The assessment of the 10% interconnection target: security of supply, market integration and CO₂ impacts

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INTRODUCTION

The interconnection of electricity networks is considered to be an essential precondition for the realization of an integrated, competitive and sustainable European electricity market. The European Commission has reiterated the conclusion of the European Council in 2014 October on the target of achieving interconnection of at least 10% of the installed electricity production capacity for all Member States by 2020 in the context of the envisaged Energy Union, and extended the 2020 interconnection target to 15% by 2030.[1] The Communication identifies widespread benefits deriving from well interconnected energy systems:

- increase of security of supply

- affordable prices via market integration

- decarbonisation: accommodation of increasing level of renewable generation.

The 10% interconnection indicator is more than an academic benchmark: it will serve as the basis of EU fund allocation. The interconnection target is planned to be reached through the implementation of the Projects of Common Interest (PCIs) with special priority given to those projects where the current interconnection capacity is well below the 10% objective. In addition to the Connecting Europe Facility (CEF) the European Structural and Investment Fund launched in early 2015 could provide funding for such PCIs.

The aims of the present paper are twofold. First, it analyses the applicability of the 10% interconnection indicator with respect to medium/long term security of supply and market integration: Does it accurately consider the SOS situation of the Member States? Does it reflect the level of market integration of the neighbouring Member States/regions? Second, it estimates the effect of full compliance with the 10% interconnection target on EU wide CO_2 emissions by 2020.

We find that the 10% rule that aims at improving both the security of supply and market integration position of countries fails to do so. It disregards factors that affect security of supply (availability of generating capacities and load) and with respect to market integration the criterion misses the level of analysis i.e. focusing on countries instead of borders.

SECURITY OF SUPPLY

Energy security is one of the main pillars of EU energy policy and it is a fundamental concern of national energy policies as well. The 2009 Ukrainian gas crisis highlighted the vulnerability and adaptation skills of the European gas market and infrastructure. Security of supply (SOS) can be analysed in different time horizons both for gas and electricity. Kaderják

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[1] COM (2015) 82 final

(2011) provides an overview of the potential indices for short and medium/long term for both energy carriers. The medium/long term security of supply position of a country in terms of electricity supply depends on various factors such as the origin of resources, the generation and transport infrastructure and also the level and variability of consumption. Gouveira et al. (2014) analyse the impact of higher renewable penetration on the SOS situation of Portugal using utilisation rate for interconnectors, gross capacity margin (based on installed capacity and annual peak demand) and de-rated capacity (considering the capacity factor of each technology). Portugal-Pereira et al. (2014) prepared a similar analysis for Japan and assessed the security of supply consequences of various generation portfolio scenarios for 2030. The infrastructure component of this analysis uses a system stress indicator (the period when the system reaches 85% of total electricity supply capacity) as this analysis considers the daily fluctuation of load and production as well.

The 10% interconnection target set by the EU is based on the net installed generation capacity (NGC) and the net transfer capacity of interconnectors (NTC_I). The group of 9 countries below (or equal to) this level of interconnection in 2014 consists of Germany, Spain, France, Great Britain, Ireland, Italy, Poland, Portugal and Romania.[2]

The 10% interconnection target does not reflect the fact the installed capacities are not always available and the security of supply position of a Member State is affected not only by the supply side capacities (transfer and generation) but by the load as well.[3] Reliable available capacity (RAC) is - on the ENTSO-E average - 69% of the net generation capacity (NGC) and this deviation is due to Maintenance and Overhauls, Outages and System Services Reserve and Non-Usable Capacity that is closely linked to variable RES penetration because of the limited availability of certain primary energy sources. Substituting NGC with RAC alters the position of some Member States with high RES penetration (DK, DE) and Slovakia. If the threshold for critical countries is set at 15% (considering the lower level of RAC compared to NGC) then only Bulgaria joins the group of 7 critical countries and no one exits the group.

In order to include both the availability of generation capacity and the load of the country in the approximation of "interconnectedness" we have constructed the following indicator that measures the residual supply capacity compared to peak load (PL): (NTC_I+RAC-PL)/PL.[4]
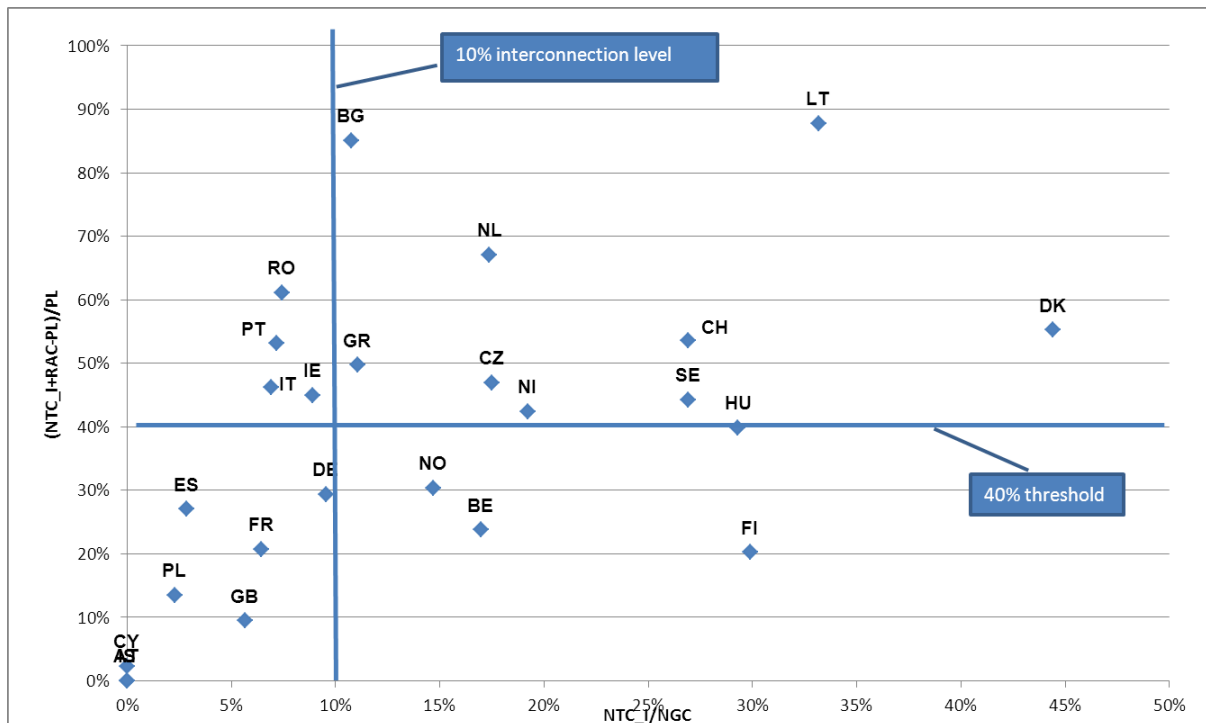
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[2] In our analysis we considered the Baltic states individually but did not include Malta and Cyprus as opposed to the list of the Communication.

[3] Data used in the calculations are the from SO&AF_2014-2030_Dataset of ENTSO-E and all refer to January 2014 and Scenario A ("Conservative") that is derived from Scenario B („Best Estimate"), taking into account only the generating capacity developments which are considered secure.

[4] Kaderják (2011) uses a similar medium term security of supply index for electricity: NTC_I+RAC-PL)/NGC. Residual supply index – in the context of short term gas security of supply – measures the effect of the outage of the single largest import infrastructure.

On the basis of this indicator the original group of 9 critical countries alters. Whereas there is a core group that performs poorly according to both indicators (Poland, GB, Spain, France and Germany), on the basis of our indicator the critical group is extended to Belgium, Finland, Norway and Hungary (at a 40% threshold). These countries rely more heavily on imports to meet their peak load and as such for them the interconnection level available for import is more important. These countries need import capacity to cover their peak load but have moderate interconnections. On the other hand countries that have relatively large generation capacities and are less reliant on import capacities, such as Portugal, Italy, Ireland and Romania, exit the critical group at 40%. In sum, the two indexes arrive in partially overlapping but fundamentally different results. We believe that the incorporation of load and the discounting of net generation capacities due to availability improve the indicator.

Figure 1: Performance of EU countries (plus Norway and Switzerland) against the residual supply capacity and the 10% target indicator

Note: Austria is not included in the figure as ENTSO-E does not define NTC_I for Austria.

PRICE CONVERGENCE

Failure to reach the 10% interconnection level is claimed to be a red flag signalling a bottleneck in market integration and, as such, it is meant to direct attention and funding to these borders. We argue the identification of these bottlenecks is more appropriate on the basis of wholesale price convergence among the countries. First we have an overview of the literature dealing with the European price convergence, focusing on those studies using higher geographical coverage or more recent data on the European wholesale electricity prices

applying various statistical methods to assess market integrations. Then we introduce two straightforward price convergence indices as a measure of the market integration of the various European countries, which could serve as basis for our assessment.

Price convergence literature

Price convergence of European electricity markets is a well-researched field. Several studies assess if price convergence takes place in Europe as an assumed consequence of the energy policy instruments targeting an integrated electricity market (Table 1). The methodologies differ in many dimensions such as the time horizon of the analysis (short or medium-long term price convergence) or the geographical scope (two-country comparison or regional assessment). They also differ in their objectives: many search for relationship of prices in the analysed markets, while others look for potential events that disrupt the normal functioning of the electricity markets. The assessments are usually limited by data availability as many energy exchanges had more limited liquidity in the first years of operation.
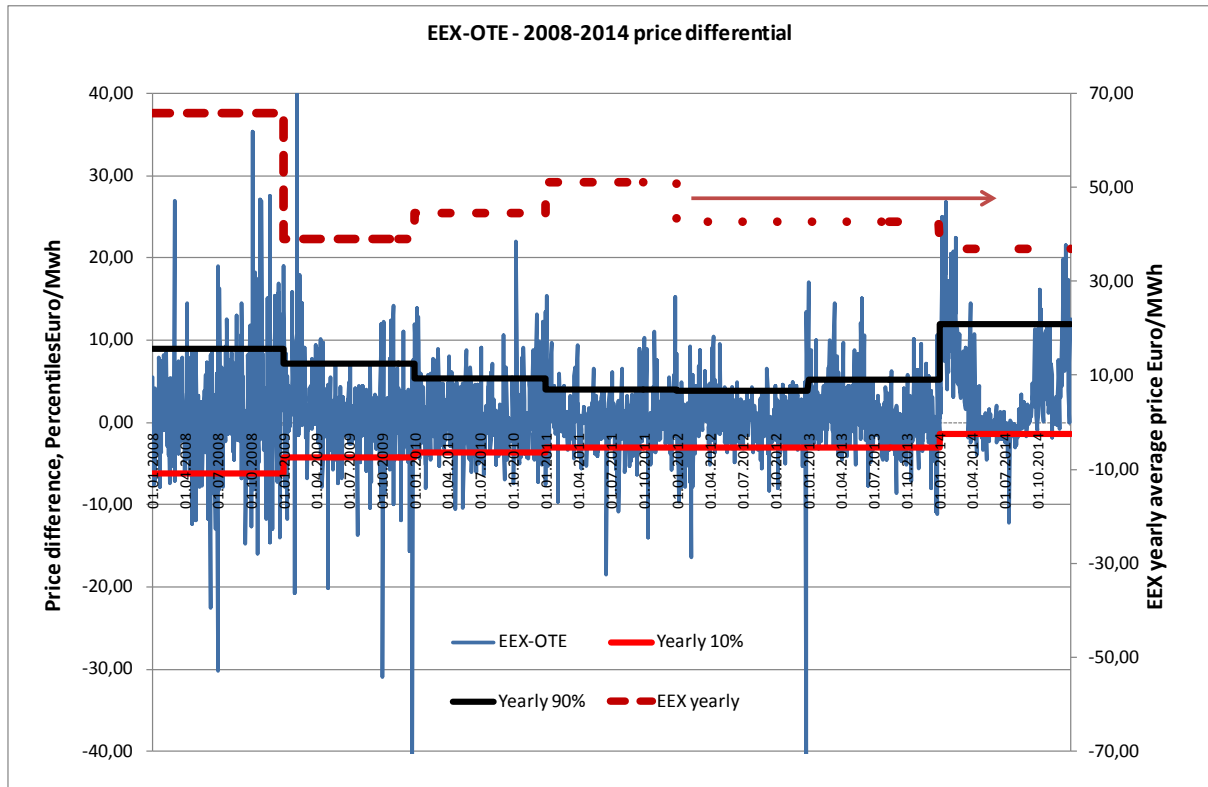
Table 1: Studies assessing price convergence in the EU electricity markets

Author	Method	Coverage	Time series	Price used	Result
Zachmann (2008)	Principal Component Analysis and Unit root (KPSS and ADF)	11 EU power exchanges (NL, DE, AT, DK-E, DK-W, SE, FR, PL, GB, ES, CZ)	2002-2006	Hourly day-ahead prices	No full integration in the EU electricity markets, some bilateral convergence
Armstrong-Galli (2005)	Exploratory data approach	FR, DE, NL, ES	2002-2004	Day-ahead prices	Price convergence
Bunn-Gianfreda (2010)	Causality tests, cointegration, impulse-response technique	FR, DE, GB, NL, ES	2001-2005	Day- ahead, 1 and 2 month ahead price	Increasing integration
Cassagneto-Gissey et al. (2014)	Dynamic Granger causality	12 EU members (BL, DK, FI, FR, DE, IT, NL, NO, PL, ES, SE, CH, GB)	2007-2012		Price integration increases with market coupling
Pellini (2013)	Fractional cointegration, multivariate GARCH model, dynamic conditional correlation (DCC) models	AT, BL, CZ, FR, DE, GR, IE, IT, Pl, PT, Nordpool, CH, NL, GB	Varying, 1998-2012	Day- ahead prices, hourly and half hourly	41 out of 105 market pairs present convergence. (mainly core continental countries) 61 pairs show no convergence
De Menezes-Houllier (2014)	Fractional cointegration	9 EU spot markets (APX-UK, APX-NL, Belpex, EPEX-FR, EPEX-DE, IPEX, Nordpool, Omel, OTE)	2000-2013	Daily spot prices and one-month-ahead price	Increased convergence and greater reactivity to shocks

These studies arrive at diverse conclusions: depending on the methodology, the covered market and used time series they either reject or support higher electricity market and price integration. Most studies use shorter time series (3-5 years) so the conclusions depend strongly on the timeframe of the data. A recent study using the long time series (de Menezes, 2014) shows that the time series of hourly spot prices are a fractionally integrated and mean reverting, so the conclusion of the author's is that the frequently applied unit-root tests alone are inadequate to assess electricity spot market convergence. Pellini (2013) used long time series data to study borders rather than countries and found that there is a core country group (continental Europe) that has reached significant level of convergence, while the rest of the markets are not converging. Interestingly, Pellini found that the Noordpool market shows little evidence of convergence to the core continental group and explained it by the very different composition of the Northern national generation portfolios compared to the continental core (similar to Italy). She concludes that "*the level of interconnectivity and geographical proximity play the most important role in explaining volatility transmission across regional markets and hence market integration*" (Pellini, 2013, p33). Interestingly, most of these studies use only price information to capture integration and pay no attention to additional driving factors, e.g. joining a coupling process, starting a new interconnector or new allocation method of the available interconnection capacities. ACER/CEER (2014) analysed the efficient use of interconnectors in the context of market integration. According to their assessment the efficient use of the interconnectors in the 'right direction' (export from low priced region to higher priced one) is continuously increased from 2010 to 2013 reaching 77% of efficient use of the cross border capacities. Their assessment also underlines the ongoing market integration process where ACER expects further efficiency gains if more markets will be coupled in the future.

To illustrate price convergence, the following figure shows the evolution of the difference between the German and Czech electricity exchange prices (EEX-OTE) in the period of 2008-2014. The figure also shows the 10-90% quantiles similar to Armstrong-Galli (2005) for each year (Yearly 10% and Yearly 90%).

Figure 2: Price difference between the German and Czech electricity exchange day-ahead baseload prices (€/MWh, daily averages, 2008-2014)

The figure effectively illustrates the converging prices in the two exchanges between 2008 and 2012: the difference between the two quantiles (10% and 90%) reduced from 15 €/MWh to 7 €/MWh. From 2013 the gap started to increase again, and interestingly it also had a bias toward a higher positive divergence (positive value means higher EEX prices). This data illustrates that a study based on a period of 2008-2012 would probably support the price convergence hypothesis while the inclusion of 2013 and 2014 would challenge it, if no further information is included in the assessment.

Factors that could affect price convergence:

- Higher RES penetration levels in the connected markets: intermittent RES generation (wind and solar) increase price variability the extent of which depends on its scheduling regime

- Geographical proximity to the core region: the more border traders have to cover, the higher the uncertainty regarding the availability of transfer capacities. An example: change in the Hungarian/Balkan demand can drive the coupled CZ/SK/HU prices and can deviate it more from German prices. So prices in countries further from the core markets can deviate more from Central European prices. The coupling and NTC allocation mechanism could play a significant role in this process.

The impact of high level of RES employment on the market integration process is also assessed by Glachant - Ruester (2014). They also highlighted the importance of uncoordinated national policies on RES support and capacity mechanisms.

The absolute level of prices influences the price differential as well: the smallest price gap is in 2010 when prices were the highest in Germany and in Central Europe. This diminishing price difference is likely to be explained by the fact that at higher prices gas fired CCGTs are the price setting plants in both markets. Both fuel price and technology efficiency are similar in the case of this technology regardless the country of operation, so price difference reduces to the minimum.

Price convergence analysis

As we are interested in the longer term impacts of the market integration (rather than what happens on the hourly spot market) we have applied a simple method to assess the level of market integration and to identify the 'hotspot' borders. We define regions (European sub-markets) of high price convergence using two alternative indices for each border:

- Yearly average utilisation rate,

- Sum of square of the difference between two countries day-ahead baseload prices (price convergence index).[5]

Utilisation rate is calculated by dividing the commercial day-ahead schedule by the net transfer capacities: the higher the utilization rate is, lower the market integration between the two countries. Sum of square is calculated as the difference between the daily baseload prices of the bordering countries and reflects the price differences between neighbouring countries.

Our analysis does not provide full coverage of the continent due to data limitations. There are 65 borders within the ENTSO-E region (assuming one country is one node) but our analysis includes the utilisation rates for those 51 borders where ENTSO-E publishes data on. The two price convergence indices are calculated only for 39 borders based on the availability of electricity exchange prices or electricity exchanges that can potentially provide transparent price information: the most recent data available for a majority of the electricity exchanges is from 2014 as this is the dataset we used.
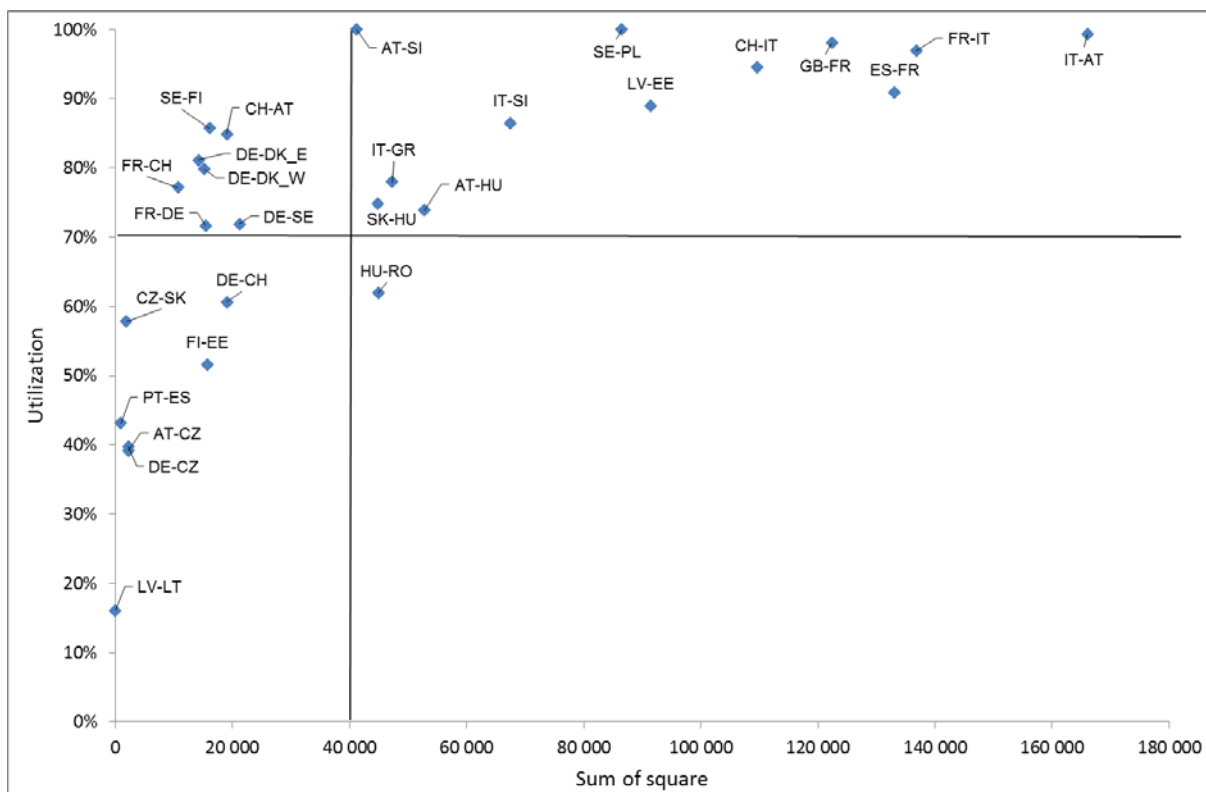
On the basis of these two indices we identify those European borders where price convergence is not observed due low NTC values or as a result of lower share of implicit allocation method of the given border. It should be noted that high utilisation per se does not necessarily mean capacity shortage but can simply signal an efficient utilisation of the existing infrastructure (if coupled with price convergence). Using the indices for each border, we identify countries, or group of countries constituting a sub-region with high price

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[5] No price data is included in the analysis on the Netherlands, Belgium and Bulgaria.

convergence. This market integration assessment is based on individual borders and can identify smaller regions that are integrated with each other but not integrated with an outside region. As an example we could think of GB and Ireland or Spain and Portugal, which might be closely integrated with one another but not to the core continental countries.

Once we identified these regions, we return to our security of supply analysis and apply the same indices to the regions to examine whether clustering the countries on the basis of market integration changes their SOS status.

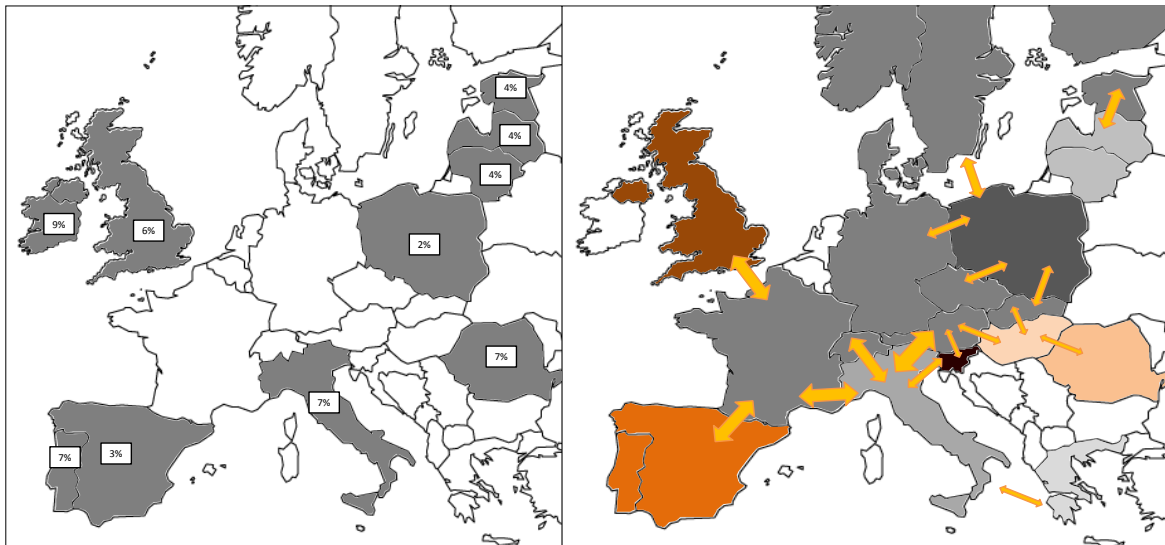**Figure 3: Utilization rate and price convergence of the analysed European borders**

Note: Data can be found in the Annex.

The figure shows that there is a group of borders with high utilisation rates coupled with high price convergence. In these cases the capacity of the available interconnecting infrastructure is just appropriate: it is used extensively but does not create a bottleneck for market integration. On the other hand, some borders seem to constrain market integration (low price convergence and high utilisation rate) and as such should be priorities for infrastructure development plans (those above the 70% and 40 000).

The two methods yield very similar regions that can be considered European sub-markets. Some of the difference is explained by the lack of price data (Bulgaria, Ireland, Belgium and the Netherlands). Romania is close to both thresholds. In addition, both France, DE/CH/CZ/SK and Nordic countries form separate regions.

Figure 4: Countries below the 10% interconnection level (left) and regions defined by price convergence (right)

On the basis of the two indices (utilisation rate and price convergence index) we identify those countries that are less integrated with their neighbours. This method uses available market information – price convergence between countries and the utilisation rate of existing lines – and arrives at different conclusions regarding network development priorities compared to the 10% rule of the European Commission.

We can conclude from the results that both the 10% interconnection level requirement and the price convergence index define a single core region: the Central Continental Europe Region which is highly integrated with the present cross-border capacities being sufficient to reach high price convergence, and performing well concerning both indexes. This region includes Austria, Czech Republic, France, Germany, Switzerland, Luxemburg, the Nordic countries and Slovakia. Although Hungary satisfies the 10% rule by a high margin, it performs poorly according to the price convergence index that excludes Hungary from the core continental group. Consequently, its integration to the core market requires further cross-border network development and would be essential for the incorporation of the Romanian electricity system to the group as well.

The Polish-Baltic region where all countries are under the 10% interconnection level disintegrates to three smaller regions on the basis of price convergence. Estonia joins the group of Nordic countries (and hence the core continental group), Latvia and Lithuania constitute a separate region, while Poland is still an 'island' on the electricity network map. The integration of this region to the core countries would require the better interconnection of Poland to Germany or the Czech Republic and to Lithuania. The increase of NTC between Latvia and Estonia would bring additional benefits.

Greece is an additional electricity 'island' which is less integrated with its neighbours. Although the data is absent on the wholesale prices of its neighbours, its utilisation rate defines it as a separate region, which would need higher interconnection levels. A similar situation could be observed for Belgium and the Netherlands, where the high utilisation rates identify them as a separate region from the core continental one.

We can conclude the following:

- By the assessment of individual cross-border relationships we can clearly identify the borders defining countries or group of countries that follow an independent price path from the continental core region. An independent price path followed by a single country or a smaller region would probably also mean independent reaction to 'shocks' to the system thus imposing additional security of supply risk for these smaller regions.

- The 10% rule is less suitable to identify these impacts, and leads to inappropriate identification of vulnerable countries that require interconnectivity upgrade. It can exclude countries (e.g. Hungary) and it does not provide precise information on which borders the interconnection should be reinforced.

- These results are in line with the results of Pellini (2013) confirming the importance of pairwise border-based assessment, as well as the importance of the geographical relation of the national electricity markets. Cross-border capacity (CBC) bottlenecks could prevent countries in the periphery to join the core continental region if a non-integrated country is wedged in between them (e.g. case of Hungary and Romania, Spain and Portugal, Ireland and the GB).

Besides identifying individual borders with relatively high price divergence we calculated a Europe-wide price convergence value for 2020 in various alternative infrastructure developmental scenarios with the help of the European Electricity Market Model (EEMM). EEMM is a simulation model of the European electricity wholesale market that works on a perfect competition assumption in a stylized manner. EEMM covers 36 countries with rich bottom-up representation, where all ENTSO-E countries are modelled in full detail. In the electricity production sector 12 technologies have been differentiated. We assume that one country is one node, the limit between the countries are represented by NTCs. EEMM models the production side at the unit level, which means that at a greater European level almost 5000 units are included in the model runs. Reaching equilibrium (in prices and quantities) takes place simultaneously in the producer and transmission segment. These units are characterized by various technological factors, allowing the construction of the merit order for the particular
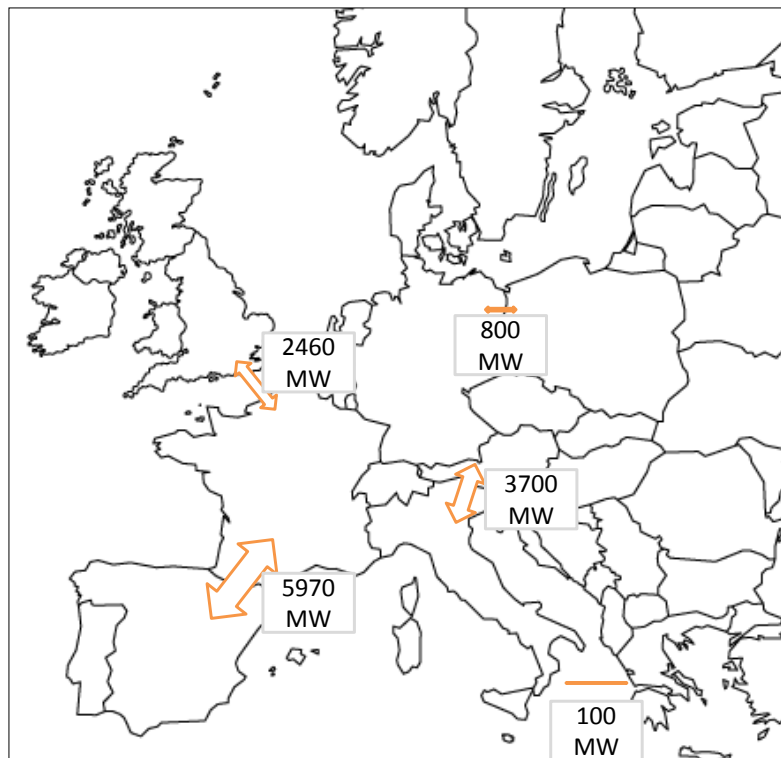
time period. In each year we have 90 reference hours to represent the load curve with sufficient details for each European country.[6]

The three scenarios used are the followings:

- reference case: completion of new capacities (generation and cross-border) with already approved investment plan

- 10% compliance case: all interconnectors capacities are built so that each MS complies with the 10% requirement, and

- price divergence case: cross-border capacities (CBCs) are built according to the levels of price divergence of individual borders.

We have determined the new interconnectors necessary to comply with the 10% requirement on the basis of the price convergence value of the borders. We assumed that the missing interconnection capacity of a country is built on the border with the highest price difference. We have also fixed the rest of the base assumptions in the scenarios, such as the renewable electricity generation and the applied carbon value. The RES generation increase follows the indicative path of the NREAPs of the Member States, while the carbon value is set at the present 7 €/t CO_2 level.

Figure 5: The additional interconnection capacities to meet the 10 % rule, used in the modelling
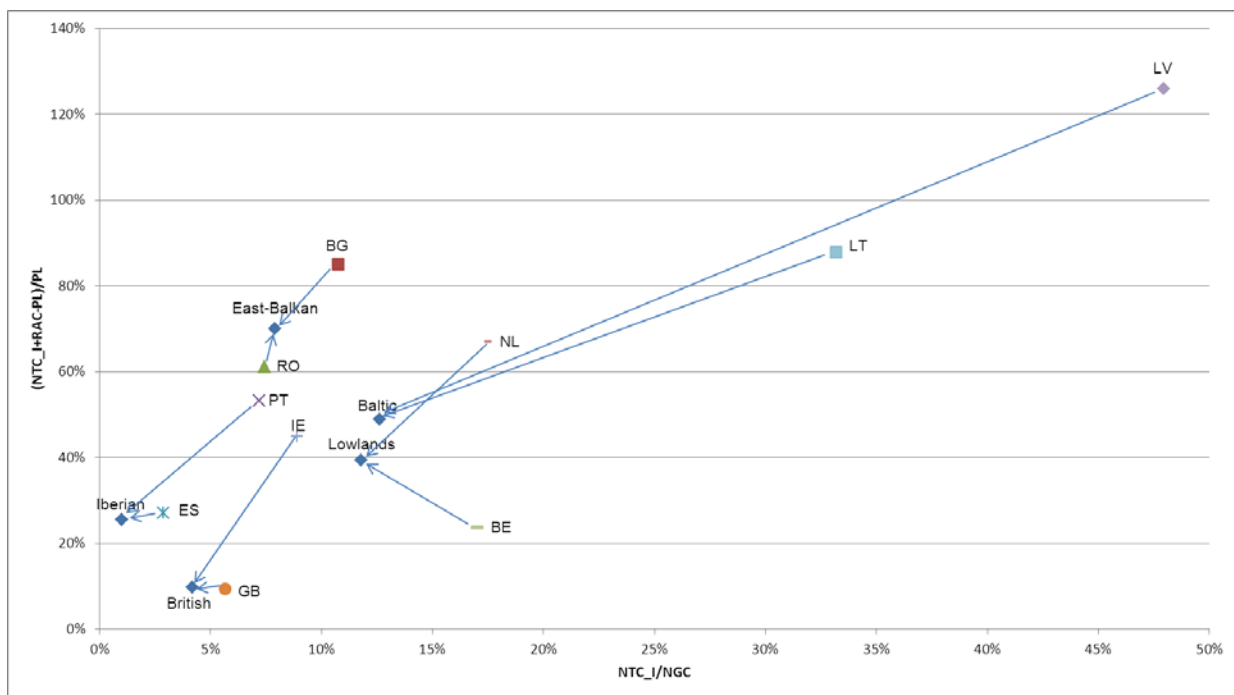

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[6] For a more detailed description of the model see Mezősi, Szabó (2014).

We have calculated the absolute value of the price difference of each country for the 90 reference hours of the model to the German price (weighted with the hourly production and the consumption of the countries). In the reference case this yields a 4.67 €/MWh price difference. If all interconnector capacities are built so that each MS complies with the 10% requirement then the difference decreases to 3.9 €/MWh. However, if CBCs are built according to the levels of price divergence of individual borders then it is even lower, only 3.76 €/MWh.

THE SOS POSITION OF REGIONS DEFINED BY PRICE CONVERGENCE

In this section we assess the impact of changing the level of analysis (from national to regional) on the security of supply position of the countries. Regions are created on the basis of price convergence exhibited on the map to the right of Figure 4 (with the exception that Ireland-GB and Romania-Bulgaria form common regions).

Figure 6: The changing SOS positions due to regional level of analysis and the alternative indicator

If Member States are considered by the alternative indicator, and not on a national but a regional level, their SOS positions of the depicted countries will change, and this will have implications on the their priority status in EU infrastructure funding.[7] The results indicate the following:

- The direction of change for all but two countries (RO, BE) deteriorate significantly in both indicators.

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[7] In the chart we have only identified those countries and regions where the change is significant.

- The peripheral regions (Iberian, British Isles and East-Balkan) are under the 10% interconnectivity value just like their individual constituents and the SOS position of the smaller countries in these regions (Portugal, Ireland and Bulgaria) – however – deteriorates. Ireland and Portugal become critical using the alternative index ((NTC_I+RAC-PL)/PL) at a 40% threshold level.

- Whereas Lithuania and Latvia are well above the 10% level (NTC_I/NGC), if they are considered as a region then they are just above this level (13%) and their position deteriorates significantly on the basis of the alternative indicator as well (they are well connected with each other but not with the rest of Europe). The situation is similar with the Netherlands and Belgium, except that the position change is asymmetrical; the position of the former worsens in both dimensions, whereas the latter only on the basis of the 10% indicator.

THE DECARBONISATION EFFECT OF THE 10% INTERCONNECTION TARGET

One of the major justification of well interconnected grids - according to the Energy Union package - is that is facilitates the decarbonisation of the generation mix by accommodating an increasing amount of renewable generation resulting in lower CO_2 emission in the power sector. Facilitating the integration of renewable energy into the grid is a stated goal for the projects of common interest as well. Edmunds et al. (2014) simulate the GB electricity market, analysing the effect of a better interconnection with the neighbouring countries on wind penetration to show that better interconnectivity helps to increase the maximal wind capacity that can be integrated to the electricity system and hence lower the CO_2 emissions.

Meeus et al. (2013) study on cost-benefits analysis in the context of Energy Infrastructure Package argues, on a general level, that in a more integrated system coal-based power generation can be substituted by gas plants that in turn reduce CO_2 emissions. In addition, the consequent reduction of system losses less fossil-based power generation is required.

However, none of the mentioned literature calculates the effect of a better interconnectivity on CO_2 emission resulting from the modified production portfolio due to the new trans-boundary infrastructure at the European level. In the following, we attempt to quantify the CO_2 effect of those new infrastructure elements that would be required for the full compliance of the 10% interconnectivity requirement of the Energy Union Package with the European Electricity Market Model.

In order to arrive to a workable scenario of the 10% NTC case we have used the assumptions discussed above: the missing interconnection capacity is built on the border with the highest price difference to meet the 10% threshold (Figure 4) and RES generation (NREAP) and the CO_2 price are constant (7 €/t CO_2). In this way any difference in the CO_2 emissions between

the Reference and the 10% NTC case is only due to the changed pattern of the cross-border capacities. The impacts of these cross-border developments are measured on the electricity system of 2020.

The modelling results (Figure 7.) show that CO_2 emissions increase in many countries due to the higher level of integration. The dominant share of additional emissions is generated in Germany, Czech Republic and the Netherlands due to increased coal based generation. In Italy, the British Isles and the Iberian Peninsula the failing coal and gas production is substituted by import. In France the marginal increase of coal and nuclear is accompanied matched by a reduction in gas.

In sum, better interconnection expands the production possibilities of cheap coal first then of some cheaper gas producers as well. More efficient coal power units in Germany increase their production more than the Polish coal PPs.

Figure 7: CO_2 emissions change due to new interconnection capacities, Mt CO2. 2020
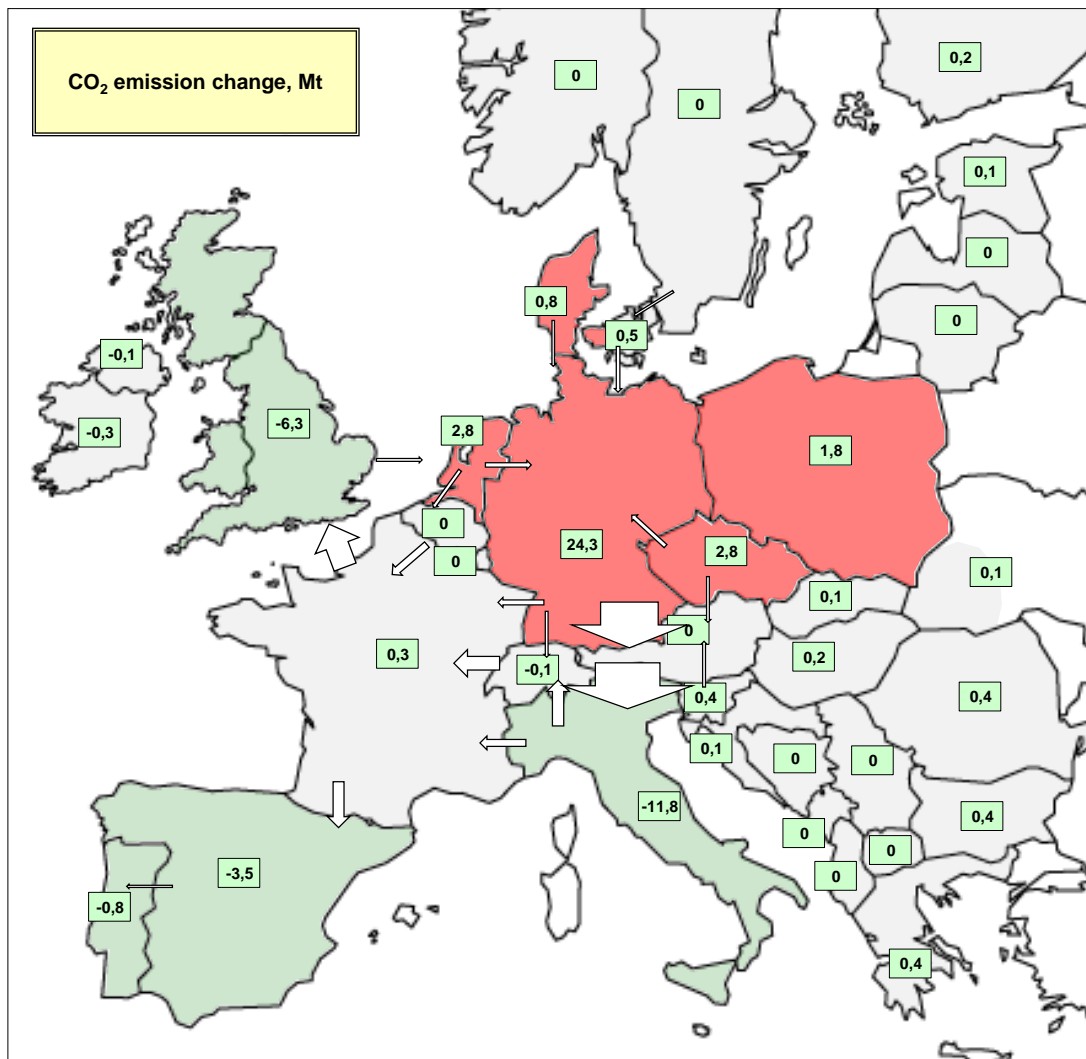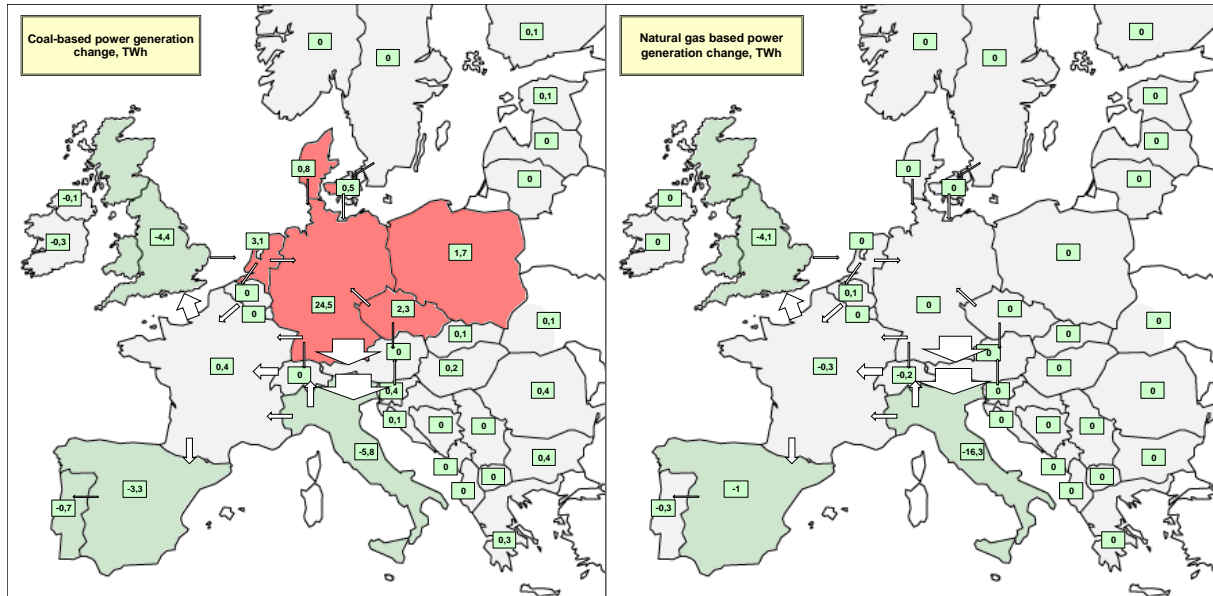
Figure 8: Coal and natural gas production change due to new interconnection capacities, TWh 2020

On the European level the CO_2 emissions increase by 13.1 Mt that roughly equates to the Estonian, Hungarian or the Irish emission levels from combustion in 2014

The additional coal generation crowds out gas based production with a marginal increase of nuclear output.[8]

Table 2: Modelling results for Europe (the whole modelled region)

	REF	10% Scenario	Difference	
			ABS	REL
Electricity production, GWh				
Nuclear	819 863	820 855	991	0.12%
Coal	819 896	841 019	21 123	2.58%
Natural gas	207 720	185 506	-22 214	-10.69%
CO_2 emission, kt	952 853	966 013	13 160	1.38%

CONCLUSIONS

This paper had two aims. First it analysed whether the 10% interconnection rule defined by the Energy Union Package assesses the security of supply and market integration position of the Member States accurately with the goal of achieving a more secure, sustainable and

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[8] Renewable generation is kept on a fixed growth path in the modelled scenario based on the NREAPs of the countries.

integrated EU energy system and market. Second, we analyse the impact of the targeted 10% interconnectivity on carbon emissions in the ENTSO-E region. Our hypothesis was that by increasing the interconnection levels in countries with excess capacities in coal and lignite based generation CO_2 emissions would increase in the EU.

We have proposed an alternative index better capturing the security of supply situation of the Member States. This index considers the residual supply capacity to peak load rather than the transfer capacity to the generation capacity. So it is more oriented toward load rather than production, placing higher emphasis on the ability to securely cover demand while using only the reliably available generation capacities. The two indices arrive at significantly differing country classifications. Whereas there is a core group that performs poorly according to both indicators (Poland, GB, Spain, France and Germany), on the basis of our indicator the group of critical countries is extended to Belgium, Finland, Norway and Hungary (at the 40% threshold). Portugal, Italy, Ireland and Romania on the other hand exit the group of vulnerable countries, as they have relatively large generation capacities and are less reliant on import.

We have also defined regions that follow a different level of integration with neighbouring countries based on the price convergence indicators of the respective borders. The regions are defined based on their price integration measured by the price convergence indicator and the utilisation rate of interconnectors at each border. We have identified a group of core countries of continental Europe already reaching a high level of market integration, including Austria, Czech Republic, France, Germany, Switzerland, Luxemburg, the Nordic countries and Slovakia. The rest of the countries are classified as regions less integrated to their neighbours according to relative price developments (Italy, Hungary, Romania, Poland) or as pairs of countries integrated with each other but less integrated with the continental core group (e.g. Portugal and Spain, GB and Ireland and the Baltic countries). Based on this regional classification, we recalculated our security of supply indicator demonstrating the need to include additional countries to the group of vulnerable countries. Not only Bulgaria and Portugal, but also the Netherlands and Belgium move closer to meeting the 'vulnerable' group criteria.

This assessment also shows that country level analysis of market integration can be more refined if replicated at a regional level. Some European countries integrate bilaterally with a neighbour but still fail to integrate to the greater European energy markets by extension. These countries, e.g. the Baltic countries, GB and Ireland and the Iberian Peninsula still constitute 'energy islands' even though some of them comply with the 10% interconnection rule. An additional insight is that regional electricity market integration is better derived from the analysis of individual borders.

Lastly we have assessed the impact of increasing cross-border capacities on CO_2 emissions under the assumption of full compliance with the 10% rule. The findings are in line with our hypothesis, that – if all other kept constant – carbon emissions will increase in Europe due to the availability of presently cheap coal and lignite fired power capacities. Interestingly, the increase from coal based production is not concentrated in Poland as we expected but in Germany, due to its higher efficiency plants and better connectivity with its neighbours. It has to be emphasized, that this analysis assesses the impact of the NTC increase exclusively, something that can be easily overridden by changes in those other factors, e.g. by higher carbon prices or by higher penetration of RES-E that are kept constant in this assessment.

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Border	Sum of square	Utilization	Border	Sum of square	Utilization
IT-AT	166 039	99%	DK_W-DK_E	4 180	n.a.
LT-SE	164 580	n.a.	DK_W-SE	4 063	n.a.
FR-IT	136 808	97%	AT-CZ	2 199	39%
ES-FR	133 093	91%	DE-CZ	2 199	40%
GB-FR	122 397	98%	CZ-SK	1 890	58%
CH-IT	109 569	94%	PT-ES	922	43%
LV-EE	91 425	89%	LV-LT	2	16%
SE-PL	86 468	100%	DE-AT	0	n.a.
DE-PL	67 508	n.a.	GR-BG	n.a.	100%
IT-SI	67 458	86%	IE-GB	n.a.	99%
PL-CZ	64 385	n.a.	NL-NO	n.a.	96%
PL-SK	60 613	n.a.	GR-MK	n.a.	93%
AT-HU	52 818	74%	NL-DE	n.a.	92%
IT-GR	47 291	78%	RS-AL	n.a.	86%
HU-RO	44 917	62%	MK-BG	n.a.	86%
SK-HU	44 859	75%	FR-BE	n.a.	81%
AT-SI	41 186	100%	RO-RS	n.a.	75%
DE-SE	21 213	72%	RS-MK	n.a.	69%
CH-AT	19 027	85%	RS-BG	n.a.	67%
DE-CH	19 027	61%	BA-ME	n.a.	47%
SE-FI	16 114	86%	RO-BG	n.a.	57%
FI-EE	15 731	52%	HU-RS	n.a.	50%
FR-DE	15 432	72%	BE-NL	n.a.	61%
DE-DK_W	15 214	80%	RS-ME	n.a.	34%
DE-DK_E	14 214	81%	SI-HR	n.a.	34%
DK_W-NO	12 212	n.a.	HR-RS	n.a.	32%
FR-CH	10 706	77%	HU-HR	n.a.	25%
DK_E-SE	8 956	n.a.	BA-RS	n.a.	20%
NO-SE	5 768	n.a.	HR-BA	n.a.	21%