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Wind and other CO_2-free assets replacing coal in 2030

A scenario analysis based on the EUCO3232.5 scenario with the METIS model

Kanellopoulos, K.

Kavvadias, K.

De Felice, M.

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Joint Research Centre

EUR 30343 EN

Contact information
Email: konstantinos.kanellopoulos@ec.europa.eu

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Authors

Kostas Kanellopoulos

Kostas Kavvadias

Matteo De Felice

Abstract

An up-to-date partial coal phase out scenario, based on the power system and prices defined in the EUCO3232.5 scenario for 2030 is analysed with the METIS power system model. Following the removal of coal and lignite fleets, in excess of half the capacity present in the EUCO scenario, the power system experiences more often power scarcity, primarily in the Central-West region of Europe. The study explores the potential of new wind capacity to fill the vacuum created by the coal fleet retirements both in energy and capacity terms. The conclusion of the previous similar study of 2018, that new wind capacity predominantly placed in peripheral regions of Europe (South-east, South-west and the North) has the potential to balance the system, is tested for multiple climatic years. The modelling analysis showed that new capacity consisting of 85 GW of additional wind power (compared to the EUCO3232.5) supported by additional infrastructure would be sufficient to restore adequacy. The additional infrastructure identified in this study consists of approximately 8.2 GW of batteries, very limited new peaking generation (up to 0.5 GW) and 53 GW of interconnection upgrades.

The interconnector's role as a definitive enabler, not only of market integration, but also of a path towards a renewables-based power system is strongly supported by the results. The identified transmission upgrades alone have the potential to reduce the carbon footprint of the European power system by more than a quarter, compared to the EUCO3232.5, with minimal additions of peaking capacity.

The modelling results in a scenario variant, where no additional wind is added to the system, indicate that only an additional 4.2 GW of peaking capacity (OCGTs) and 14.8 GW of battery storage on top of the EUCO3232.5 capacities, would be sufficient to restore adequacy to the power system, following the assumed coal fleet decommissioning. In a second scenario used to benchmark the results, with no interconnection upgrades, we find that the flexible resource requirements rise sharply to 21 GW of battery storage and 22.3 GW of thermal peaking capacity.

The cost of the additional infrastructure was estimated for all scenarios and benchmarked against the potential CO_2 savings. Under the EUCO3232.5 fuel price assumptions, replacing coal with wind power would lead to an annual additional cost ranging between 1.9 and 4.5 € Billion, which corresponds to an incremental abatement cost between 7.4 and 18.2 €/tonne CO_2 in 2030.

1 Introduction

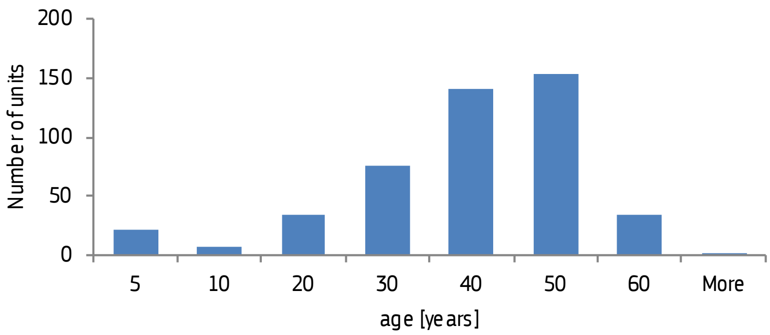
The communication "A Clean Planet for All" (European Commission, COM(2018) 773) defined a European vision to achieve climate neutrality by 2050. "Maximising the deployment of renewables and the use of electricity to fully decarbonise Europe's energy supply" was identified as one of the seven building blocks of the strategy and may be considered as the power sector's main contribution towards this goal.

Taking the discussion one step further, the European Commission in the communication "The European Green Deal" (European Commission, 2019) published a roadmap for achieving a carbon neutral society by 2050 which proposes to increase the EU's greenhouse gas emission reductions target for 2030 to at least 50% and towards 55% compared with 1990 levels in a responsible way. The transformation of the power sector in a way that it may accommodate and rely upon increasingly more renewable sources, in parallel with the rapid phasing out of coal are identified as key policies to achieve this goal.

1.1 Phasing out coal

The European coal-fired steam fleet was the workhorse in most European power systems for more than half a century. The average age of a coal power plant in the EU is 35 years (Figure 1).

Figure 1. Age distribution of the EU coal power plant fleet (2016).



Source: JRC, 2018

The declining role of coal-fired power plants has become even more evident in the last years as retirement of the older units accelerated after 2015. This trend is partly driven by increasingly restrictive pollutant emission standards and partly by the market conditions. In the meantime, governments in many European countries, including Austria, Denmark, France, Greece, Italy, the Netherlands, Finland, Portugal, Spain, Sweden and the UK have announced plans to enable a complete phase-out of their coal-fired fleet within the next decade. Countries whose power sector has traditionally depended heavily on solid fuels (Coal, lignite and shale oil) are carefully preparing the partial phase out (Commission on Growth, Structural Change and Employment Final Report, 2019). As these processes are increasingly gaining momentum, and given the importance of this fuel in specific EU Member States economy and employment, taking a closer look at the opportunities presented by a faster than initially anticipated coal phase-out policy, is today highly relevant. To this date there are few publications on this topic, many of them not extending the analysis beyond National borders.

Alves Dias et al. (2018) mapped the coal activity in the EU and quantified in temporal and geographic detail the potential impact of decarbonisation (coal phase out in power generation) on employment.

Jewell et al. (2019) quantified the benefits, in terms of emissions reduction, of the Powering Past Coal Alliance (PPCA) commitments to 0.5-2.5 $GtCO_2$ between 2019 and 2050, under the assumption that coal is replaced by low emission technologies, or half that number if they are replaced by gas.

Due to the comparatively lower emission factor, natural gas is considered to be the bridge-fuel for the energy transition to a zero-carbon energy system. However recent evidence indicates that the sharp rise in methane emissions to the atmosphere is tied to fossils fuels (Hmiel, Petrenko, & Dyonisius, 2020). This means that finding a replacement for the exiting coal fleet which is not based on fossil fuels becomes an increasingly critical step in the transition to a GHGs emissions-free power system.

The retirement of coal and lignite fleets, hitherto base-load generation, will leave a significant energy and capacity gap, which must be filled from other sources (Kanellopoulos, 2018). Kefford (2018) assessed the challenges of an early retirement of coal fleets in deep decarbonization scenarios by mid-century discussing extensively the unlikelihood of coal units slated for retirement, in transitioning towards limited operation to provide spinning reserves.

The replacement of conventional thermal capacity with variable renewable energy sources (VREs) is an option that presents challenges when the share of VREs in the national power systems exceed certain levels (IEA/OECD, 2018). Ensuring the balance of supply and demand when VREs are not generating (power system adequacy) is one challenge which must be dealt at the planning level.

The periods with potential lack of power system adequacy are attributed to the occurrence of blocking weather regimes with extended periods of no wind over central and Northern Europe (Grams, Beerli, Pfenninger, Staffell, & Wernli, 2017). During these regimes the installed wind capacity in the North Sea will not be generating sufficient power. The authors analysed the variability of wind power coupled with weather regimes across Europe and concluded that wind power deployment pathways that minimize this variability are possible. Specifically deploying in the Balkans instead of the North Sea would minimize these variations and increase fleet wide minimum output. Wohland et al. (2017) found similar patterns and reported that these may be further enhanced by strong climate change.

1.2 The 2018 study on coal phase out

In our previous study (Kanellopoulos, 2018) we arrived at a very similar conclusion by simulating the operation of the European power system in 2030 under a scenario involving the retirement of a significant part of the existing coal-fired fleet. The study concluded that targeted investments in infrastructure encompassing additional wind power in the Nordics, the Iberian and the Balkans, supported by interconnection upgrades and limited battery storage capacity in the Central-West would be sufficient to restore adequacy and balance the system during weather patterns observed in one climatic year. The results indicated that the back-up thermal peaking capacity can be significantly reduced if alternative infrastructure based on interconnections, wind power and short-term storage (batteries) is developed. Under optimal planning scenarios it is possible to reduce the backup power requirement to zero.

The optimal scenario was defined in a sequential process that initiated with a zonal (North-South) optimisation, the results of which were extrapolated to the detailed model in order to create the renewables-based scenario with restored adequacy based on carbon-free infrastructure. This leapfrogging decarbonised scenario is compatible with the newly embraced target of 55% emission reduction by 2030.

However the robustness of the results should be verified methodologically, scenario-wise and climate-wise since analysis by other researchers on a 2050 fully renewable power system seem to refute the claim that spatial optimisation of VRES can significantly reduce peak residual power demand (Zappa & Van den Broek, 2018).

1.3 Study objective

The present study aims to verify and extend the conclusions of the previous 2018 study, based on the newest EUCO policy scenario under updated assumptions regarding a likely coal phase out scenario by 2030, and across multiple climatic years. In particular the study aims to shed further light to the climatic benefits of exploiting the geographic differentiation of the wind resource, to replace the retired coal capacity with carbon-free technologies. In particular the following questions are being addressed:

1. Are the aforementioned conclusions regarding the potential of optimally placed wind to successfully replace thermal capacity, valid for multiple climatic years?
2. What are the interconnection capacity upgrades required to make this work?
3. How much backup thermal capacity would still be needed?
4. How would such a path compare cost-wise and emissions-wise to a more conservative approach involving less wind and more natural gas or less interconnections and more local flexibility solutions?

2 Context and methodology

A complete power system scenario consists of generation, storage and interconnections assets, as well as demand and renewable timeseries. All of the above are used within METIS, a power system model that simulates the cost optimal operation of the day-ahead market.

2.1 The METIS model

The power system in the METIS model is represented by a network in which each node stands for a geographical zone, linked to other zones with power transmission capacities. Exchanges of energy between nodes are limited by the NTC, which is exogenously defined.

The simulation consists of optimising the operation of the system assets over a year, at an hourly time step, by minimizing the overall cost of the system, while maintaining supply/demand equilibrium at each node. The optimisation problem is linear and is solved using a rolling horizon approach.

The powerplants are represented as fleets of similar technological characteristics. Units are grouped by fuel and technological development in each node. The model can simulate the dynamic constraints and starting costs in a relaxed (LP) unit commitment, without using binary variables. A detailed description of the model is available by (Sakellaris, Canton, Zafeiratou, & Fournier, 2018)

2.2 Limitations of the model setup

The geographically extended modelled area and detailed temporal resolution (hourly time-step) lead to some compromises or limitations, the most important of which are listed below:

Table 1. Modelling limitations summary

Limitation	**Impact**
One node per country	- Internal transmission bottlenecks not captured. - Renewable generation curtailment underestimated
Static representation of the transmission grid with NTCs	- Physical transmission constraints not modelled.
Linear representation of powerplant technical constraints	- Full detail of the cycling effects and costs of powerplants not captured. - Renewable curtailment probably underestimated
Limited representation of demand-side response	- Demand response potential contribution to adequacy not modelled
Weather sensitivity of demand similar to today's level	- Demand gradients of extreme weather years may be underestimated

Source: JRC, 2020.

2.3 Scenario definition

The scenario should satisfy the following conditions: a) it implements the accelerated coal phase out pledges set by different member States on top of the latest official scenario, b) it maximises the replacement of coal with zero emissions assets and c) it does not present any adequacy issues.

The basis for the present analysis is the European Commission's EUCO3232.5[1] scenario (DG ENERGY, 2019), which models the impact of achieving an energy efficiency target of 32.5% and a renewable energy target of

(1) The scenario used to support the Commission's June 2019 assessment of the draft national energy and climate plans (NECPs), submitted by Member States

32%, as agreed in the “Clean energy for all Europeans package” for 2030. A dataset compatible with the EUCO3232.5 scenario was generated for analysis with the METIS model. This dataset is expanded geographically to include neighbouring to the EU countries, with which significant energy exchanges take place (Norway, Switzerland and the western Balkans), as well as temporally, in order to analyse the operation of the power system at hourly resolution over an entire year, over multiple climatic years.

The scenarios in the present study are derivatives of the EUCO3232.5 regarding the following parameters:

- Hard coal and lignite installed capacity
- Onshore and offshore wind installed capacity
- Peaking (OCGTs) and Li-ion storage capacity
- Cross border transmission (NTC) capacity
- Solar pv capacity (in one of the scenarios)

The updated capacities of the scenarios are calculated according to the workflow presented in the following paragraphs.

2.3.1 Optimisation of wind, peaking and NTC capacities

The ensuing analysis was carried out according to the following methodological/process steps, whereby the derivative scenarios were generated:

1. Creation and simulation of the EUCO32325 scenario within METIS.
2. Creation and simulation of the derivative EUCO32325_RC scenario after the removal of the coal capacity defined in the previous paragraph. Following the removal of the hard coal and lignite fleets, the system is impacted in both energy and capacity terms (see paragraph 3.4.2).
3. Minimisation of the loss of load (LoL) generated in the previous step by gradual additions of wind capacity. This external optimisation process is used to identify the locations (at country level) where incremental wind capacity to replace coal has the biggest potential to restore adequacy due to the wind resource being available during times of scarcity.
4. Identification of the optimal, additional wind capacity in the areas identified in step 3 as well as interconnection upgrades required to allow power flows from areas with excess to areas with scarcity and local flexibility resources (OCGTs and lithium ion short-term storage) required to restore adequacy in the affected regions. These three variables (wind capacity, interconnections and flexible resources) serve to maintain adequacy in the power system at every node following the retirement of the coal assets. This step was carried out within the capacity expansion module in METIS.
5. Scenario evaluation on the basis of different performance metrics: LoL, curtailment, emissions, marginal prices, investment costs, cost abatement.

The process described (steps 1-4) above led to the definition of the main scenario of the present analysis, which is the WRC (expansion based on wind and interconnection upgrades). Subsequent optimisations described in step 4 were applied to establish the IRC (based on Interconnection upgrades) and LRC (focusing on local expansion instead of interconnections) derivative scenarios. An overview of the scenarios is provided in Table 2 in the following page.

Table 2. Overview of scenarios

Name	Description	Coal	Added Transmission capacity (GW)	Added wind Generation capacity (GW)	Added storage capacity (GW)	Added peaking capacity (GW)	Added solar PV capacity (GW)

EUCO32325	Base scenario implemented in METIS						
EUCO32325_RC	Base with reduced coal	-53GW	0	0	0	0	0
WRC	Optimal WRC		Optimised	Optimised	Optimised	Optimised	0
IRC	Zero additional wind		Same as WRC	0	Optimised		0
LRC	Zero additional interconnections		0	Optimised			

Source: JRC, 2020.

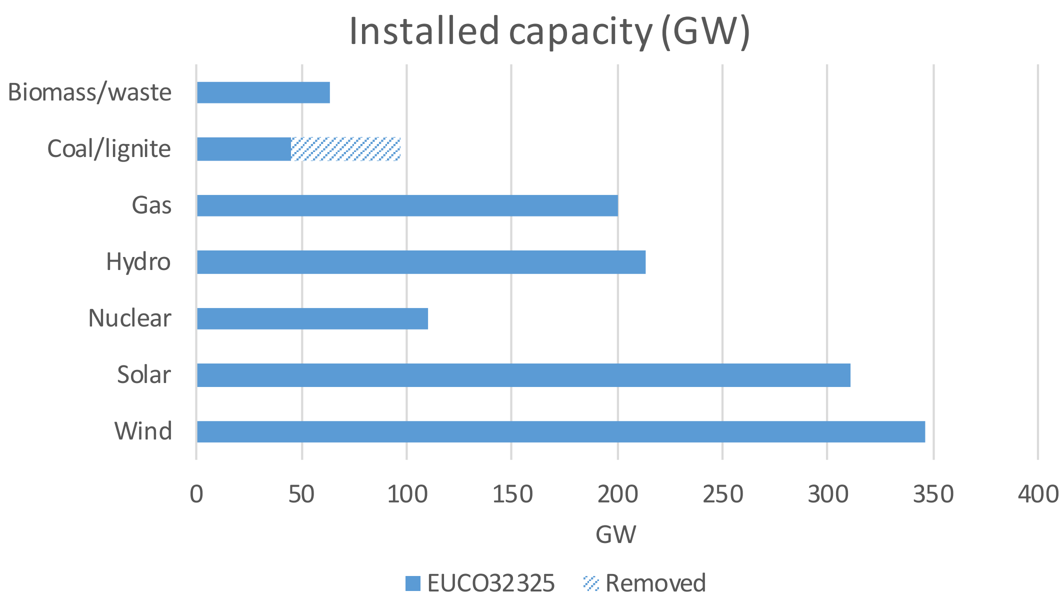
3 Scenario definition and results

The process for defining the new scenarios described in section 2, as well as the modelling results are presented in the following paragraphs. The starting point for all new scenarios is the METIS implementation of the EUCO3232.5 for 2030, adjusted to consider a coal phase-out plan scenario implemented by EU member states by 2030, as described below.

3.1 Coal installed capacity

The installed capacity of coal fleets in 2030 is reduced in order to match coal fleet retirement scenarios either from member state announcements or ENTSO-E's TYNDP 2016 vision 4 scenario. This represents in total a reduction of 51 GW or 52 % of the EUCO3232.5 scenario installed coal/lignite-fired capacity in the modelled area (details of the retired capacity at national level are provided in the annex 2). The resulting scenario is the EUCO3232.5_RC (Reduced Coal).

Figure 2. Generating fleets on the EUCO3232.5 scenario and coal capacity removed (EUCO32325_RC)



Source: JRC, 2020.

It is assumed that the aforementioned thermal capacity is permanently removed from the power system. This assumption may deviate from the anticipated practice that countries will pursue, since a share of the fleet could remain on a standby regime as part of strategic reserves, at least during the first years. However, this practise entails significant costs associated with maintaining the human resource capability and may only be affordable over a short term – transitory phase (Kefford, 2018). Therefore, in the present analysis of a 2030 power system we do not consider any backup coal capacity.

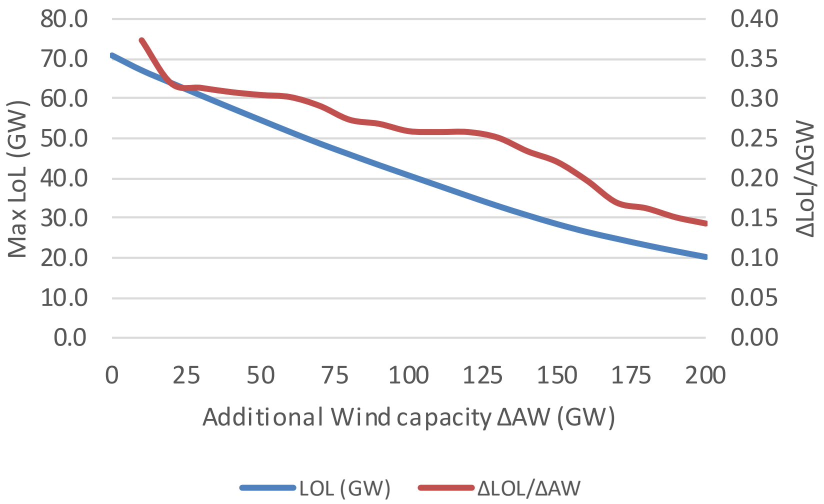
Subsequently, the capacities of wind, interconnections and other resources are adjusted, in sequential optimization steps, which are described in the following paragraph.

3.2 Identifying locations with the optimal balancing potential

The loss of load timeseries obtained from the simulation within METIS of the EUCO3232.5_RC are first used in an external optimisation process to identify which wind locations have wind resource patterns that cancel out the temporal values of loss of load (LoL).

Figure 3, in the next page illustrates the potential of additional, optimally placed wind capacity to reduce the maximum total loss of load in the modelled area, over multiple climatic years. The red line expresses how much additional capacity in GW of wind is required to cancel out 1 GW of LoL. It is evident from the graph that the effectiveness of new wind capacity, in cancelling out LoL is reduced, as wind capacity is increased. This is due to the fact that the most effective locations are selected first and become saturated. The first 70 additional GW are the most effective: one additional GW of wind in the identified locations has the potential to cancel out more than 0.3 GW of the maximum LoL, over the full set of climatic conditions. This ratio is maintained above 0.25, up to 130 GW of additional wind and drops quickly as wind is installed beyond this capacity in other locations.

Figure 3. Optimisation results in incremental addition of wind capacity



Source: JRC, 2020.

The above are evident by examining the derivative curve ΔLoL/ΔGW (red line), were two plateaus are revealed: the first one, stopping at around 70GW and the second at 130 GW. Both plateaus end at the point where wind capacity is added from countries not previously selected. This interpretation of the results enables us to classify countries in three groups, in terms of LoL-abating effectiveness with their wind resource. The countries belonging to each group are listed in Table 3. Spain and Sweden are present in both groups 1 and 2. Both countries contribute by 60% to the 70 GW of the first (additional wind) segment.

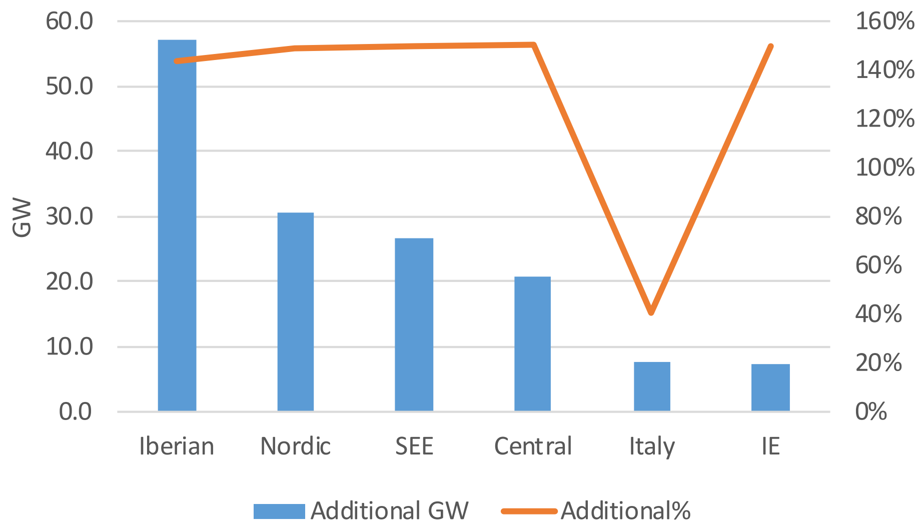
Table 3. Wind power locations grouped in terms of effectiveness in relieving the adequacy gap

1st group 1 (0-70 GW)	2nd Group (70-130 GW)	3rd Group (>130 GW)
BG, ES (28GW), FI, EL, SE (14GW), IT	ES (22GW), SE (7GW), PL, RO	IE, LT

Source: JRC, 2020.

The optimal locations (in terms of their overall system balancing potential) for the additional wind are found at the frontiers of the European power system. Figure 4, in the following page provides the distribution of new wind installed capacity, if this is limited to 150 MW. The majority of the wind capacity is located in the Southern Europe (Iberia, Italy and the Balkans), while approximately one third would be located in Northern Europe, primarily in the Nordic countries.

Figure 4 Optimally placed 150 GW of additional wind in European regions to support adequacy in a copper plate system (brown line shows additional capacity relative to already installed wind capacity in the respective region under the EUCO scenario)



Source: JRC, 2020.

The external to the METIS model optimisation procedure, described in the present paragraph identified the most favorable wind resource profiles to cancel out the imbalance of supply and demand, present in the EUCO3232.5_RC power system, after the removal of the coal capacities. The wind capacity values identified are subsequently used as an upper bound in the subsequent capacity expansion run within METIS, to co-optimise wind, transmission upgrades and local flexibility assets in the areas with identified lack of sufficient power adequacy.

3.3 Expanding the power system to replace coal with wind

The additional, optimally located wind capacity would serve its purpose in a "copperplate" power system. However, this is not the case, neither in reality, nor in the model used in the present study. The energy that can be transmitted between zones is limited by their interconnection capacity, modelled statically as a fixed net transmission capacity (NTC). Therefore, a second optimisation step is executed to identify the required interconnection upgrades that will allow the transmission of power from regions with a surplus, to regions experiencing a deficit, as well as any local flexibility resources required at times of scarcity. The regions where these variables were optimised, as well as the upper bound of the respective capacity are provided in Table 4:

Table 4. Optimisation variables

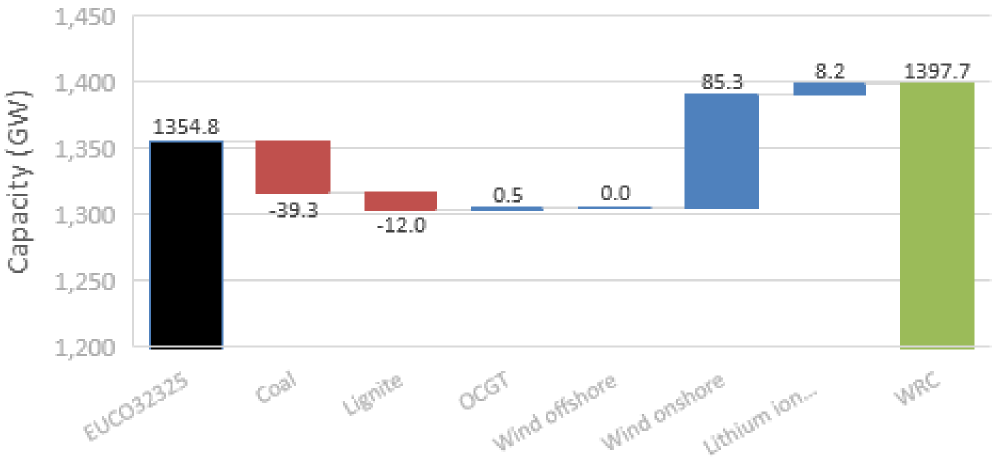
No	Country	Upper bound	Countries
1	Wind onshore	142.2	BG, ES, FI, EL, SE, PL, RO, IE, LT
2	Wind offshore	0-7.8	IT
3	Transmission upgrades	0-200% of REF2027 grid NTC	Corridors from options 1, 2, 4
4	Lithium-ion storage	0-15% of PV capacity	NL, BE, FR, DE, PL, FI
5	OCGTs	N/A	NL, BE, FR, DE, PL, FI

Source: JRC, 2020.

The optimisation was executed with the capacity expansion feature of METIS, focusing on interconnections, peaking thermal capacity and short-term storage (batteries) for two climatic years (related to 1993 and 1998) with a very high number of estimated LoL hours in the EUCO3232.5_RC.

The capacity expansion results for the two (climatic) years provided very similar solutions with respect to wind capacity and interconnector upgrades, but selected a different share of flexibility resources. The solution based on year 1998 was selected because it featured what could be considered a more sustainable in terms of CO_2 emissions solution, primarily based on Li-ion storage. The summary of the additions and removals of infrastructure (generating assets and interconnections), compared to the EUCO3232.5 is reflected in Figure 5.

Figure 5. Installed capacity changes between the EUCO3232.5 and the WRC scenario



Source: JRC, 2020.

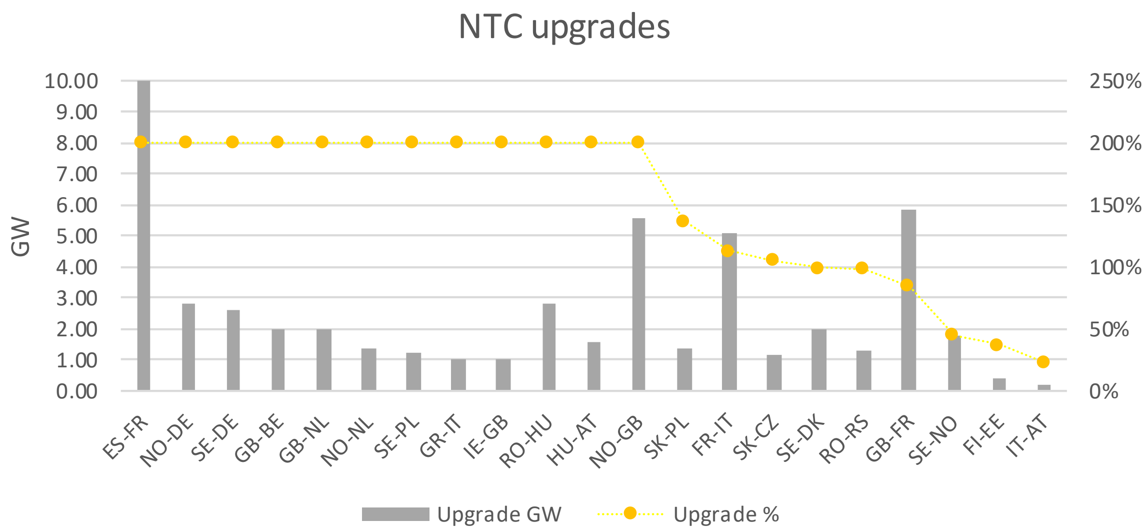
In total 85.3 GW of new wind capacity, 8.2 GW of batteries and 53 GW of interconnection upgrades would be sufficient to enable a transition from coal to wind across Europe, with minimal need of backup thermal capacity. Onshore wind is selected in favor of offshore due to the fact that the new onshore capacity is much below the upper bounds considered (see par. 3.3.2), causing the costlier offshore not to be selected.

3.3.1 Expanding the transmission grid

Figure 6 provides the interconnection capacity needed to relieve the constraints and enable the interconnected zones to exchange energy more freely. The maximum value of the transmission capacity upgrade was constrained to 200% of the NTC of the 2027 Reference Network[2] defined by ENTSO-E (2019). The upgrades are sorted in descending order according to their relative (upgrade vs REF2027 grid) and absolute values.

(2) TYNDP2018 Reference Grid (2027 Nominal Capacities)

Figure 6. NTC upgrade in GW and relative increase compared to the 2027REF grid NTCs [3]

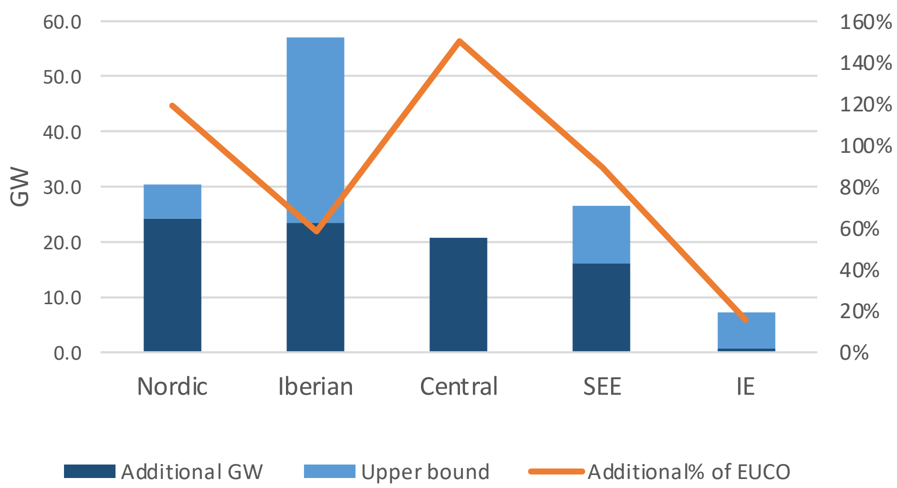


Source: JRC, 2020.

3.3.2 Optimising wind and flexibility assets (peaking and storage capacity)

The additional optimal wind capacity, derived by the capacity expansion simulation, amounts to 85.3 GW. Figure 7 below, illustrates the distribution of the additional wind capacity at regional level (dark blue bar). The light blue bars denote the optimal "copper plate" capacities, derived within the process described in paragraph 3.2. It becomes evident that the 200% constraint (over the 2027REF grid NTCs) on the transmission upgrades is activated to limit the installation of wind in the Iberian the SEE and IE. Conversely, the capacity in Central Europe (namely Poland) is fully selected. Capacity in the Nordic region is also selected to a very high degree, owing to the very strong Interconnections of this region with the Central-West, which are further upgraded as previously illustrated in Figure 6.

Figure 7. Optimal additional wind capacity in European regions in GW relative to the wind capacity in the respective region under the EUCO scenario



Source: JRC, 2020.

(3) TYNDP2018 Reference Grid (2027 Nominal Capacities)

3.4 Operation of the WRC scenario

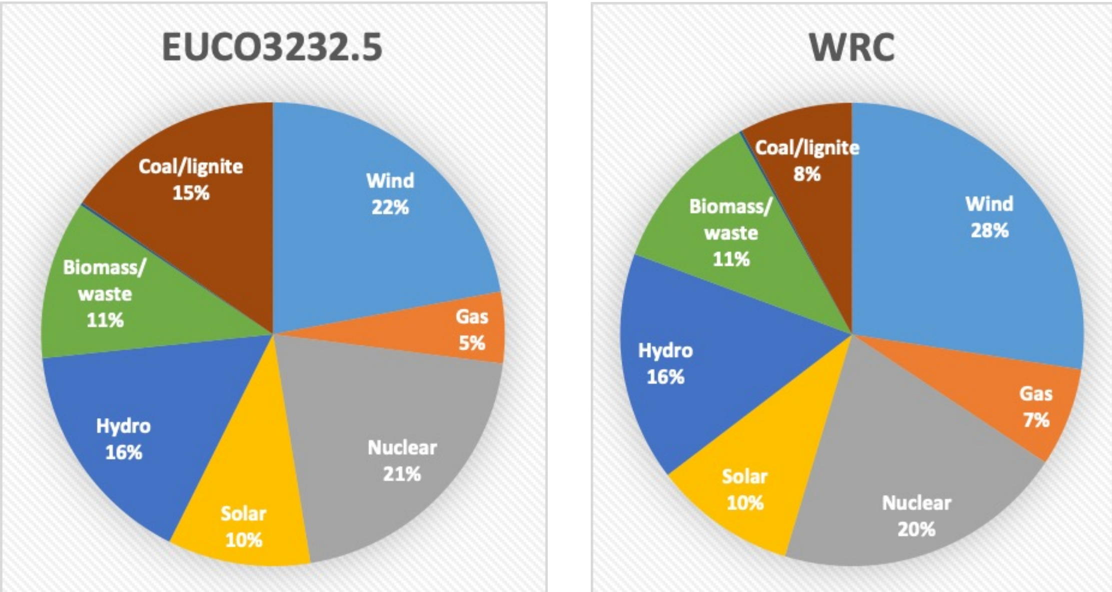
The operation of the power system within the WRC scenario for 2030 defined in the previous paragraphs was simulated over 26 climatic years, in order to allow a comprehensive comparison with the base scenario. The following paragraphs provide insight on the sustainability qualities of a scenario where legacy thermal capacity is replaced by wind backed by interconnection upgrades.

3.4.1 Fuel mix

The WRC scenario was designed to enable wind power generation to replace coal fleets that may be phased out by 2030 primarily in capacity. The model results in terms of aggregate fuel mix provided in Figure 8 shows wind replacing almost completely the retired coal and lignite.

Gas-fired generation is increased by almost 40%. A marginal reduction of nuclear generation is also observed, as nuclear fleets in France throttle back to make room for the additional wind power. Consequently the model output shows increased operation of flexible assets (OCGTS) as well as mid-merit gas fired units (CCGTs).

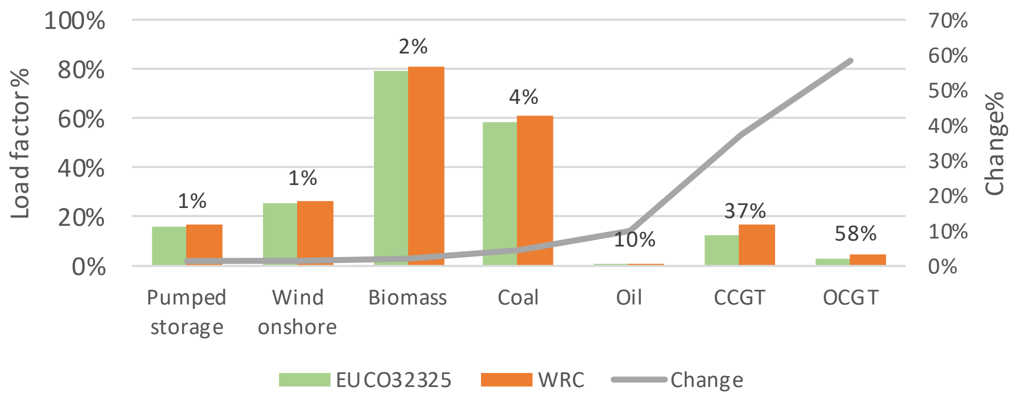
Figure 8. Electricity production shares by technology in the EUCO3232.5 and the WRC scenario



Source: JRC, 2020.

The operation of the remaining operating fleet, in terms of annual indicators is not affected significantly as Figure 9 illustrates. In absolute terms the differences are small. However, in relative terms the increase is quite evident. CCGT operation increases by 37 % while OCGTs operate on average 58% more hours.

Figure 9. Annual load factors in the EUCO3232.5. Annotated values correspond to the incremental percentage points of the load factors between the two scenarios.

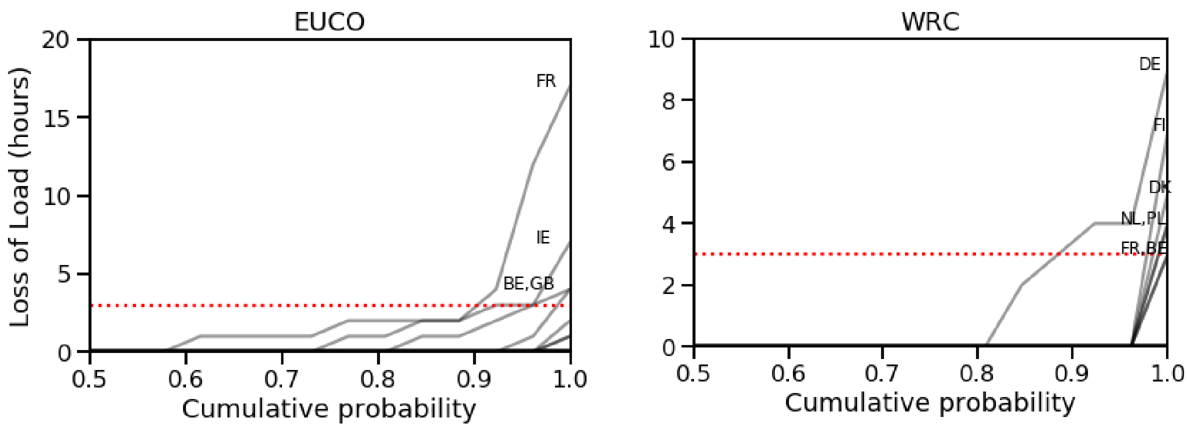


Source: JRC, 2020.

3.4.2 Adequacy

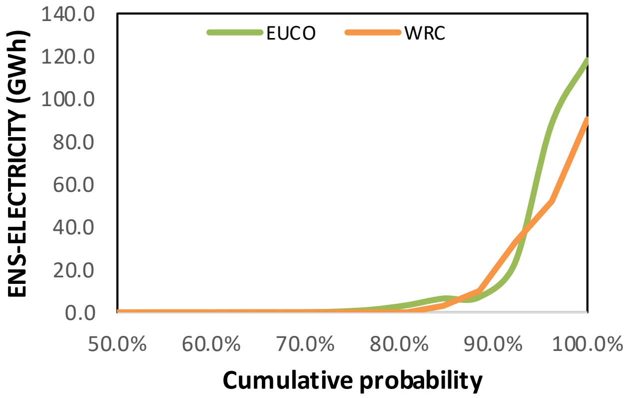
The newly defined primarily wind-based power system (WRC scenario) was simulated for 26 climatic years and was found to achieve equivalent adequacy indicators compared to the METIS implementation of the EUCO3232.5 scenario. Figure 10 below illustrates the distribution of total number of hours with energy not served (ENS) per climatic year for the countries where ENS is observed. In the WRC between 0 and 90% of the future states analysed no adequacy concerns are identified (i.e the LOLE hours are less than 3).

Figure 10. Loss of load cumulative distribution function for EUCO32325 and WRC scenario (26 climatic years analysis). Countries with a value above 3 hours are annotated. The adequacy limit of 3 hours is annotated with a red dashed line.



Source: JRC, 2020.

Figure 11. Energy Not Served (ENS) cumulative distribution function of EU27+UK for EUCO and WRC scenario.



Source: JRC, 2020.

Figure 11 above illustrates the distribution of the total (sum of all countries) ENS per climatic year. Table 5 below provides the quantitative adequacy indicators in a descriptive statistics format. The results tend to support the conclusion that the WRC scenario would not raise any higher adequacy concerns than the METIS implementation of the EUCO3232.5.

Table 5. Descriptive statistics of energy not served (ENS) and number of loss of load hours

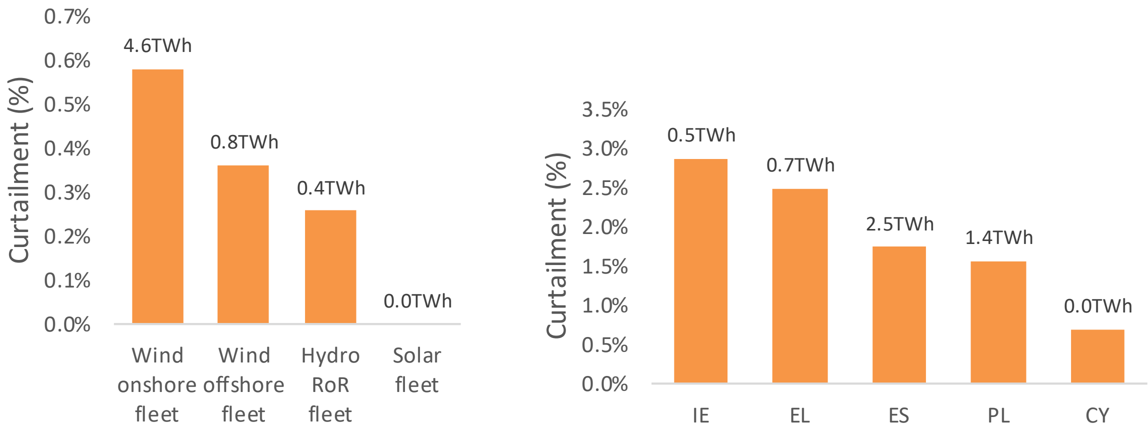
	Number of years with LoL		Average LoL hours		95th percentile LoL hours		Average EENS (GWh)		95th percentile EENS (GWh)	
area	**EUCO**	**WRC**	**EUCO**	**WRC**	**EUCO**	**WRC**	**EUCO**	**WRC**	**EUCO**	**WRC**
BE	5	1	0.4	0.1	2.8	0.0	1.1	0.4	8.4	0
DE	1	5	0.0	0.8	0.0	4.0	0.0	5.7	0	30.7
DK	0	1	0.0	0.2	0.0	0.0	0.0	0.0	0	0
FI	1	1	0.1	0.3	0.0	0.0	0.0	0.2	0	0
FR	7	1	1.5	0.1	10.0	0.0	8.1	0.6	62.2	0
UK	2	0	0.2	0.0	0.8	0.0	0.2	0.0	0.8	0
IE	11	0	1.0	0.0	3.0	0.0	0.1	0.0	0.5	0
NL	1	1	0.0	0.2	0.0	0.0	0.0	0.2	0	0
PL	0	1	0.0	0.2	0.0	0.0	0.0	0.2	0	0

Source: JRC, 2020.

3.4.3 Curtailment

Both in relative and absolute terms, curtailment of onshore wind is an order of magnitude higher than curtailments of other technologies. Figure 12 provides the curtailment values for four renewable fleets across the modelled area. Total curtailed energy is less than 6 TWh. Wind curtailment totalling 4.6 TWh almost doubles, compared to the METIS implementation of the EUCO3232.5 and is not evenly distributed across the countries. It is most prominent at the frontiers of the modelled area (IE, ES, EL), where significant wind capacity is added.

Figure 12. Curtailment at country and fleet level in relative terms. Absolute values (TWh) are annotated.

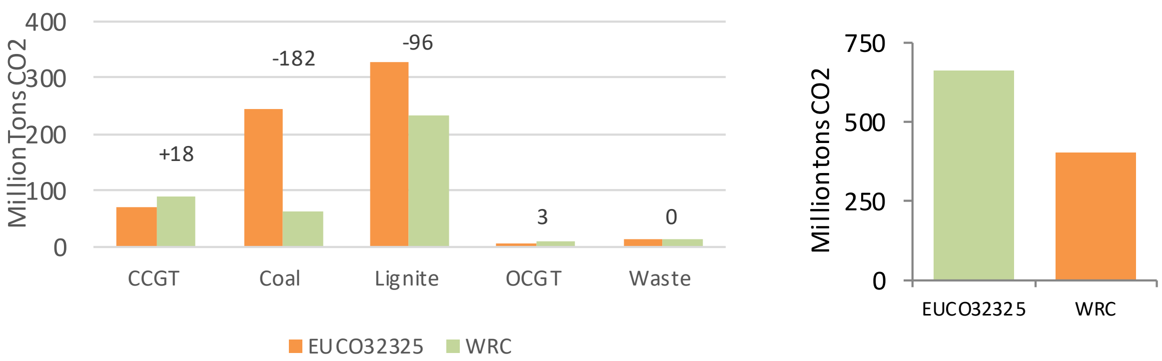


Source: JRC, 2020.

3.4.4 CO2 emissions

Based on the CO_2 emissions reduction potential, the WRC is on a potential pathway towards achieving an emissions reduction of 55% compared to 1990. Compared to the METIS implementation of the EUCO 32325, CO_2 emissions from power generation in the modelled area are reduced by 38% in 2030. The total reduction of approximately 256.7 million tonnes in 2030 is attributed to the substitution of coal and lignite by wind. A modest increase of emissions by the existing gas fired fleets is mainly attributed to increased CCGT operation to replace coal when wind is unavailable). These trends are illustrated in Figure 13.

Figure 13. Total and fleet CO_2 emissions change in the WRC vs the EUCO32325 scenario



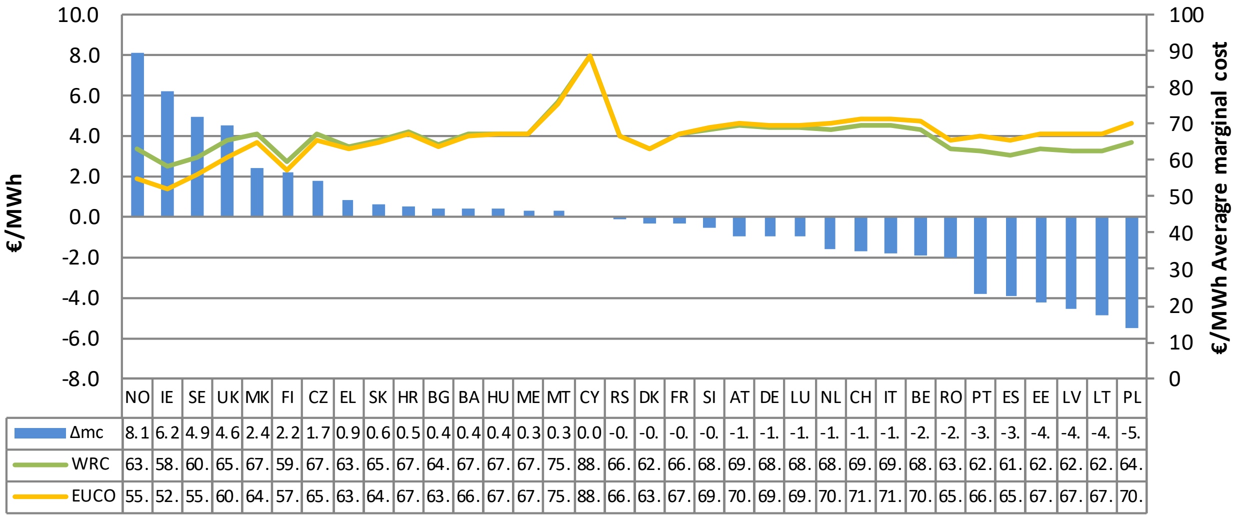
Source: JRC, 2020.

3.4.5 Effect on the day ahead electricity price

Figure 14 provides the annual average marginal price divergence calculated by the model between the WRC and the METIS EUCO3232.5 scenario. The average marginal price is also provided (solid lines). The effect of the added Interconnection capacity in reducing price divergence between countries is evident.

The most notable changes in the average marginal price are observed in countries with significant wind capacity addition (ES,PL,RO), their immediate neighbours (LT,LV and PT), and where the enhanced interconnections serve to attenuate the price difference with neighbouring areas (IE, NO, SE and UK).

Figure 14. Difference in average marginal cost between the WRC and the EUCO3232.5



Source: JRC, 2020.

3.5 CAPEX and OPEX cost of the WRC scenario

The realization of a scenario like the WRC entails significant investments, while affecting the power generation fuel mix. Table 6 provides an estimate of the CAPEX costs of the infrastructure that should be deployed to make a WRC scenario a reality. The figures are annualized, based on assumptions provided in Annex 4.

Table 6. Additional infrastructure in the WRC scenario

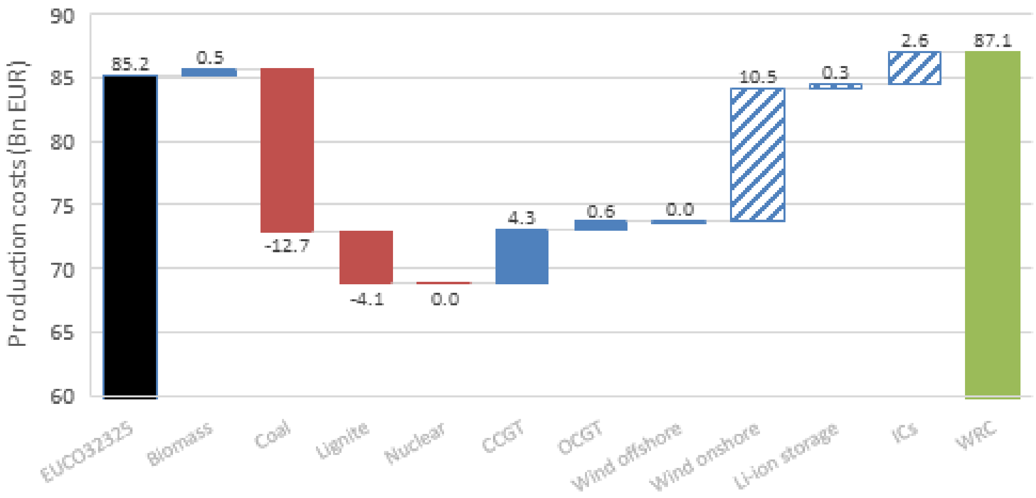
Country	Capacity (GW)	Total investment (BN EUR)	Annuity (BN EUR)
Wind onshore	85.2	119	10.4
Transmission upgrades	53.3	35-70	2.6-5.2
Lithium-ion storage	8.2	4.1	0.3
OCGTs	0.5	0.3	0.03
Total	159	159-194	13.3-15.9

Source: JRC, 2020.

The WRC scenario is more expensive compared to the EUCO3232.5, under the considered assumptions of CAPEX, fuel and CO_2 prices. The total annual production cost and additional infrastructure CAPEX in the WRC scenario is € 1.9-4.5 (low vs high interconnectors cost) billion per year higher compared to the EUCO3232.5.

Figure 15 in the following page, provides the fleet-averaged production cost differences between the two scenarios. The production costs presented therein comprise variable costs – including CO_2 costs, fixed operating costs, and the additional CAPEX for the new infrastructure, that is additional wind capacity, storage and transmission upgrades (denoted as ICs).

Figure 15. Fleet production cost change in the WRC vs the EUCO32325 scenario. Dashed bars correspond to annuity of the newly installed capacities while the rest correspond to incremental operating costs between the two scenarios



Source: JRC, 2020.

After combining the additional cost with the CO_2 abatement potential, calculated for the WRC (256.7 million tonnes in 2030), the CO_2 abatement cost lies in the range of 7.4-18.2 €/tonne. This value compares favorably with current EUA prices, and the EUCO3232.5 CO_2 cost.

3.6 Sensitivity on local vs interconnected

In order to obtain a better understanding of the contribution of the various infrastructure elements considered (wind, transmission upgrades and flexible asset additions), two additional variations on the EUCO_RC scenario were created. The first one, called (IRC for "Interconnections Replacing Coal"), is based on the WRC after removing the additional wind capacity while maintaining the NTC upgrades (according to the results presented in paragraph 3.3.1 and expanding the system further to include the additional flexibility assets (OCGTs and Li-ion storage). The second scenario, called (LRC, for "Locally Replacing Coal"), is created considering only local resource additions to the affected countries (therefore no interconnection upgrades). In this scenario solar PV additions, coupled with storage and peaking thermal power plants are optimally added to the system.

Table 7. Overview of scenarios with optimal expansion capacities

Name	Description	Added Transmission capacity (GW)	Added wind Generation capacity (GW)	Added storage capacity (GW)	Added peaking capacity (GW)	Added solar PV capacity (GW)
EUCO32325	Base scenario implemented in METIS					
EUCO32325_RC	Base with reduced coal (-51.3 GW)	0	0	0	0	0
WRC	Optimal WRC	53.3	85	8.2	0.5	0
IRC	Zero additional wind	53.3	0	14.8	4.2	0
LRC	Zero additional interconnections	0	26.7	21	22.3	158

Source: JRC, 2020.

In defining the LRC scenario, we decided to use recent low cost projections (Vartiainen & et.al., 2019) for industrial scale PV projects assumed to be realized in the second half of the decade up to 2030, in order to benchmark the WRC results against a scenario with the most favorable local expansion options.

The scenario creation is implemented by executing a capacity expansion of the model for one climatic year corresponding to the weather in 1998 (similarly to the WRC). An overview of the scenarios discussed so far, focusing on the infrastructure changes relative to the EUCO323.5, has been provided in Table 7.

A glimpse of the interconnection upgrade significance is provided by the result that in the more interconnected system (Scenario IRC) only 10.2 GW of flexibility assets (OCGTs and li-ion storage on top of what is specified in the WRC) are required to replace 85 GW of the additional wind (or 51 GW of coal and lignite) at times of scarcity. On the other hand, in the less-interconnected scenario (LRC) an additional 34.5 GW of local flexibility resources would be required, and the optimal expansion would include an additional 184.5 GW of renewable generation (wind and solar).

This is explained by the fact that interconnectors enable the supply of surplus capacity of dependable generation (not only wind) in areas with adequate margins to areas facing scarcity. Table 8 below, provides the change in total costs of the considered investments per scenario, compared to the METIS implementation of the EUCO3232.5, while Figure 16 provides the distribution of production and CAPEX costs in the considered scenarios, as well as the variation of the total cost.

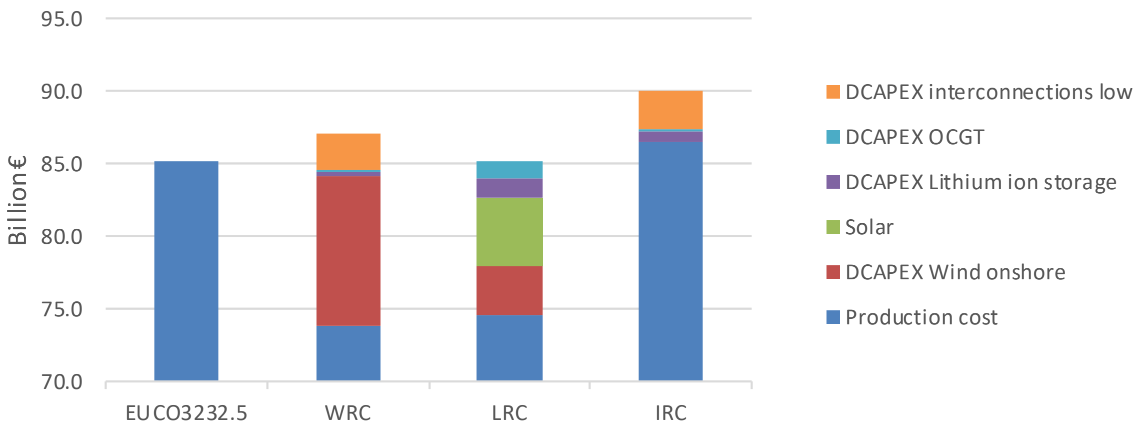
Table 8. Total cost differences and CO_2 abatement in the 3 scenarios compared to the EUCO3232.5 in METIS

Scenario	WRC	LRC	IRC
Additional CAPEX (billion EUR / yr)	13.3-15.9	10.5	3.5-6.1
ΔCO2 emission abatement in 2030(tonnes 10^6)	257	246	183
ΔTotal cost (billion EUR)	1.9-4.5	-0.1	4.8-7.4

Source: JRC, 2020.

The cost distribution provided across scenarios illustrates the rate at which different investments replace the coal resource. In the IRC scenario coal energy is primarily replaced by gas. The interconnection upgrades enable the efficient transfer of energy between regions. The higher variable costs in this case are attributed to the high price of gas in the EUCO3232.5 scenario. Meanwhile in the WRC scenario, electricity produced by coal is primarily replaced by wind and the associated fuel costs are taken over by the CAPEX component of the new infrastructure (Primarily Wind and Interconnections). In the LRC scenario coal is replaced by a mix of wind, solar and gas. It features slightly higher total production cost, compared to the WRC but lower total costs. This is attributed to the fact that the most recent cost projections regarding industrial PV cost development in 2030 are used (see Annex 4).

Figure 16. Production cost and ΔCAPEX across scenarios

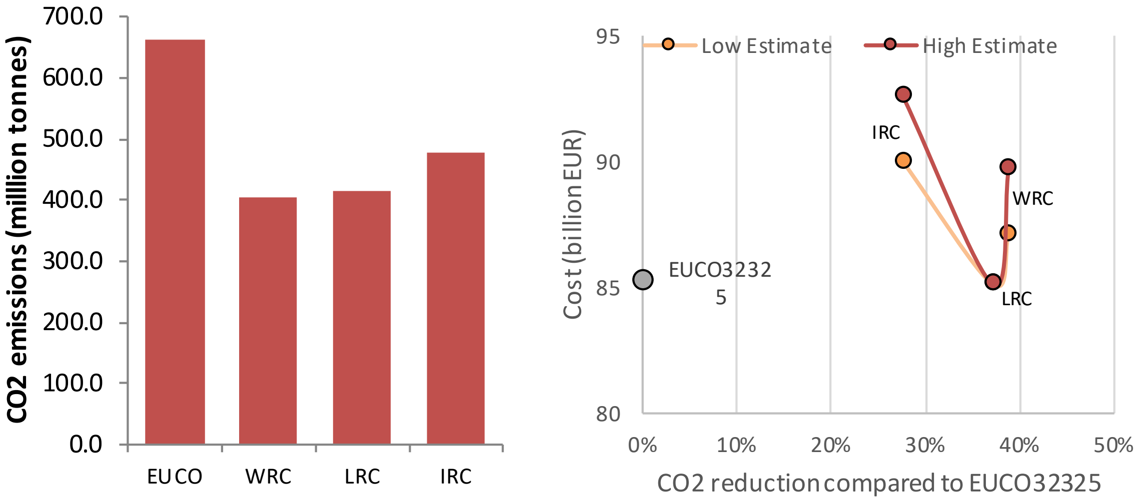


Source: JRC, 2020.

The graphs in Figure 17 provide the CO2 emissions (red bars) in the modelled area (34 countries), as well as the total costs calculated previously across scenarios (red line) vs the CO2 reduction (%) compared to the METIS implementation of the EUCO3232.5.

Figure 17. CO_2 emissions reduction vs total costs in the WRC variations vs the EUCO3232.5 scenario[4] in 2030

(a) Absolute emissions (b) Emission reduction vs costs



Source: JRC, 2020.

The WRC achieves the highest CO_2 abatement in 2030, the LRC presents the lowest total system cost, equivalent to that of the EUCO32325, while the IRC has the highest CO_2 abatement to CAPEX ratio.

3.7 Summary and discussion

The concept of exploiting the spatial variability of the wind resource at a European scale to replace coal-fired power generation, likely to retire by 2030, was assessed through the present modelling exercise. A new scenario, called EUCO3232.5_RC, was created as a derivative of the EUCO3232.5 in 2030, following the known and assumed retirements among coal fleets across the EU. An external to the model optimization step was used to identify regions in Europe with wind availability patterns best suited for balancing the system. These were subsequently used to identify the optimal interconnection upgrades, local flexibility resources and wind power additions that would restore adequacy to the EUCO3232.5_RC scenario. Although the new scenario, called WRC, was optimized for one climatic year, the simulations over 26 years revealed that this wind-based scenario, backed by transmission upgrades, has comparable adequacy indicators (LOL[h], ENS) to the base scenario (METIS implementation of the EUCO3232.5).

In terms of sustainability, the WRC is estimated to cut emissions in the modelled 34-country area by 38% compared to the METIS implementation of the EUCO3232.5 in 2030. The additional 85 GW of wind generating capacity, 53 GW of interconnections and 8.2 GW of Li-ion storage, would present an additional total cost to the European power system between 1.9 and 4.5 € Billion on an annual basis[5] compared to the METIS implementation of the EUCO3232.5. These results were further benchmarked against two alternative-derivative scenarios of the EUCO3232.5_RC. The first, called IRC assessed the contribution of interconnection upgrades alone (without wind additions) and the second explored an alternative path of local capacity expansion without interconnection upgrades.

The benchmarking with the two scenarios reveals that the WRC, despite the significant infrastructure investments it includes, is marginally more expensive than a locally optimized scenario based on significant additions of industrial scale PV and flexibility resources, while achieving a higher (albeit marginally) CO_2 emission abatement, and requiring significantly less additional flexibility resources. The comparison to the IRC

(4) For the subsequent analysis a third variant with 120 GW additional wind is added with the peaking capacity optimized for the WRC_80 scenario.

(5) Subject to the commodity cost assumptions of the EUCO3232.5 scenario and the CAPEX assumptions reported in ANNEX4

reveals the substantial contribution of Interconnection upgrades in both abating CO_2 emissions and in balancing the power system with very low backup thermal capacity requirements.

4 Conclusions

The present analysis explored the feasibility of replacing coal with non-CO2-emitting resources at a considerably faster pace than previously considered and identified the critical elements of such a path. The following is a summary of policy-relevant conclusions:

First: **it is possible to plan the replacement of coal-fired generation capacity by deploying almost exclusively new carbon-free assets**. Wind power, transmission upgrades, storage and solar PVs would be key elements of such a system and, depending on the selected system architecture (interconnected vs decentralized), varying levels of additional thermal backup capacity to guarantee power adequacy at times of scarcity will be required. In particular a more interconnected (at European scale) system will require significantly less thermal backup capacity than a more decentralized approach.

Second: **Backup thermal capacity can be minimized by exploiting the varying complimentary patterns in wind resource availability along its temporal and spatial dimension**. The balancing capacity of geographically distant wind profiles was verified under multiple climatic years. A scenario built to exploit these patterns demonstrated very good adequacy indicators requiring only a small backup capacity 8.7GW predominantly composed of lithium ion short-term storage to even out the remaining imbalances.

Third: **transmission lines are a key component of such a system**. To this end investments to upgrade the links between regions at the European frontiers (The Iberian, Italic and Balkan peninsulas and the Nordics) and central Europe were identified that have the potential to reduce the carbon footprint of the European power system by more than a quarter, compared to the METIS implementation of the EUCO3232.5 scenario for 2030. The additional flexibility resource requirement is approximately one third of the retired coal fleet capacity or 17 GW. This is possible due to the presence of sufficient interconnection capacity that allows the transfer of energy from areas with excess to areas experiencing scarcity.

Fourth, **a transition from coal to wind will require significant investments**. The present analysis estimated that the investments required could be **as high as 194 billion €** in the interconnected wind-based scenario (WRC). The total system cost increase, compared to the METIS implementation of the EUCO3232.5, is in the order of magnitude of 1.9 – 4.5 billion € annually, in large part necessary to finance the interconnection upgrades. Given the estimated abatement potential of 257 million tonnes in 2030, the abatement cost lies between 7.4 and 18.2 €/tonnes CO_2.

Finally, the results from the comparison of the two approaches featuring more interconnection (WRC and IRC) vs more decentralization (LRC) indicate that the former requires the deployment of significantly less renewable generation capacity, as well as significantly less thermal backup capacity to achieve similar or better CO_2 abatement performance. **This result supports the view that the more interconnected system approach is on the right path towards a highly decarbonised power system based on renewables.**

Potential further work on the topic could explore the following:

1. A more advanced decarbonization scenario of a complete coal phase out by 2035 or 2038 and/or
2. A sensitivity analysis of the WRC vs LRC scenarios with regard to expected future CAPEX of competing technologies.
3. An in-depth technical analysis of the temporal characteristics of the scarcity periods caused by the constantly increasing variable renewable generation and the reduction of dispatchable thermal power generation. This could include an assessment of the intra-hourly wind variability and consequent power system balancing needs in a WRC – like scenario.

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List of abbreviations and definitions

CAPEX	Capital costs
ENS	Energy not served
FRR	Frequency restoration reserves
FCR	Frequency containment reserves
IRC	Interconnections replacing coal scenario acronym
LoL	Loss of load expressed in GW or hours
LRC	Local resources replacing coal scenario acronym
NTC	Net transfer capacity
OCGT	Open cycle gas turbine
TSO	Transmission system operator
WRC	Wind replacing coal scenario acronym
OPEX	Operating expenditure

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Annexes

Annex 1. Detailed input assumptions

Demand

Hourly demand profiles are constructed based on the ENTSO-E TYNDP 2018 dataset for 2030. Using 2017 demand as a base year 36 annual variations were generated based on the weather that occurred within the period 1980-2015. The following method was followed.

Hourly timeseries of temperature (at 2 meter height), wind speed (at 10 meter height) and irradiation data from the Copernicus Climate Change Service (C3S) ERA5 reanalysis were downloaded and spatially aggregated to NUTS2 administrative levels for the years 1980-2018 (De Felice & Kavvadias., 2020). Temperature and wind affect the (electric-driven) space heating, while irradiation affects also the lighting needs. The timeseries were then weighted based on the population of each region and a national weighted average was estimated.

State of the art regression-based electricity load model uses a time-of-week indicator regressor (Granderson, et al., 2016; Granderson, Touzani, Fernandes, & Taylor, 2017; Mathieu, Price, Kiliccote, & Piette., 2011).

This captures the variance of weather sensitivity on energy demand for each hour of the day and each day of the week. Demand is more elastic to weather conditions during periods of high economic activity and less elastic during off-peak times, where people are sleeping and shops/industry is closed.

The feature selection of the regressions was based on that hypothesis. More specifically, features for each of the three variables were generated using one-hot encoding for different days of the week and for type of day (weekdays, Saturdays and Sundays and bank holidays) was regressed with hour of the day. In order to account for the inertia in the system to big distortions a 3 hour exponential weighted rolling window was used to smoothen the series. These features were used to predict the energy load using XGBOOST, a parallel tree boosting under a Gradient Boosting framework (Chen & Guestrin, 2016). This algorithm is robust in overfitting and can generalize accurately.

Based on that fitted model, the weather parameters of the years 1980-2016 were used as regressors though the model and the new demand timeseries were constructed.

The base year was scaled up proportionally to align the total annual demands (area under curve) with the annual amounts of total final energy demand in the EUCO32325 scenario. The rest of the climatic years were adjusted with the same correction factors as the base year. Countries that are not part of EU27 +UK maintained the same demand levels as today.

Renewable availability time series (Wind / solar / hydro)

Hourly wind solar time series are based on the "*Renewables.ninja*" datasets (Staffell & Pfenninger, 2016). This dataset is based on weather data from global reanalysis models and satellite observations such as NASA's MERRA reanalysis. The choice of this dataset over JRC's in-house EMHIRES was based on their coverage of multiple years (1980–2016) not currently present in EMHIRES and coverage of most countries within the geographical scope of this analysis.

In case where there are no existing projects, e.g. wind offshore, the time series of the nearest country have been used.

Hydropower inflow

The present study was initially conducted with Hydro inflows are obtained from METIS DB. The final results reported in the current report were limited to 26 climatic years, after the incorporation of time-series based on the output of a LISFLOOD hydrological model (De Felice, M et al, 2020).

Transmission capacity

National power systems are modeled as nodes connected with their neighboring power systems via interconnections with a capacity equal to the Net Transfer Capacity (NTC) of the respective physical cross border lines. The NTC values are based on the TYNDP 2018 2027 reference grid (ENTSOE, 2019). As an upper bound on the interconnection capacity expansion a 200% increase with regards to the abovementioned reference grid.

Storage capacity

Only existing reservoir hydro power capacity is considered in the EUCO3232.5_RC setup. Capacity expansion is used to restore adequacy by adding batteries where needed in the derivative scenarios.

Reserves

Reserves are modelled as synchronous reserves (FCR + aFRR) and mFRR, according to the definitions of the balancing guidelines[6]. Reserve requirements for the individual countries are based on the reserve sizing requirements calculated METIS for the year 2030 for the EUCO30 scenario, according to the methodology provided in (Artelys, 2017).

(6) Commission Regulation (EU) 2017/2195

Annex 2 Coal capacities

Table 9. Coal and lignite installed capacity and removals compared to the EUCO3232.5

Country	Hard coal in WRC (MW)	Lignite in WRC (MW)	Total coal in WRC (MW)	Reduction % compared to the EUCO3232.5	Reduction (MW) compared to the EUCO3232.5
AT	0	0	0	100%	78
BG	0	710	710	79%	2642
CZ	0	4734	4734	46%	4064
DE	8000	9000	17000	48%	15599
DK	0	0	0	100%	1075
EE	0	656	656	54%	757
ES	0	0	0	100%	3968
FI	0	0	0	100%	1274
FR	0	0	0	100%	3744
UK	0	0	0	100%	501
EL	0	0	0	100%	2628
HR	655	0	655	0%	0
HU	0	0	0	0%	67
IE	0	0	0	100%	842
IT	0	0	0	100%	3892
NL	0	0	0	100%	3485
PL	5364	5356	10720	34%	5550
PT	0	0	0	0%	0
RO	0	1251	1251	35%	659
SI	0	545	545	3%	19
SK	0	0	0	100%	454

Source: JRC, 2020.

Annex 3 Initial and new wind capacity

Table 10. Installed capacities and technical potential of onshore and offshore wind

Country	EUCO32325	Externally opt capacity (150GW)	WRC added capacity	Total capacity	Technical potential	Coverage (%)
	Onshore wind					
AT	7.2	0	0	7.2	24.4	30%
BG	2.9	4.4	1.9	3.8	29.1	13%
EE	0.4	0	0	0.4	23.0	2%
ES	39.7	56.9	23.3	63	535.3	12%
FI	4.4	6.6	6.6	11.0	26.3	42%
FR	25.6	0	0	25.6	261.1	10%
UK	29.6	0	0	29.6	165.9	18%
GR	7.6	11.3	4.1	11.7	145.4	8%
HR	1.3	0	0	1.3	10.8	12%
IE	4.9	7.33	0.8	5.7	70.9	8%
IT	15.5	0	0	15.5	131.6	12%
LT	1.2	1.81	1.81	3.0	57.3	5%
LV	0.5	0.42	0.19	0.7	50.9	1%
PL	13.9	20.9	20.9	34.8	116.4	30%
RO	7.3	11	9.9	17.2	99.2	17%
SE	14.3	21.5	15.7	30	121.5	25%
SI	0.3	0	0	0.3	0.9	33%
	Offshore wind					
ES	0.1	0.14	0	0.1	1.0	10%
UK	20.9	0	0	20.9	190.8	11%
GR	0.0	0.01	0	0.0	0.0	0%
IT	3.0	7.54	0	3.0	13.6	22%
LT	0.0	0.01	0	0.0	7.7	0%
LV	0.1	0.14	0	0.1	36.3	0%

Source: JRC, 2020.

Technical potentials are based on JRC ENSPRESO dataset. Potentials for onshore are estimated based on the Low Wind Scenario and high wind regions (with a capacity factor above 20%). Setback distances in all countries converge in 2030 to the highest setback currently observed: 1200 m and 2000 m for small and large turbines, respectively. Setbacks remain the same in subsequent years. Potentials for the offshore are estimated based on the low restrictions scenario which assumes a low level of exclusion of surfaces for wind, for a water depth up to 60 m. Potential for floating platforms is not considered but could increase the potential heavily.

Annex 4. Technology data used in the capacity expansion

Table 11. Technology data used in the capacity expansion

Technology	Capex €/kW	Discount rate	Capex €/MW-Year	Technical data
OCGT	569	6%	€ 49 604	Efficiency: 39% (HHV)
Onshore wind	1 400	6%	€ 122 000	
Offshore wind	2 500	6%	€ 218 000	
Lithium ion battery storage[7]	380	4%	€ 27 960	Discharge time: 1 h
Lithium ion battery storage	718	4%	€ 52 830	Discharge time: 2 h
Lithium ion battery storage	878	4%	€ 76 525	Discharge time: 4 h
New Solar PV[8]	350	6%	€ 30 515	
Transmission lines[9]				
Low cost	660	4%	€ 48 564	
High cost	1 320	4%	€ 97 128	

Source: JRC, 2020.

([7]) The capex of lithium ion storage based on (Tsiropoulos & et al, 2018)

([8]) Industrial scale solar PV costs based on (Vartiainen & et.al., 2019)

([9]) Transmission upgrade costs are based on actual PCI project costs constructed or under construction totaling an NTC upgrade of 10.8 GW with a total budget of 7.2 billion €. The low cost is based on the average investment cost per kW of upgrade, while the highest value is based on the group of PCIs (1.4.1-3) to upgrade the net transfer capacity between Germany and Denmark.

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