Figure 9. The new Interconnection Targets were proposed operationalised by considering any of the following three thresholds[5]:

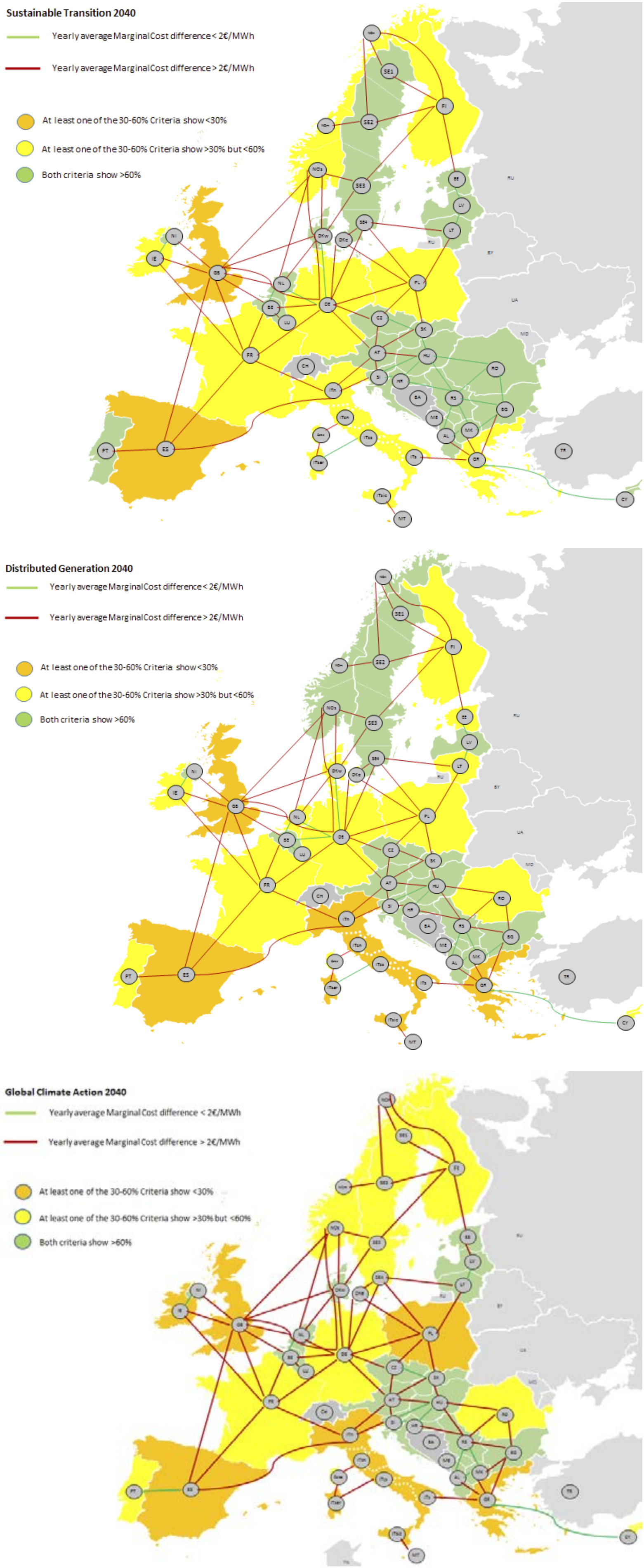
— A well-functioning internal market should lead to competitive electricity prices for all Europeans. Member States should therefore aim at minimising differences in their wholesale market prices. Additional interconnections should be prioritised if the price differential exceeds an indicative threshold of 2€/MWh between Member States, regions or bidding zones to ensure all consumers benefit from the internal market in a comparable manner. The higher the price differential, the greater the need for urgent action.

— Every Member State should ensure that peak demand can be met in all conditions through a combination of domestic capacity and imports. Therefore countries where the nominal transmission capacity of interconnectors is below 30% of their peak load should urgently investigate options of further interconnectors.

— The further deployment of renewable energy should not be hampered by a lack of export capacity. Renewable production in any Member State should be optimally used across Europe. Therefore countries where the nominal transmission capacity of interconnectors is below 30% of installed renewable generation capacity should urgently investigate options of further interconnectors.

[5] Communication from EC https://ec.europa.eu/energy/sites/ener/files/documents/communication_on_infrastructure_17.pdf

Figure 9: New Interconnection Targets for 2040[6]



The following countries were considered for the computation of interconnectivity levels at the EU perimeter (including Switzerland and Norway, as recommended by the Interconnection Target Expert Group) and for the computation of all the input network and market related data (nominal transmission capacities of the interconnectors, net generating capacity, peak load figures):

AT
BE
BG
CH
CY
CZ
DE
DK
EE
ES
FI
FR
GB
GR
HR
HU
IE
IT
LT
LU
LV
MT
NI
NL
NO
PL
PT
RO
SE
SI
SK

[6] Germany-Luxembourg is one bidding zone.

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