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THE IMPACT OF PCI PROJECTS ON THE CURRENT AND FUTURE EUROPEAN POWER & GAS SYSTEMS

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Abstract

The present study documents the methodology and results of modelling in order to quantify the benefits of electricity and gas related Projects of Common Interest (PCIs) for the European Power and Gas systems. The quantitative scenario analysis was conducted using the METIS model and quantified the potential benefits of already commissioned, under construction and planned PCI projects to the power and gas systems. The section on the analysis of the power system presents the impact of PCI projects on market integration, CO_2 emissions, renewable curtailment, marginal price, power adequacy, and welfare indicators. The impact of climatic variability on the calculated benefits provided by the 4th list of PCIs was also assessed for 2030. The section on the analysis of the gas system presents a similar approach on the evaluation of welfare indicators, adding insight on crisis scenarios simulating disruption of gas supply to EU through Ukraine, to assess the benefits of security of supply derived from the implementation of new projects.

1 Introduction

The Regulation on trans-European energy networks (TEN-E), adopted in 2013, lays down rules for the timely development and interoperability of trans-European energy networks to achieve the energy policy objectives of the Treaty on the Functioning of the European Union (TFEU)[1] to ensure the functioning of the internal energy market and security of supply in the Union, to promote energy efficiency and energy saving and the development of new and renewable forms of energy, and to promote the interconnection of energy networks.

Priority corridors and three thematic areas[2] have been defined in the implementation of the TEN-E[3], with the purpose of enhance the existing cross-border interconnection among EU Member States. Pursuant to article 3(4) and Annex VII of the TEN-E regulation, clusters of electricity-related infrastructure projects have been identified as corridors:

- NSOG (North Sea Offshore grid)
- NSI West electricity (North South electricity Interconnection in western Europe
- NSI East electricity (North-South electricity Interconnections in central eastern and south eastern Europe)
- BEMIP Electricity (Baltic Energy Market Interconnection Plan in electricity)

The corridors for gas-related infrastructures are the following:

- NSI West Gas (North-South gas interconnections in Western Europe)
- NSI East Gas (North-South gas interconnections in central Eastern and south Eastern Europe)
- SGC (Southern Gas Corridor)
- BEMIP gas (Baltic Energy Market Interconnection Plan in gas)

Within these corridors, single infrastructure projects have undergone a process of candidature and selection of Project of Common interest (PCI). The status of PCI allows a project to benefit from accelerated permitting, improved regulatory conditions and lower administrative costs.[4] The PCI status also gives eligibility for funding from the Connecting Europe Facility (CEF) funds. In 2020, EUR 998 million in CEF grants have been allocated to 10 PCIs, (2 for electricity transmission infrastructures, 1 for smart electricity grids, 6 for CO_2 transport, and 1 for gas related infrastructure projects). Up to now, four lists of PCIs have been identified, and a process of assessment was launched in 2020 to ensure the consistency of the TEN-E with other EU policies and legislative initiatives, as the framework of the European Green Deal.

In order to quantify the benefits stemming from the implementation of the current TEN-E regulation, in the field of electricity and gas, from its entering into force until the full implementation of the latest PCI list (4th list), the JRC was asked to provide a quantitative assessment of indicators related to the monetary and physical impact of realised and planned gas and electricity PCIs projects. This modelling activity is not related to the identification of projects for a selection or to assign a PCI status. Instead it aims to quantify some benefits of socioeconomic, technical and environmental nature provided by the realisation of realised and planned gas and electricity PCIs projects. To this end recently realised and future PCI projects where grouped in two separate lists for power and gas and simulations of the current and future electricity and gas systems were conducted.

(1) Articles 170-172 TFEU
(2) The three thematic areas include Smart Grids Deployment, Electricity Highways and Cross-border Carbon Dioxide Network (https://ec.europa.eu/energy/topics/infrastructure/trans-european-networks-energy_en)
(3) From the Commission website, priority corridors and documentation consulted at https://ec.europa.eu/energy/topics/infrastructure/trans-european-networks-energy_en
(4) https://ec.europa.eu/energy/topics/infrastructure/projects-common-interest/key-cross-border-infrastructure-projects_nl

2 Methodology

The Current and future European Power & Gas systems are modelled by the JRC using METIS in two time-horizons, the current (2020) and the mid-term future (2030). The scenario setup in each time horizon was designed to provide insights on how the PCI projects currently commissioned or under construction, as well as those currently on the full 4th list will affect the European Power and Gas systems. A baseline (which acts as the counterfactual scenario) and two TEN-E scenarios (a current and a future) were created.

2.1 Scenario input

The baseline power system setup for 2020 is based on the "current context" scenario [1], updated with the power generation fleets at the start of 2020 and the actual time-series for electricity demand, solar and wind availability of 2019.

The baseline 2030 power system is modelled based on the generation fleet projections in the European Commission's EUCO3232.5[5] scenario [2] which emulates an energy system capable of achieving the energy efficiency target of 32.5% and the renewable energy target of 32%, as agreed in the "Clean energy for all Europeans package" for 2030. Interconnection capacity ratings equal to the Net Transfer Capacity (NTC) of the respective physical cross-border line values used by the model to connect neighboring zones, are based on the TYNDP 2018 2027 reference grid [3]. The above parameters are adjusted to reflect the implementation of the PCI project lists considered for the 2020 and 2030 timeframes.

The PCI project list considered in the 2020 timeframe includes all projects under construction with an expected commissioning date in 2020, for which a cross-border impact, in terms of NTC values has been quantified by ENTSO-E. The respective list for the 2030 timeframe includes all projects in the 4th PCI list with a commissioning date no later than 2030. The two lists with project details are provided in Annex 2, Table 22 - 21. Table 1 below provides an overview of the project lists considered here.

Table 1. PCI project list summary

Type	PCI list	Type	Added Capacity	CAPEX (million EUR)	OPEX (million EUR/y)
Power	Commissioned (PCIc)	Interconnection	10.4 – 12.3 GW	7301	62
	4th list (PCIf)	Interconnection	36.7 – 37.8 GW	28447	230
	4th list (PCIf)	Storage	8.5 GW	6422	142.5
Gas	Commissioned (PCIc)	Interconnection	52 GW	1954	39
		LNG	4.4 GW	208	4,2
	4th list FID (PCI fid)	Interconnection	105.7 GW	5245	105
		Storage	3.5 GW	88	1
		LNG	13 GW regas	27,3	0,6
	4th list all (PCI all)	Interconnection	293 GW	21064	421
		Storage	10 GW	646	13
		LNG	36.3 GW	2443	49

Source: JRC 2021

The already commissioned project list (PCIc) consist of transmission line upgrades with positive impact on cross border capacity (NTC), totaling more than 10 GW, requiring investment in the order of magnitude of EUR 7 billion. The 4th PCI list (projects due in the current decade) are expected to create four times as much additional cross-border capacity with an estimated budget exceeding EUR 28 billion. In addition to the transmission upgrades the 4th PCI list includes 13 storage projects totaling 8.5GW generation capacity.

Table 2 provides an overview of the scenarios designed for the METIS power system model, and those for the METIS gas system model. The set-up was coordinated by ENER, aligning, to the extent possible, the input parameters used in this study and by the analysis developed by REKK [4].

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

Table 2. Scenarios

Scenario	Current (2020)	Future (2030)
METIS Power system model		
Baseline power	Current power system without PCIc	METIS EUCO32325 without PCIc and PCIf
TEN-E	Baseline + PCIc	Baseline + PCIc
(F)TEN-E	N/A	TEN-E + PCIf
METIS Gas system model		
Baseline gas	Current gas system without PCIc	Gas METIS EUCO32325 without PCIc
TEN-E gas	Current gas system including PCIc	Gas METIS EUCO32325 PCI fid
(F)TEN-E gas		Gas METIS EUCO32325 PCI all
Security of Supply gas	Disruption UA corridor + high gas demands	Disruption UA corridor + high gas demands

Source: JRC 2021

Where:

- PCIc: PCI projects with a commissioning date no later than 2020
- PCIf; PCI projects with a commissioning date after 2020 and no later than 2030
- PCI fid: from the 4th PCI list, the gas projects with final investment decision (FID)
- PCI all: the full set of the gas projects in the 4th list

2.2 The model

The METIS model is a tool designed to provide quick robust insight on complex energy related questions, focusing on the short-term operation of the energy system and markets [5]. Each node in the model represents a country and can be linked to other zones via interconnectors. Exchanges of energy between nodes are limited by interconnector's predetermined fixed capacity. The simulation consists of optimising the operation of the system assets over a year, at a user-defined time step while minimizing the overall cost of the system to maintain supply/demand equilibrium in each node. The optimisation problem is linear and is solved over an entire year using a rolling horizon approach. A detailed description of the model is available in [6].

The power system is modelled with an hourly time step. The power plants are represented as fleets of similar technological characteristics. In METIS, units of the same technology or using the same fuel in each zone are bundled together into the same asset in a cluster model which simulates the dynamic constraints and starting costs in a relaxed (LP) unit commitment, without using binary variables.

The gas system/market is modelled with a daily time step. The model structure defined by Artelys for gas[6] market contexts has been maintained, while parameters and constraints describing the market/technological components were updated as follows:

- Gas production: production potentials defined for 2020 scenarios are based on ENTSO-G studies[7] and EUROSTAT[8], while the input parameters for 2030 are consistent with the policy scenario EUCO32325[9].
- Gas pipelines: cross-border interconnection capacities are consistent with the model JRC model GEMFLOW, updated with ENTSO-G information and specific input provided by DG ENER.
- Underground Gas storages: country-level parameters as storage maximum volumes, withdrawal and injection rates and inventory levels are taken from the AGSI+ webpages[10].
- LNG regasification and liquefaction terminals: the sources for the characterization of global liquefaction capacity allocated to EU comes from GIINGL and IHS Waterborne. Information on LNG regasification from ALSI.

(6) METIS Gas Module documentation is available at https://ec.europa.eu/energy/sites/default/files/documents/t7_-_metis_gas_module.pdf

(7) Winter maximum production potential are quantified by ENTSO-G, consulted at https://www.entsog.eu/sites/default/files/entsog-migration/publications/sos/Annex%20II%20-%20National%20Production.xlsx and

(8) For the characterization of monthly constraints we adopted historical gas statistics by Eurostat (available at https://ec.europa.eu/eurostat/databrowser/view/nrg_cb_gasm/default/table?lang=en

(9) EUCOs scenarios available at https://ec.europa.eu/energy/data-analysis/energy-modelling/euco-scenarios_en

(10) Underground gas storage data accessed at https://agsi.gie.eu/#/

- Gas demands. Total demands of natural gas on daily bases from 2019 are used to model the 2020 scenarios. Various sources of data complement each other to define the full set of model regions in METIS (TSOs transparency platforms, ENTSO-G and EUROSTAT[11])

2.3 The climate effect in the scenarios

The operation of energy systems is intrinsically affected by weather conditions [7]. With the introduction of more renewable resources, this weather-induced variability, which acts on the supply and demand balance is expected to increase further and will affect both generator income and end consumer prices. The 2030 power system scenarios in the present study were executed for a wide range of climatic conditions (in this case 21 climate years) in order to assess the effect of this variability on the results and in particular the benefits offered by PCI projects to the European energy system. Details of the datasets used to simulate the climate effect within the METIS model are provided in Annex 1.

Since the counterfactual scenarios (Baseline and TEN-E) involved less transmission and generating capacity compared to the initial EUCO3232.5 scenario, the simulations in these two scenarios revealed some scarcity hours in a few countries, which in reality would be mitigated through appropriate local generation investment. In order to account for this we calibrated these two scenarios for the median climatic year, by optimising peak generation capacity. This calibration was deemed necessary as otherwise the benefits of the PCI projects could be overestimated, due to a significant improvement of the adequacy indicators. Table 3 provides the estimated additional peaking capacity to align adequacy in the median climatic year across scenarios.

Table 3. Additional peaking capacity

Scenario (2030)	Additional peaking capacity (MW)	Estimated CAPEX (million EUR/yr)
Baseline	9 600	480
TEN-E	5 900	290

Source: JRC 2021

2.4 Limitations of the modelling

In order to make the problem tractable (EU and seven neighbouring countries at an hourly time-step) requires some compromises or limitations, the most important of which are listed below:

- One node per country. Effects of PCI projects in relieving internal bottlenecks cannot be assessed. For national large systems in gas, for example, transmission system operators may decide on strategies to redispatch volumes selecting to allocate more pressure to specific areas. Local use of compression or local restrictions on unused capacities cannot be seen as the model aggregated at a country level. The spatial granularity simplifies the technology detail to better capture the economic structure (size of market areas in both on wholesale power and gas markets).
- Static representation of the transmission grid with NTCs. This approach does not model the detailed technical constraints of the transmission system.
- Linear representation of power plant technical constraints. Power plants in each node are grouped in two to three classes based on their technological advancement. This simplification required to make the problem tractable may not capture in full detail the cycling effects and costs of power plants.
- The indirect benefits of projects on the rest of the economy deriving from income/substitution effects (lower gas/electricity prices have consequences on consumer budget constraints both for industry and households). The welfare changes calculate by the model refer strictly to the functioning of the markets, but without general equilibrium, no intersectoral implications are modelled).
- Limited representation of demand-side response. Demand response is currently only considered in providing reserves.
- The approach quantifies two snapshots of the impacts to provide values for a cost-benefit exercise. The time span of the modelling in METIS is one year, so every transition of process taking gradually place is simplified, adopting for the period 2020-2030 the annual benefits generated by the modelling of the 2020 energy system, while the period after 2030 through the results of the 2030 scenarios. This implies that while the investment and operative costs are allocated to a realistic point in time, the allocation of the benefits can be postponed with effects of underestimation of the present value of the net benefits.

(11) LNG terminal data accessed at https://alsi.gie.eu/#/ and monthly data for gross inland consumption by Eurostat available at https://ec.europa.eu/eurostat/databrowser/view/nrg_cb_gasm/default/table?lang=en

2.5 Selected indicators

To quantify the differences between the analysed scenarios we have used the indicators summarized in Table 4 throughout the report.

Table 4. Description of the indicators

Indicator	Description
Marginal costs	The marginal cost is the incremental cost of generating electricity in the system in a given zone and in a specific moment. The average marginal cost is defined here as the average of all hourly values during the year for each zone. Whenever the average cost is computed for multiple zones (e.g. EU) a weighted average, using annual electricity demand as weight, has been used.
Price divergence	The price divergence for a simulated zone is defined as the ratio between the standard deviation and the weighted average of the marginal costs
Transmission usage	Transmission usage is defined as a ratio, expressed as a percentage, between the total electricity flow on a transmission line and its capacity.
Congestion hours	A line is defined congested if its usage in a specific hour is above 99.9%. In this report, the congestion hours are calculated on the entire simulated year (8 760 time steps).
Yearly trade	This index defines the total amount of electricity exports and imports in a group of zones. The sum considers the flows for each zone among the considered countries and with the neighbours.
CO_2 emissions	Annual emissions from power generation
Curtailment	Curtailed renewable generation in one year in TWh
Welfare	The sum of consumer surplus, producer surplus and half the congestion rent for the power transmission lines connected to each zone. It is reported as change imparted by the introduction of PCIs and is expressed in million EUR.

Source: JRC 2021

3 Power system results

3.1 Current system 2020

As specified in Section 2, the current system is modelled with two infrastructure setups:

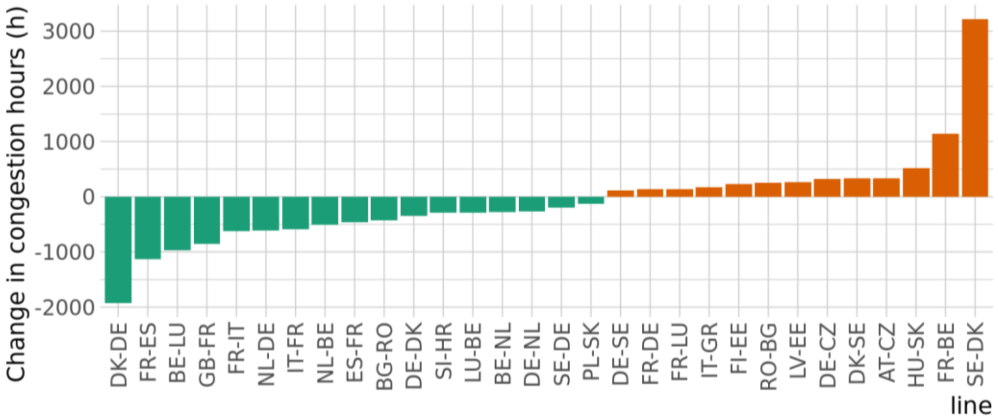
1. Baseline: with no PCI projects,
2. TEN-E: with the PCI projects commissioned by 2020

The following paragraphs provide a comparison of the power system results in the 2020 baseline configuration and TEN-E configurations.

3.1.1 Market integration

The difference between TEN-E and baseline on the congestion of the interconnectors is mixed, as the Figure 1 indicates. The number of congestion hours drops at cross-border interconnections where upgrades take place. It can also be observed that these projects, while removing the identified bottlenecks, create conditions for this to propagate upstream or downstream. Such is the case of SE-DK-DE.

Figure 1. Change (TEN-E minus Baseline) in congestion hours in 2020

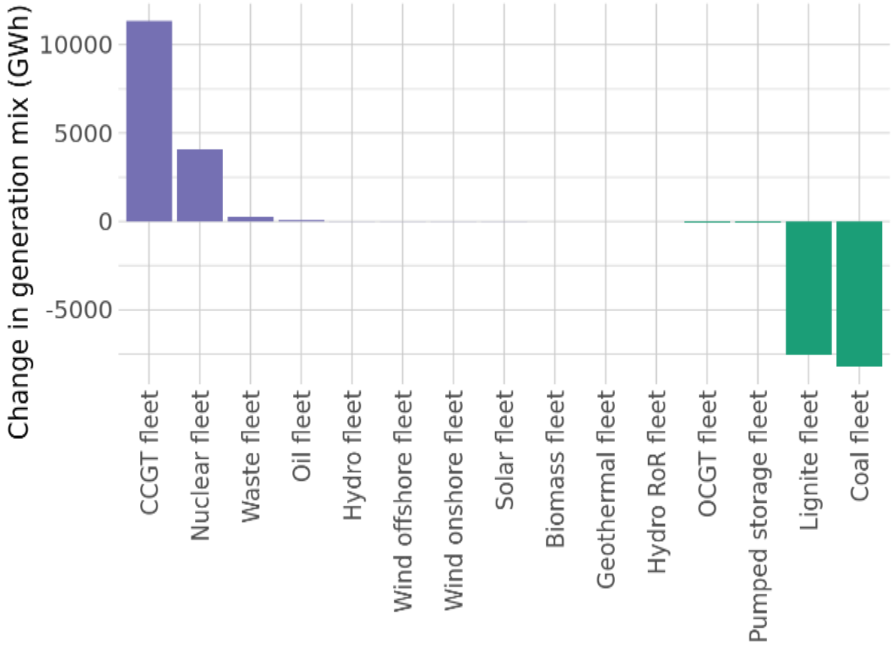


Source: JRC 2021

3.1.2 Power plant operation

The upgraded capacity (NTCs) of the interconnectors allow a less expensive fuel mix which includes more generation from CCGTs and nuclear instead of lignite and coal-fired generation.

Figure 2. Difference in the EU plus UK generation between the TEN-E and baseline scenario in 2020

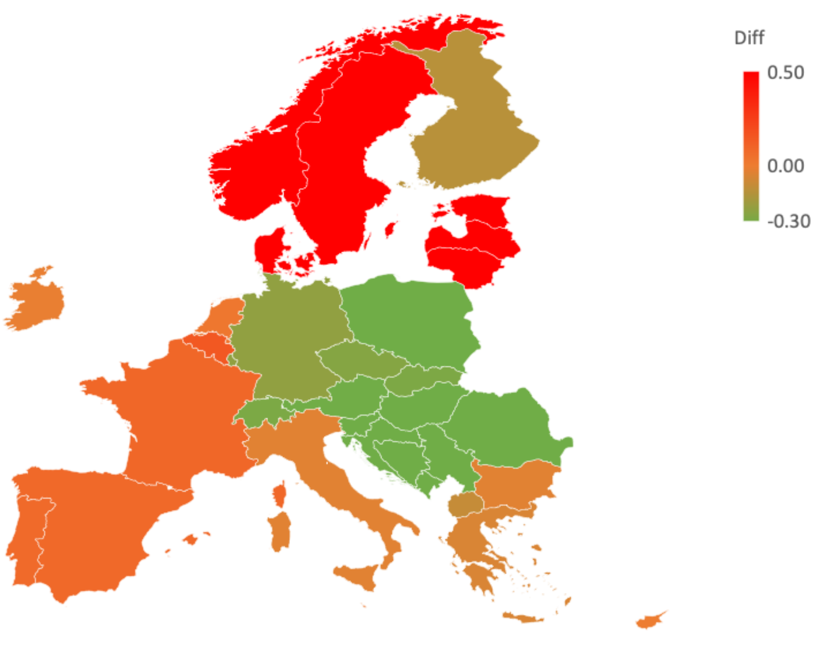


Source: JRC 2021

3.1.3 Marginal cost

The impact of the commissioned PCIs on the average marginal cost is negligible. The map in Figure 3 details country specific changes in the simulated values marginal costs. Marginal prices in the Nordic area (Denmark, Sweden, and Norway) and the Baltics are affected upwards by the DK-DE interconnection upgrades.

Figure 3. Average marginal costs changes in TEN-E vs Baseline in 2020



Source: JRC 2021

Table 5 summarises the values at the EU+UK level. A decrease in the standard deviation of the average marginal cost reveals the positive effect of the commissioned PCI projects on the interzonal price convergence.

Table 5. Marginal electricity costs: average and standard deviation across EU and UK

EU and UK	Baseline	TEN-E	delta
Average (EUR/MWh)	47.3	47.7	+0.4
Load Weighted Avg (EUR/MWh)	47.1	47.1	+0.0
Std. Dev. (EUR/MWh)	3.8	3.3	-0.5
Price Divergence (Weighted)	8.7%	7.5%	-1.2

Source: JRC 2021

3.2 Future system 2030

The future system is modelled with three infrastructure setups, as outlined in section 2.1, namely:

1. The Baseline: with no PCI projects,
2. The TEN-E: with only the PCI projects commissioned by 2020
3. The (F)TEN-E: with all electricity PCI projects (commissioned projects and the ones in the 4th list)

As previously explained in paragraph 2.3, we simulated the future system under a set of varying climatic conditions, affecting the availability of renewable resources. In this section we provide a comparison of the power system results across the 3 configurations for one representative climate year. This year was identified as the one where the climatic conditions for wind, solar and inflow were closest to the median values. The selected "median year" is based on weather conditions observed in 2013.

3.2.1 Security of supply

The PCI projects have a very positive effect on the calculated security of supply indicators. The modelled impact on Loss of load hours and Expected energy not served is provided in Table 6. The 12 hours of loss of load that we see in the Baseline are distributed among seven countries, with only France and Poland with values above 1 hour (respectively 3 and 4 hours). However, all loss of load disappears after the introduction of the 4th list PCIs in the (F)TEN-E scenario.

Table 6. Impact on loss of load indicators

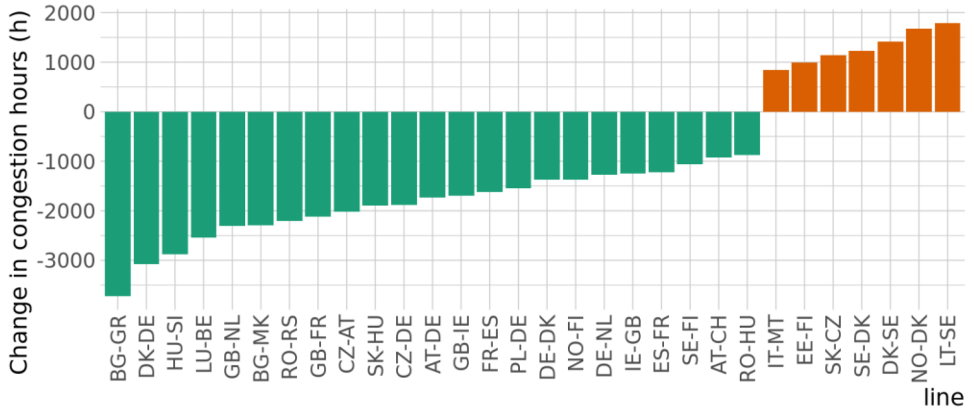
Indicator (Sum of all nodes)	Baseline	TEN-E	(F)TEN-E
Loss of Load (LoL) hours	12h	10h	0h
Expected energy not served (EENS)	16.6 GWh	10.4 GWh	0 GWh

Source: JRC 2021

3.2.2 Market integration

Our analysis shows that the PCI project lists are expected to significantly relieve congestions on cross-border interconnections. Comparing the Baseline with F(TEN-E), the average number of congested hours on all interconnectors (in the EU&UK area) decrease by 14.9%, from 2 581 to 2 197 hours. Figure 4 provides the 30 out 99 cross-border interconnections most affected and the difference imparted by the PCI projects.

Figure 4. Change in Interconnector congestion hours in 2030 comparing (F)TEN-E and Baseline for EU and UK. The change is calculated only on the interconnections defined in both the scenarios.



Source: JRC 2021

Modelling results indicate that already commissioned and future 4th list PCI projects investments could enable the increase of cross-border trade by more than 30%. Net total exchanges (export and imports) could increase overall by 357 TWh as indicated in Table 7.

Table 7. Impact on exchanges in EU&UK

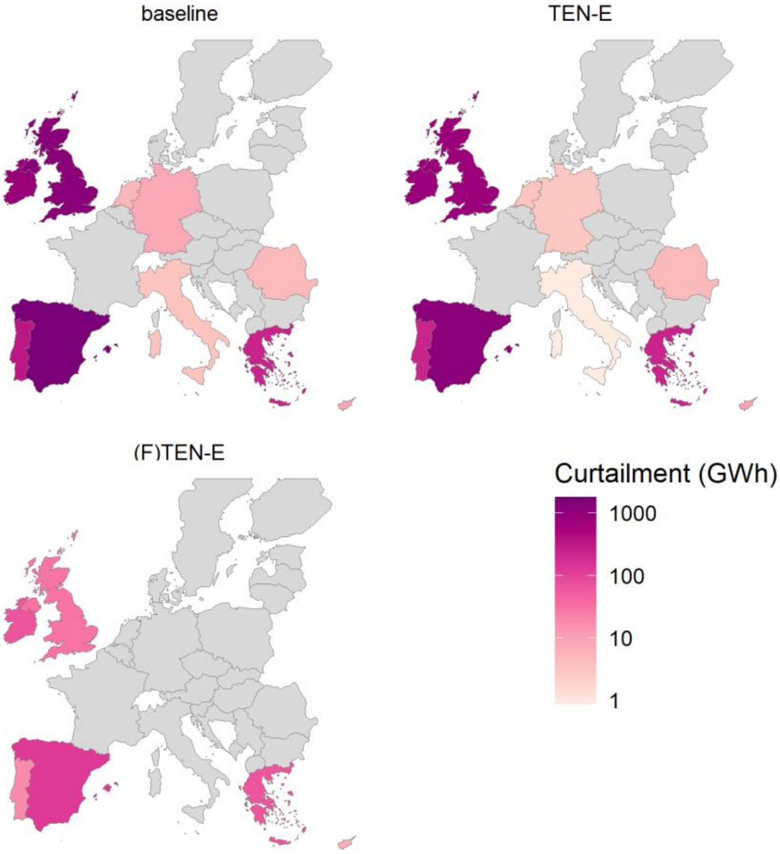
	Baseline	TEN-E	(F)TEN-E
Net Exports (TWh)	481	542	660
Net Imports (TWh)	483	544	661

Source: JRC 2021

3.2.3 Curtailment

In the F(TEN-E) scenario a significant reduction of curtailment, particularly of onshore wind is observed. Figure 5 maps the curtailment of all renewable generation in the three scenarios. The highest benefit is expected in UK & Ireland and the Iberian Peninsula. In the former region, the TEN-E scenario can potentially reduce curtailment by 406 GWh (-20.3%) and the F(TEN-E) by 1 904 GWh (-95%). In the latter, the reduction is 715 GWh (-34%) and 1 962 GWh (-93%) respectively.

Figure 5. Curtailment in the future setups in 2030



Source: JRC 2021

Modelling results indicate that the commissioned PCI projects by 2020 (TEN-E scenario) have the capacity to reduce the amount of curtailed renewable generation in all the regions compared to the baseline scenario by 1.1 TWh (-26%). The realization of all PCI projects leads to a reduction by 4.1 TWh (-93%). A breakdown of the calculated curtailment reduction per type of resource is provided in Table 8.

Table 8. Difference in curtailment per technology (GWh)

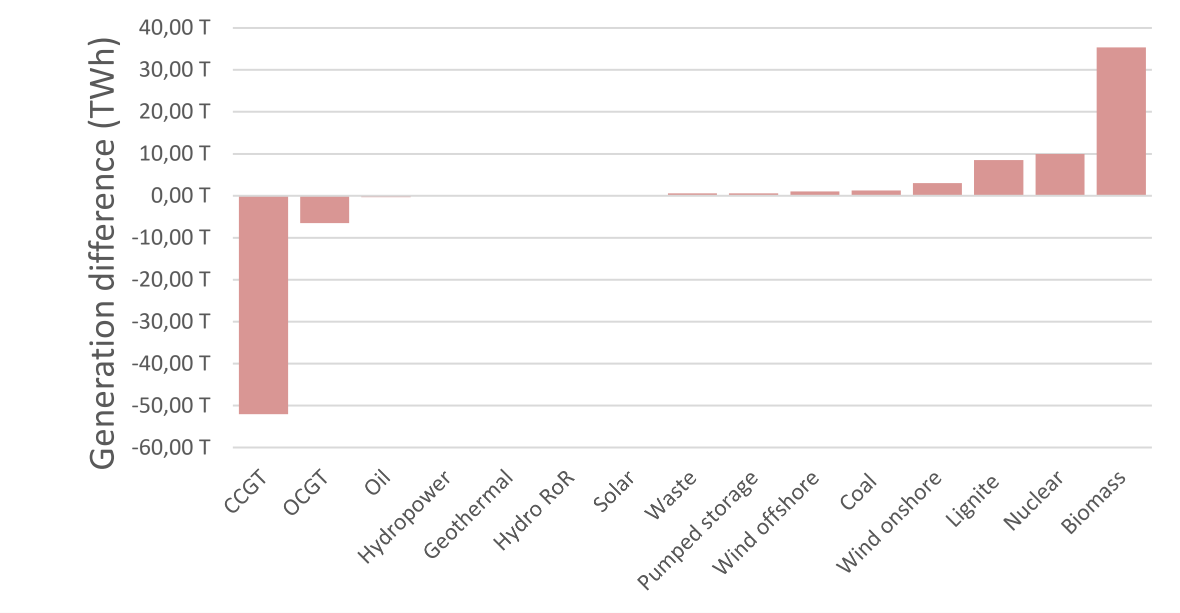
Type	(F)TEN-E – TEN-E	(F)TEN-E – baseline
Hydro RoR fleet	0	0
Solar fleet	0	0
Wind offshore fleet	-748	-1 029
Wind onshore fleet	-2 187	-3 037
Total	-2 935	-4 067

Source: JRC 2021

3.2.4 Generation

The upgraded transmission capacity of the interconnectors and the additional 8.5 GW of storage capacity allow a more optimal fuel mix which includes more generation from coal and lignite (in the EUCO3232.5 coal is before gas in the merit order), nuclear and wind (through less curtailment). Expensive OCGT operation is also reduced, further improving costs. The change in the generation fuel mix enabled by the already constructed and 4th list projects is visualized in Figure 6.

Figure 6. Difference in the EU plus UK generation between the (F)TEN-E and Baseline



Source: JRC 2021

3.2.5 Marginal cost

Marginal costs show a clear reduction with the (F)TEN-E scenario. The marginal-cost-related indicators for each 2030 setup are provided in Table 9. The price divergence decrease is largely attributed to the relief of congestions and is an indication of increased market integration.

Table 9. Marginal cost average (EUR/MWh), price divergence and standard deviations across EU and UK

	Baseline	TEN-E	(F)TEN-E
average	70.4	71.5	68.7
average (weighted)	70.8	71.7	69
std. dev.	9.34	8.95	3.36
Price divergence (weighted)	13.2%	12.5%	4.86%

Source: JRC 2021

3.3 Indicators across scenarios and climate years

Table 10 summarises the results of our analysis related to the benefits provided by already commissioned and 4th list PCI projects to the power system in 2020 and 2030. The indicators provided reflect impact on cross-border trade and transmission usage, the wholesale price, renewable curtailment and CO_2 emissions.

Table 10. Summary of indicators for electricity for EU and UK

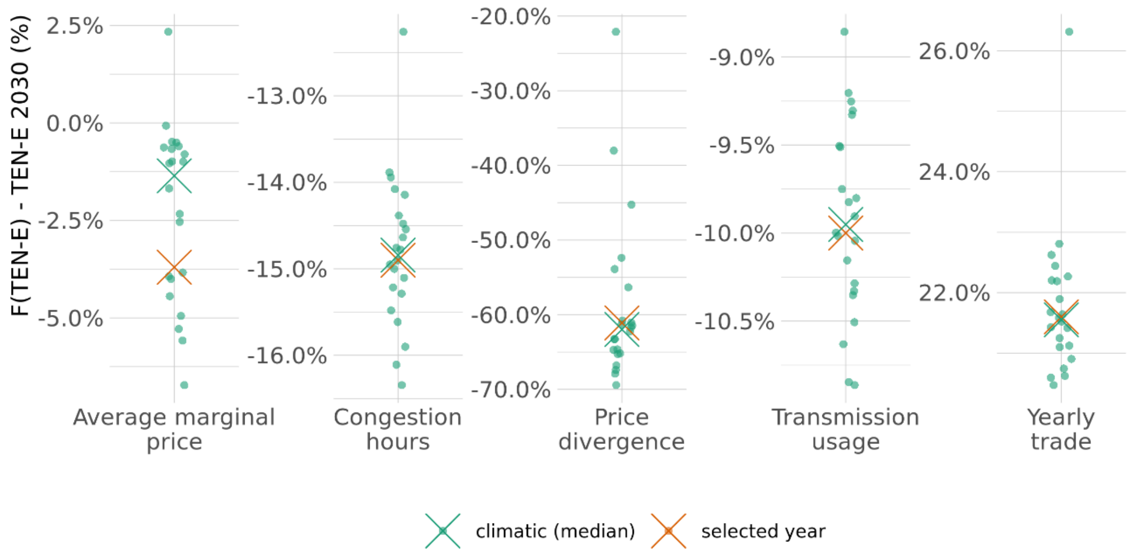
	2020 TEN-E - Baseline	2030 TEN-E - Baseline	2030 F(TEN-E) – TEN-E	2030 F(TEN-E) – Baseline
Change in number of congestion hours (%)	-1.6%	0%	-14.9%	-14.9%
Change in total yearly trade (%)	+16.9%	+12.7%	21.6%	37.1%
Overall transmission usage (%)	-0.06%	+0.2%	-10%	-9.8%
Change in average wholesale electricity generation price (%)	+0.1%	1.2%	-3.7%	-2.5%

Price divergence change (%)	-2.7%	-5.3%	-61.1%	-63.1%
Reduction in energy curtailment (TWh/year)	-26.1 GWh	-1.13 TWh	-2.93 TWh	-4.07 TWh (IB : -1.64 TWh)
Change in CO_2 emissions	-12.6	-3.6 (-9.5)[a]	-9.3 (-19.2)[a]	--12.9 (-28.8)[a]-
Change in congestion charges	46	101	-2 681	-2 583

Source: JRC 2021

The effect of different climate years on power demand, wind, solar and water availability (affecting hydropower output) was assessed with METIS, providing the variation of the calculated indicators. Figure 7 provides the range of values of the KPI indicators based on the using 21 climate years. The red mark denotes the KPI value reported in Table 10 (that is the representative year used for the current analysis of 2030), while the green mark is the median of the 21 climatic years. The positions of the red marks in the climatic scenario range of values verify that the positive impact of the PCIs is to a large extent representative of the entire distribution. This is in line with the results reported in paragraph 3.4.3 on the welfare change.

Figure 7. KPIs variation across 21 climatic years. The green cross represents the median value of the climatic years and red cross shows instead the KPIs computed on the "median" year used as representative year.



Source: JRC 2021

3.3.1 Sensitivity of 2030 results on the gas price

The effect of the gas price was assessed through a version of the EUCO3232.5 scenario with significantly lower gas price (16.8 EUR/MWh). This change affects the merit order in the day-ahead market, placing gas-fired generation before coal. The consequence of this change is a higher CO_2 abatement potential as provided in Table 11.

Table 11. Change in CO_2 emissions in a low gas price scenario (million tonnes)

	2030 (F)TEN-E – TEN-E	2030 (F)TEN-E – Baseline
Change in CO_2 emissions (million tonnes)	-19.2	-28.8

Source: JRC 2021

The potential for CO_2 reduction more than doubles in a low gas price scenario (19.2 vs 8.1 million tons) by the 4th PCI list projects, while it almost triples (28.8 vs 10.2 million tons) when all electricity PCI projects are considered.

3.3.2 Climatic year effect on adequacy indicators

Table 12 provides the EU plus UK total hours with loss of load averaged over the 21 climate years.

Table 12. Impact on loss-of-load indicators as an average of 21 climate years

Indicator	Baseline	TEN-E	(F)TEN-E
Loss of Load average	21.6h	14.1h	2.4h
Loss of Load max	94h	64h	31h
EENS average	44.8 GWh	29.7 GWh	9.3 GWh
EENS max	474.1 GWh	315.6 GWh	151.4 GWh

Source: JRC 2021

3.4 Benefits vs costs

3.4.1 Welfare

The impact on welfare for the EU and UK is positive for the electricity PCI projects lists in 2020 and 2030. The calculated welfare increase (see Table 13) in 2020 for the already commissioned projects is calculated at EUR 195 million. This figure rises to EUR 851 million in 2030. The additional welfare increase brought about by the electricity PCI projects in the 4th list is EUR 1 728 million.

Table 13. Welfare indicator change (million EUR) for EU + UK

Year	Scenario	Consumer surplus	Producer surplus	Congestion rent	Welfare
2020	TEN-E – baseline	-41	190	46	195
2030	TEN-E – baseline	-3 245	3 994	102	851
2030	(F)TEN-E – TEN-E	15 207	-11 069	-2 410	1 728
2030	(F)TEN-E-baseline	11 962	-7 075	-2 308	2 579

Source: JRC 2021,

3.4.2 Sensitivity of 2020 results on the price of CO_2 allowances (EUAs)

A sensitivity check of the 2020 results on the CO_2 costs reveals that a higher CO_2 price would lead to an overall welfare increase of EUR 60 million per year. A significant redistribution of the benefits between consumers and producers and a higher congestion rent imply a higher usage of interconnectors.

Table 14. Welfare indicators in the high CO_2 price vs the base case (million EUR)

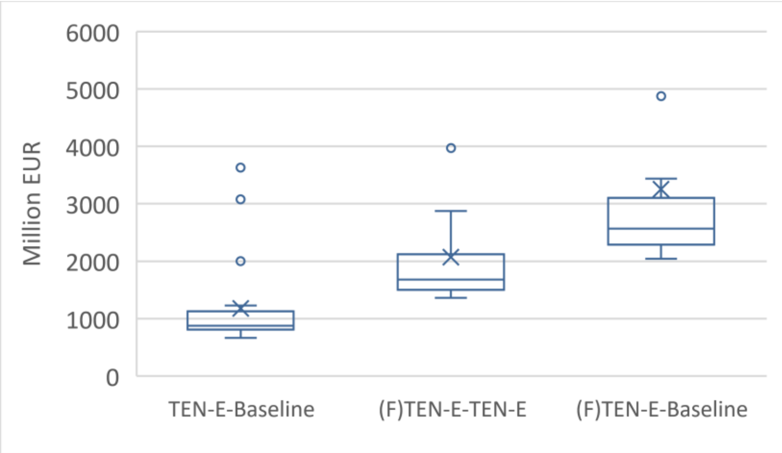
Year	CO_2 cost	Consumer surplus	Producer surplus	Congestion rent	Welfare
2020	19.7 EUR/ton (base)	-41	190	46	195
2020	25 EUR/ton (sensitivity)	72	70	114	256

Source: JRC 2021

3.4.3 Welfare sensitivity on climate

Table 15 provides the variation of the calculated welfare change attributed to the 4th list (future) PCI projects in 2030 across 21 climate years. The single-year results reported in Table 13 (EUR 1 728 million) while the average value of the welfare increase is somewhat higher (EUR 2 087 million). Figure 8 provides the range of values for the three project setups in 2030 across the 21 climate years.

Figure 8. Welfare indicator variation across climatic years



Source: JRC 2021

Table 15. Welfare change of the (F)TEN-E vs TEN-E across 21 climate years (million EUR)

	Median year	Sum of Welfare change EU & UK	Sum of Welfare change ALL
Average	1 728	2 087	2 162
Median	1 728	1 696	1 740
min	1 728	1 360	1 437
max	1 728	6 547	6 196

Source: JRC 2021

3.4.4 Cashflow analysis

Throughout this analysis PCI projects are classified in two groups (commissioned and 4th list) and assessed in two time-frames, 2020 and 2030. Table 16 lists the total investment and OPEX cost associated with the two groups as well as the period in which their commissioning takes place. The two groups consisting of projects and their union (All) are assessed with regard to their cost vs benefit relationship. The benefit is identified as the welfare increase provided in the previous paragraph plus the estimated avoided cost of peaking capacity identified in paragraph 2.3. The cost-benefit indicators are calculated for each group based on cashflows generated over the commissioning period (defined in Table 16) plus 24 years (after the commissioning year of the last project) for each group.

Table 16. Investment groups considered

No	Project group	Total investment (million EUR)	Total OPEX (million EUR)	Commissioning period	Modelled year
1	Commissioned	7 300	62	2016-2020	2020, 2030
2	4th list	34 870	373	2021-2030	2030
3	All	42 170	435	2016-2030	2030

Source: JRC 2021

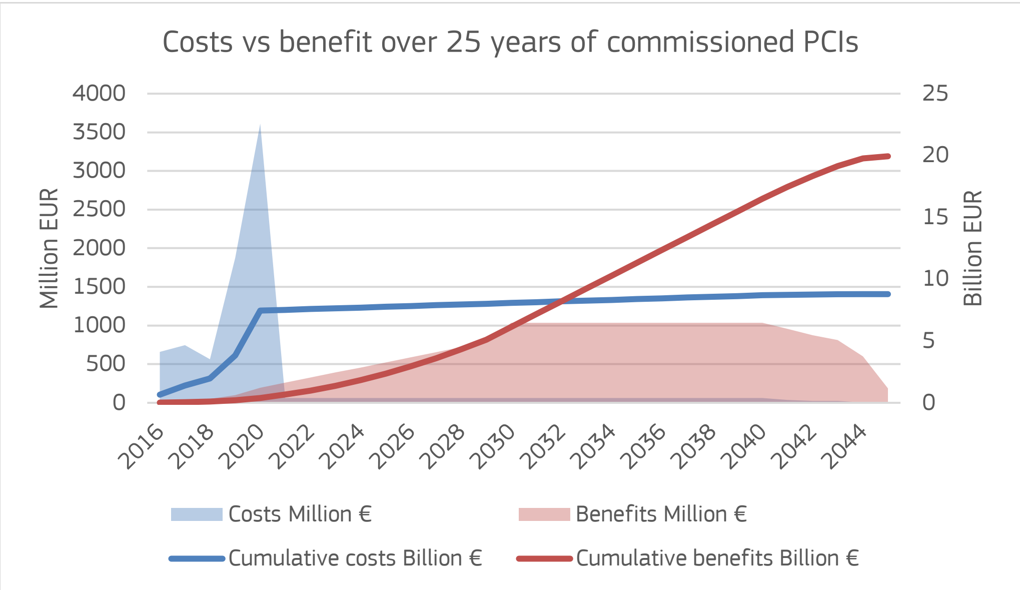
The following assumptions are used in order to enable the comparison of all projects and groups on an equal basis:

- The investment cost is considered as "overnight cost" in the commissioning year of the project
- The OPEX cost is considered fixed for 25 years including the commissioning year
- The welfare increase attributed to each project group after the end of the commissioning period is maintained fixed and equal to the welfare increase calculated for the last year of the commissioning period.
    - For each group the benefit after the last modelled year (2030) is constant and equal to welfare increase calculated for 2030.
    - For each group the benefit during the commissioning period (see Table 16) is proportionally increased according to the cumulative investment, up to the modelled welfare increase in the last year of the commissioning period (EUR 195 million for the 1st group, EUR 1.73 billion for the 2nd group and EUR 2.58 billion for the 3rd group)
    - For the 1st group (commissioned projects) the welfare increase is available over the two horizons (2020 & 2030). Therefore only for this group's assessment the welfare in the years between 2020 and 2030 is linearly interpolated between the two welfare values (195 and EUR 851 million).
    - The peaking capacity cost is introduced in 2030 as an additional benefit to the welfare increase and is maintained constant over the considered timeframe.

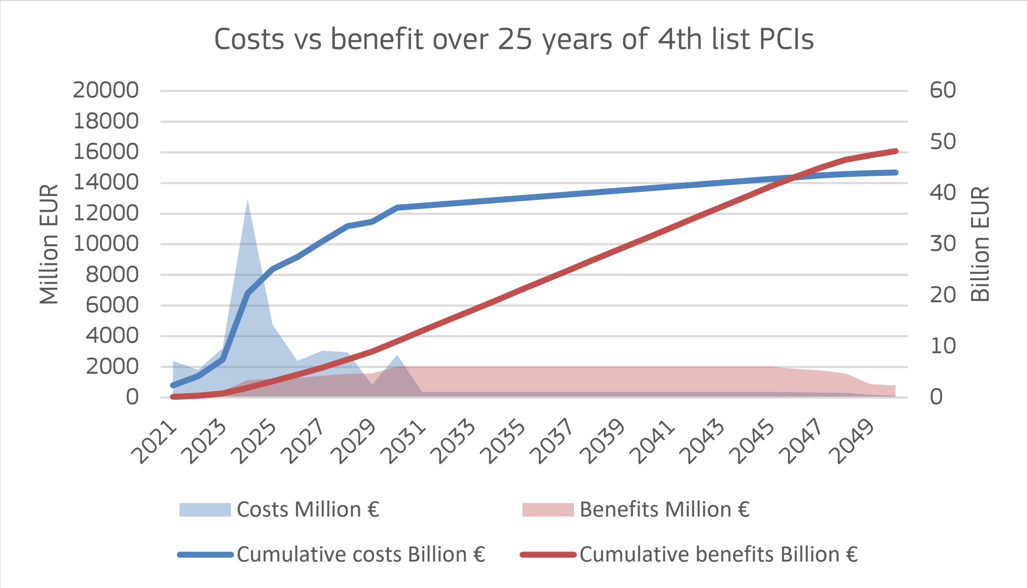
Simplified cashflows generated for the three project groups are illustrated in Figure 9. The blue-shaded area corresponds to the investment and annual OPEX, while the red-shaded area corresponds to the benefit based on the welfare increase computed by the model. The blue and red lines provide the cumulative cost and benefits respectively.

Figure 9. Investment and OPEX vs benefit of constructed projects for 25 years for the (a) commissioned PCIs, (b) the 4th list PCIs and (c) all.

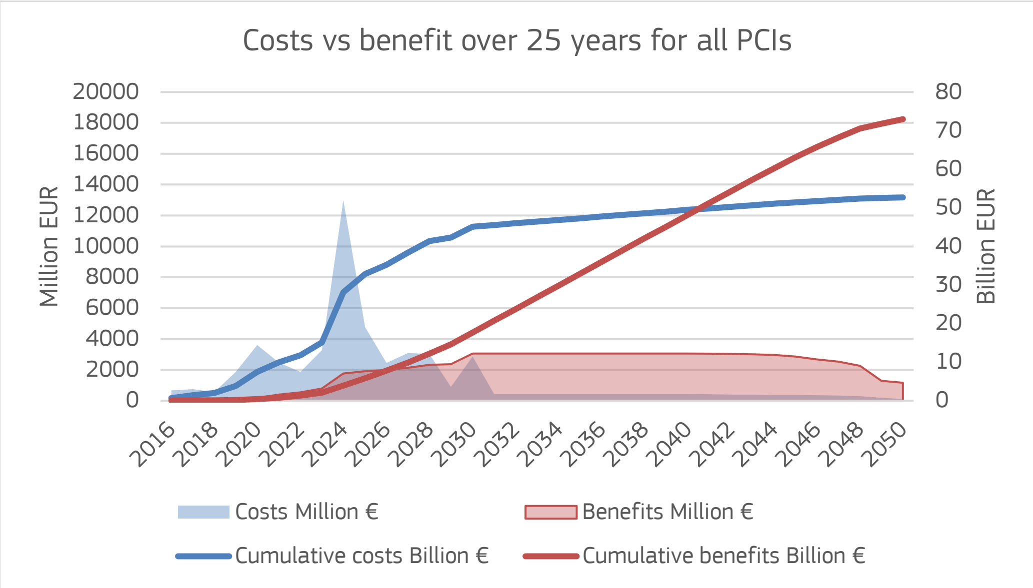
(a)



(b)



(c)



Source: JRC 2021

Table 17 provides the indicators derived from the cashflows of the three PCI project groups over a 25-year period, as illustrated in the figures above.

Table 17. Cost - benefit indicators

Indicator	Commissioned	4th liist	All
NPV (million EUR)	3 150	-7 300	-1 409
IRR	7.1%	1.4%	3.6%
NPV benefits (million EUR)	10 271	26 651	33 524
NPV costs (million EUR)	7 121	33 951	34 933
benefit/cost ratio	1.44	0.78	0.96

Source: JRC 2021

The above results indicate that the infrastructure projects considered in the present analysis are of high value to the Power system, and that this benefit is expected to increase during their lifetime as we move towards a more renewables-driven power system. In particular, in 2020, the year of completion of the commissioned PCIs, the calculated welfare increase is EUR 195 million . This figure quadruples to over 800 million a decade later. Their assessment over a 25-year period yields a benefit to cost ratio of 144%.

A similar pattern can be expected for the 4th list PCI projects. The assessment of the impact of these projects over the existing system (with the already commissioned PCIs) yields a benefit to cost ratio below unity. This is attributed to the fact that the benefit is based on welfare calculations for 2030, that is within the first 5 years of the lifetime of these projects. The anticipated benefits, like those calculated for the commissioned projects, are very likely to be more prominent in the years after the modelling timeframe of the present assessment, as more renewable capacity is gradually introduced to the EU energy mix. Therefore, we can safely assume while the current assessment captures the benefits of the already commissioned projects, it falls short of fully capturing the benefits of PCI projects belonging to the 4th list.

4 Gas system results

In this section we report a summary of results of the analysis of 2020 and 2030 scenarios for gas. The METIS gas market model, is used to provide monetary values as input for the cost-benefit tests, applied to different sets of gas PCI inititatives. These sets are incrementally enlarging the scope of the cost-benefits, repeated three times on these three groups:

- a set of gas PCIs already commissioned in 2020. This provide estimates of welfare change for the cost-benefit that are used to represent the welfare effects starting from the year 2020;
- a larger set including the previous, plus the gas PCIs that are already having a positive Final Investment Decision (FID). This set is assessed with regard to the year 2030.
- the full 4th list of gas PCIs.

Box A: Welfare change under the expected utility framework

The exercise developed in this chapter follows the standard approach presented by Atkinson and Mourato in OECD (2018). It is adapted to the case of gas infrastructures.
Under a deterministic economic approach to the evaluation of projects, suppose that a project provides an uncertain net benefit in cash terms of NB. Suppose also that the background level of income, Y, is also uncertain. I.e., it is not known how rich society will be when the net benefits arrive. The current value of additional welfare at a particular point in time with the project is given by its expected utility:

$$E[U(Y_{pci} + NB_{pci})] \quad [1]$$

and expected utility without the project, with the reference system (ref) is given by:

$$E[U(Y_{ref}) \quad [2]$$

The welfare change associated with implementation of a set of projects (pci) is specified as difference between the two corresponding expected values of utility, :

$$\Delta w = E\left[U\left(Y_{pci} + NB_{pci}\right)\right] - E\left[U\left(Y_{ref}\right)\right] \quad [3]$$

The analytical framework adopted makes use of METIS Gas model to provide monetary values of Δw that are derived from point values of consumer surplus, producer surplus, and congestion rent nder a detailed technoeconomic characterisation of the full EU system. By assuming a sum of these surpluses as a monetary realization of the function U, we compute in METIS a full year of infrastructure usage, under specific set of exogenous assumptions. The two most interesting exogenous factors, for the case of investment in gas transmission infrastructures, are

- the severity of the winter, that drives the temporal distribution of the demand profiles, and
- adverse events to the system, as disruption of other components of the gas system.

As a generalisation of the [3] we can specify an overall sum of expected net benefits of a set of projects under a set of mutually exclusive conditions, as follows:
An aggregate expected welfare change becomes:

$$\Delta W = p_A \Delta w_A + p_B \Delta w_B + \ldots + p_Z \Delta w_Z \quad [4]$$

Where $p_a, p_{b,} etc.$ are joint probabilities, assessing the likelihood of each specific set of exogenous assumptions.

The analysis consists of three steps, each of them incrementally adding a group of PCI projects to the one considered in the previous step. First the commissioned projects. In the second block the Commissioned and the FID gas PCIs. In the last is added the full 4th list of gas PCIs.
The impact of the deployment of sets of projects is based on the following comparisons:

- 2020 commissioned gas PCIs vs 2020 Baseline
- 2030 commissioned gas PCIs + gas FID PCIs vs 2030 Baseline
- 2030 commissioned gas PCIs + all gas projects in the 4th list of PCIs

For each of the comparisons the value of monetary benefits derives from two components:

I. Socioeconomic benefits, as expected differences in welfare change from the comparison of the modelled scenarios, under an assumed weight (likelihood) of 95%.

II. Security of supply (SoS) benefits, as expected difference in welfare change under disruption conditions. We opted for running multiple scenarios, then grouping into three ranges the monetary benefits according to their magnitude.

The JRC crisis scenarios foresee a one-month disruption of the Ukrainian transit of natural gas to the EU, combined with some demand increases. The Box B illustrates in detail how the different assumptions on demand translate into different economic assessment of the net benefit from Securoty of Supply (SoS).

Box B: Welfare change under disruption events

The welfare change obtainable by implementing pci, in absence of any disruption and with hystorically observed gas demand profiles is specificed as follows:

$$\Delta W_{2020} = p_A \Delta w_A,$$

with

$$\Delta w_{A,pci/ref} = \left(CS_{A,pci} + PS_{A,pci} + 0.5CR_{A,pci}\right) - \left(CS_{A,ref} + PS_{A,ref} + 0.5CR_{A,ref}\right) \quad [5]$$

In parentheses, the the consumer surplus, producer surplus and of the congestrion rent entering in the welfare indicator computed by METIS (we denote the computed value as $\widetilde{w}$). For the cases with ordinary gas demand profile, the value of p is assumed at 0.95.

For the cases of disruption, we simultaneously apply as exogenous stress, a disruption in combination with a gas demand profile B, that corresponds to a higher degree of severity of weather conditions. Under a counterfactual logic, we can then express the net benefit of securoty of supply as Δw as follows

$$\Delta w_{B,pci/ref} = \left(\widetilde{w}_{pci\&crisis} - \widetilde{w}_{pci}\right) - \left(\widetilde{w}_{ref\&crisis} - \widetilde{w}_{ref}\right)$$

For each disruption scenario to be assessed, four runs are computed. The first difference identifies the impact on welfare from the disruption on the system with pcis, the difference in the second parenthesis capture the impact on the reference system as a baseline, and only h evariation in damage, i.e. the difference-in-differences is the net gain in terms of avoided financial losses.
Looking at the [4] in Box A, the set of joint probabaility $p_{B,,}, p_C, p_D$, ... are not driven by from the duration of the disruption eventm that is constant over the runs, but entirely on the gas demand profile adopted as exogenous assumption. Table 18 with results fom the cost-benefit test, specifies each likelihood levels and the relative economic benefit from security of suppply (SoS) deriving from a coprresponding winter severity.

For the 2020 runs with METIS, demand profiles representing peak consumption conditions are specified as follows:

- Demand profile A-2020 is obtained from the demands of the five years 2015-2019. For the first 90 days of the simulation the daily consumption is the maximum gas consumption among the corresponding Julian date of the five years. The remaining 9 months follow the 2019 daily demand values.

- Demand profile B-2020 is computed using two sources: the 2018 historical daily consumption data and cold winter demand data published by ENTSO-G in the Winter Supply Outlook 2018/19[12]. The computation is done by rescaling the first three months daily demand of the year 2018 such that the average daily demand of each of the three month is equal to the monthly value provided by ENTSO-G. Starting from the 1st of April, the original 2018 daily values are used.

(12) Text is available at https://www.entsog.eu/sites/default/files/2019-10/SO024-19%20Winter%20Supply%20Outlook%202019-20.pdf

- Demand profile C-2020 is based on the B except for the first two weeks. The values for those 14 days are rescaled such that the average daily demand of each one of the two weeks is equal to Week1 and respectively Week2 given in the 2 weeks cold spell / cold winter demand published by ENTSO-G in the Winter Supply Outlook 2018/192

- Demand profile D-2020 is based on the B, except for the first two days. The demands for those 2 days were replaced by the value identified as DC (design case) in the cold winter demand published by ENTSO-G in the Winter Supply Outlook 2018/19.

- Demand profile E-2020 is based on the B, except for the first two weeks. The values for those 14 days are replaced with the demands of the 14 consecutive days out of the first 90 days (of the demand of 2018) with the highest cumulated demand. This is the methodology used in the definition of a 14 days high demand employed by JRC for the GEMFLOW model.

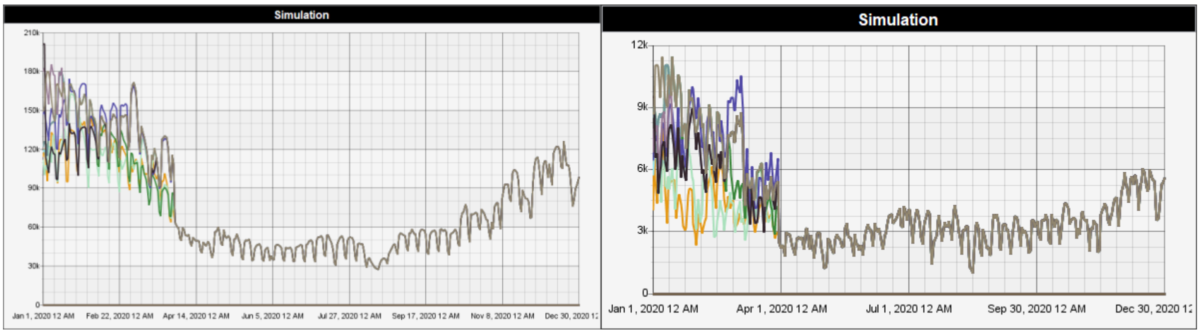
Security of supply (SoS) demand profiles for 2030 scenarios build on the EUCO3232.5 profiles, with increases applied to the first three months. We defined nine profiles, as follows:

- Demand profile A-2030: to define an increased demand level with peaks levels for winter months it combines the first three months of the A-2020 with remaining months from the EUCO32325.
- Demand profile B-2030: as the previous, combines the first three months of the B-2020 with remaining months from the EUCO32325.
- Demand profile C-2030: as the previous, combines the first three months of the C-2020 with remaining months from the EUCO32325.
- Demand profile D-2030: as the previous, combines the first three months of the D-2020 with remaining months from the EUCO32325.
- Demand profile E-2030: as the previous, combines the first three months of the E-2020 with remaining months from the EUCO32325.
- Demand profile F-2030: It assumes the historical values of the daily gas demands of 2016 for the first three months, with remaining months from the EUCO32325.
- Demand profile G-2030: It assumes the historical values of the daily gas demands of 2017 for the first three months, with remaining months from the EUCO32325.
- Demand profile H-2030: It assumes the historical values of the daily gas demands of 2018 for the first three months, with remaining months from the EUCO32325.
- Demand profile I-2030: It assumes the historical values of the daily gas demands of 2019 for the first three months, with remaining months from the EUCO32325.

4.1 Cost-benefit analysis and welfare change indicators

Socioeconomic benefits of the PCI the impacts of the deployment of the PCI on the welfare indicator computed by METIS. For the SoS benefits, four scenarios are run: two are the states of the system (baseline and PCI) with augmented demands in absence of disruption. Two others add the disruption of the Ukrainian transit to the previous ones. The SoS benefit is then evaluated as reduction of the economic cost of the crisis, computed as difference between the losses of welfare induced by the disruption.
The expected benefits are quantified by a single point value through a weighting procedure: an expected value is defined by the outcome weighted by the likelihood of the respective scenario input. As we decompose in three levels the severity of the demand conditions, the 5% likelihood assigned to SoS cases is here disentangled in three values assigned to the magnitude of the stress on the demand side: the value of likelihood assigned to the 2020 demands A,B and C is 3.625%, to the demand E a more intense stress level is associated to a lower probability (1.25%) and the last demand profile E has a value of 0.125%. Table 18 presents in detail the SoS benefits, from the raw METIS results (on the left), grouped into three levels weighted and aggregated to the point value used for the cost-benefit analysis. For the 2020, 4 out of the five SoS runs highlighted a share of unserved demand in Romania, between 0.06% and 0.2% of the total demand (between 48 and 192 hours of lost load).

Figure 12. Demand profiles for the case of Italy (left) and Greece (right), under the demand profiles used for the analysis of SoS scenarios.



Source: JRC 2021

Table 18: 2020 Commissioned PCIs - Expected benefits from SoS scenarios for the cost-benefit analysis

SoS benefits by scenario (EUR)	Stress levels	Welfare losses by level	Likelihood	Expected SoS benefits (million EUR)
111 360 509	low	117	3.625%	4.25
117 800 779	mid	250	1.250%	3.12
122 929 161	high	642	0.125%	0.80
249 951 588				
641 804 966		**Total SoS benefit (million EUR)**		**8.18**

Source: JRC 2021

2020 Commissioned gas PCIs: for this set of PCI the analysis is built on a horizon 2015-2045. Considering for each project a 25 years period for both costs and benefits, the weighted socioeconomic component results on a value of EUR 45.7 million (weighted by 95%). Security of Supply benefits provide an additional EUR 8.18 million (weighted as 5%).

Table 19: 2030 Commissioned PCI by 2020 and FID PCIs - Expected benefits from SoS scenarios for the cost-benefit analysis

SoS benefits by scenario (EUR)	Damage levels	Welfare losses by level	Likeliho od	Expected SoS benefits (million EUR)
345 550 885	low	673	3.625%	24.4
656 679 562	mid	3 785	1.250%	47.3
784 004.507	high	1 737 770	0.125%	2 172.2
907.061.735				
909 915 869				
1 812 295 022				
6 110 348 514				
6 307 169 964				
1 737 770 332 062		**Total SoS benefit (million EUR)**		**2 243.9**

Source: JRC 2021

2030 Commissioned gas PCIs + FID gas PCIs: for this set of PCI the CBA is built on a horizon 2015-2050. Considering for each project a 25 years period for both costs and benefits, the weighted socioeconomic component results on a value of EUR 204.98 million (weighted by 95%), while the Security of Supply benefits provide an additional EUR 2 243.9 million (weighted as 5%).

Under the assumption of SoS benefits with a total weight of 5%, the NPV of the analysis amounts at EUR 20 648.66 million, with a Benefit/Cost ratio of 6.73.

Table 20: 2030 Commissioned PCI by 2020 and ALL PCIs from the 4th list- Expected benefits from SoS scenarios for the CBA

SoS benefits by scenario (EUR)	Damage levels	Welfare losses by level	Likelihood	Expected SoS benefits (million EUR)
290 936 887	low	677	3.625%	24.6
656 679 562	mid	3 873	1.250%	48.4
852 478 877	high	1 738 870	0.125%	2 173.6
909 028 761				
911 209 717				
1 700 881 284				
5 829 926 619				
7 048 592 904				
1 738 870 107 765		**Total SoS benefit (million EUR)**		**2 246.5**

Source: JRC 2021

2030 Commissioned gas PCIs + all gas PCIs from 4th list: for this set of PCI the CBA is built on a horizon 2015-2050. Considering for each project a 25 years period for both costs and benefits, the weighted socioeconomic component results on a value of EUR 357.28 million (weighted by 95%), while the Security of Supply benefits provide an additional EUR 2 246.5 million (weighted as 5%).

Under the assumption of SoS benefits with a total weight of 5%, the NPV of the CBA amounts at EUR 796.05 million, with a Benefit/Cost ratio of 1.03. Table 19 offers more detail on the aggregation of results for the SoS runs.

The results indicate that adding the full list of gas PCI does not lead to a welfare increase, with respect to the FID only scenario. On the other hand, investment costs grow substantially when adding the full list, This cut the value of the benefit cost ratio, sustained by the effects captured by security of supply.

Hence, the full set of the Commissioned and all the gas PCIs from the 4th list passes the CBA tests, with a much lower contribution in terms of welfare effects. From the analysis of the three groups of projects, it emerges that only the group of FID gas PCIs clearly adds a major contribution in terms of social welfare. The SoS play a key role as driver of the overall performance in terms of benefits/cost ratio.

From the analysis of the subgroup of 2020 Commissioned gas PCIs, it emerges that this subset of projects alone would not bring a positive net present value or an adequate B/C ratio. In overall terms, the results show that the full bundle of TEN-E investments in gas infrastructures brings a positive outcome in terms of socioeconomic convenience.

4.2 Indicators for the functioning of the system and market

The indicator of *total trade* is here computer referring to the flows within EU borders among member states. This therefore excludes flows from extra EU suppliers and LNG inflows. The total trade is calculated adding imports and exports flows within the borders of the EU + UK. As the indicator is a gross amount and is double counting the flows, in the comments of specific variations on single routes. we report instead a net value of the energy trade change between two countries.

Under the 2020 scenarios, the routes with increased trade are EE-FI (+17.5 TWh), LV-EE (16.80 TWh), RO-HU (23.5 TWh) and SK-HU (46.34 TWh). The calculated total increase in trade adding up imports and exports is 186.4 TWh.

The comparison between the FID gas PCIs and the baseline foresees increases on the on the BG-GR (47.5 TWh), on the GR-IT (185.8 TWh), on the IT-AT (32.5 TWh) on the LT-PL (14.2 TWh) and on the SK-PL pipeline route (+63.7 TWh). The calculated total increase is 401.9 TWh.

2030 ALL PCI scenario: Additionally to the 2030 FID changes in trade, the implementation of the complete 4th PCI list brings increases in the following connections: SK-HU (+55.8 TWh), IT-MT (+20.44 TWh), HR-SI (+7.39 TWh), GR-IT (+239 TWh).

Overall transmission usage
Transmission usage is calculated as the ratio between the average flow and the capacity of pipelines. Averaging over the full set of pipelines in the system, the results provided for the 2020 Baseline scenario show an average of 18.5%, increasing of 0.27% under the 2020 PCI 2020 scenario.
For 2030, the Baseline value (16.5%) increases to 21.8 % under the FID PCI case, and to 20.22% under the PCI ALL scenario.

Decrease in average wholesale price (EUR/MWh)
In the analysis of the METIS model, the results for 2020 showed a limited reduction of wholesale gas prices (-0.01 Euro/MWh). Under the 2030 FID the average price lowers of 0.09 Euro/MWh and under the PCI ALL of 0.17 Euro/MWh).

Table 21. Summary indicators

Indicator for EU plus UK	Figures from the SWD	Commissioned PCIs vs Baseline 2020	FID projects vs Baseline 2030	All PCIs vs Baseline 2030
Change in total yearly trade in EU (TWh/year)	-	+93.2 TWh (186.4 accounting imports + exports)	+401.9 TWh (803.8 TWh accounting imports + exports)	+510 TWh (1020 TWh accunting for imports + exports)
Change in total yearly trade in EU (%)	-	+15.8%	+79%	+110%
Overall transmission usage (%)	-8.29% (flows btwn countries increased)	+0.27%	+4.5%	+3.6%
Decrease in average wholesale gas price (€/MWh)	-	-0.01	-0.09	-0.17
Decrease in average wholesale gas price (%)	-	-0.06%	-0.51%	-0.94%
Decrease in consumption-weighted average wholesale gas price (€/MWh)	-	-0.04	-0.07	-0.15
Price divergence change in EU28 (%)	-	-0.12%	-0.02%	-0.26%
Loss of load for a year-long disruption from main supplier	0.137 TWh (from 404 TWh)	406 TWh		

Source: JRC 2021

5 Conclusions

The impact on the power and gas systems of commissioned, under construction, and planned PCI projects was assessed with the METIS model. The modelling results point to the following conclusions regarding the impact of the electricity PCIs on the power system:

- Electricity PCI projects (both current and future) affect the market integration across the modelled area (EU plus UK, NO, CH and the western Balkans) very positively: cross-border trade increases by more than 16% in both 2020 and 2030 scenarios, while divergence of prices is reduced by about 3% in 2020 and by more than 55% in 2030.
- Security of supply is affected very positively in 2030. PCI projects can contribute to a reduction of the anticipated hours of scarcity by a factor of 10 in an average year and by a factor of 5 during an extreme year.
- Moreover our model runs show that without the PCI projects already constructed an additional 3.7 GW of peaking capacity would be required in 2030 to ensure similar adequacy indicators in the representative climatic year. This figure increases to 9.6 GW, when considering the entire PCI project list.
- Renewable curtailments are also significantly reduced. The model estimates a reduction of more than 4 TWh of curtailments, without considering the impact of projects on relieving national power system congestions.
- A positive climate benefit is also quantified. The CO_2 emissions reduction potential ranges from 10 to 29 million tonnes in 2030, depending on the fuel cost assumptions. The higher abatement values are possible in a low gas price scenario, where the added interconnections and storage enable a higher utilisation of the cheaper, less emitting gas at the expense of coal.
- The calculated welfare change is positive, ranging from EUR 195 million for 2020 to EUR 2 580 million in 2030, when considering the impact of all PCIs. The cost-benefit analysis based on this outcome and the published data on the PCI CAPEX and OPEX results in a net benefit in NPV-terms ranging from EUR 3.15 billion and a benefit-to-cost ratio of 1.44 for the PCI projects already constructed. The equivalent benefit to cost ratio for the entire project list is just below unity. The authors consider that the 2030 modelling horizon is too early to fully capture the potential benefits of these projects.
- The modelling results indicate that electricity PCI projects are of high value to the power system, and that their benefit increases during their lifetime, due to the gradual transition towards an increasingly RES-based configuration. This is particularly evident for commissioned PCI projects, whose potential to increase the system welfare increases six-fold in a decade (2020 to 2030). One limitation of the current modelling assessment is that it stops at 2030, therefore yielding conservative benefit-to-cost ratio estimates for the 4th list PCI projects over their 25-year lifetime, compared to a potential assessment extending to 2040 – a year close to the mid-life of most of these projects.
- The present study was based on the prevailing energy market conditions in 2019 (2020 scenario) and on the assumptions of the EUCO scenario for 2030. A sensitivity (for 2020) revealed that a higher ETS price of 25 EUR/t leads to a proportionaly higher wefare benefit due to already constructed PCIs. This result can be extended to support the view that with today's three times higher ETS price (74.2 EUR/t) PCI projects may well be of even higher value to the electricity system than what the current study results indicate.

The modelling exercises and the CBA on the gas PCIs allow some additional conclusions:

- The implementation of the TEN-E projects shows effects in terms of the reduction of gas market prices (-0.17 EUR/MWh or –0.98% on average for 2030).
- TEN-E gas projects would slightly contribute towards further market integration and a reduction of the wholesale gas price divergence (-0.24% in 2030).
- The deployment of the analysed projects would bring an increase in trade within EU borders, mostly based on the redirection of the flows due to the availability of new routes. Additional exchanges for pipeline gas are expected for 2030 at approximately +510 TWh.
- From the analysis of the three groups of projects, it emerges that only the group of FID gas PCIs clearly adds a major contribution in terms of social welfare.

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List of abbreviations and definitions

CAPEX	Capital expenditures
EENS	Expected energy not served
LoL	Loss of load expressed in GW or hours
NTC	Net transfer capacity
OCGT	Open cycle gas turbine
TSO	Transmission system operator
OPEX	Operating expenditures

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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 time-series 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 [8]. Temperature and wind affect the (electric-driven) space heating, while irradiation affects also the lighting needs. The time-series 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 [9, 10, 11]. 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 [12]. 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 [13]. 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 (see [7] for further details).

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 [3]. 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[13]. 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 [14].

[13] Commission Regulation (EU) 2017/2195

Annex 2. PCI projects (electricity)

Table 22. Commissioned projects with quantified cross-border impact

PCI	Name of the PCI – Electricity	Commissioning	Status	A	B	A>B (MW)	B>A (MW)	Cost (M€)
1.1.1	Interconnection between Gezelle (BE) and the vicinity of Richborough (UK)	2016	Completed	BE	UK	1000	1000	660
2.2.1 + 2.2.2	Interconnection between Lixhe (BE) and Oberzier (DE) + Internal line between Lixhe and Herderen (BE)	2020	To be completed in 2020	DE	BE	1000	1000	790
2.12	Germany — Netherlands interconnection between Niederrhein (DE) and Doetinchem (NL)	2018	Completed	DE	NL	1500	1500	220
1.5	Denmark — Netherlands interconnection between Endrup (DK) and Eemshaven (NL) [currently known as "COBRAcable"]	2019	Completed	DK_W	NL	700	700	620
1.4.1 + 1.4.2 + 1.4.3	1.4.1 Interconnection between Kassø (DK) and Audorf (DE) + 1.4.2 Internal line between Audorf and Hamburg/Nord (DE) + 1.4.3 Internal line between Hamburg/Nord and Dollern (DE)	2020	To be completed in 2020	DK_W	DE	700	1000	926
4.1	Denmark — Germany interconnection between Ishøj / Bjæverskov Tolstrup Gaarde (DK) and Bentwisch (DE) via offshore windparks Kriegers Flak (DK) and Baltic 1 and 2 (DE) [currently known as "Kriegers Flak Combined Grid Solution"]*	2019	Completed	DK_E	DE	400	400	349
3.15.1	Interconnection between Vierraden (DE) and Krajnik (PL)	2018	Completed	DE	PL	500	1500	225
4.5.1 + 4.5.5	4.5.1. LitPol Link + 4.5.5. Internal line between Kruonis and Alytus (LT)	2018	Completed	LT	PL	1000	1000	81,3

PCI	Name of the PCI – Electricity	Commissioning	Status	A	B	A>B (MW)	B>A (MW)	Cost (M€)
2.5.1	Interconnection between Grande Ile (FR) and Piossasco (IT) [currently known as "Savoie-Piemont"]	2020	completed	IT	FR	1000	1200	1260
2.6 + 2. 8	2.6. PCI Spain internal line between Santa Llogaia and Bescanó (ES) to increase capacity of the interconnection between Bescanó (ES) and Baixas (FR) + 2.8 Coordinated installation and operation of a phase-shift transformer in Arkale (ES) to increase capacity of the interconnection between Argia (FR) and Arkale (ES)	2017	Completed	FR	ES	1500	1900	720
3.22.5	Interconnection between Villanova (IT) and Lastva (ME)	2019	Completed	IT	ME	600	600	870
1.7.3	Interconnection between Coquelles (FR) and Folkestone (UK) [currently known as "ElecLink"]	2020	To be completed in 2020	FR	UK	1000	1000	580
All projects						10900	12800	7301,3

Source: JRC 2021

Table 23. 4th list PCI projects

PCI	Name of the PCI - Electricity	Commissioning	Status	A	B	A>B (MW)	B>A (MW)	Cost (M€)	OPEX (m€/y)
1.20	Interconnection between Germany and United Kingdom [currently known as NeuConnect"]	2022	Permitting	DE	UK	1400	1400	1500	22
1.6	France — Ireland interconnection between La Martyre (FR) and Great Island or Knockraha (IE) [currently known as "Celtic Interconnector"]	2026	Permitting	FR	IE	700	700	930	8,4
2.14	Interconnection between Thusis/Sils (CH) and Verderio Inferiore (IT) [currently known as "Greenconnector"]	2024	Permitting	CH	IT	850	850	609	1,9

PCI	Name of the PCI - Electricity	Commissioning	Status	A	B	A>B (MW)	B>A (MW)	Cost (M€)	OPEX (m€/y)
2.17	Portugal — Spain interconnection between Beariz — Fontefría (ES), Fontefria (ES) — Ponte de Lima (PT) (formerly Vila Fria / Viana do Castelo) and Ponte de Lima — Vila Nova de Famalicão (PT) (formerly Vila do Conde) (PT), including substations in Beariz (ES), Fontefría (ES) and Ponte de Lima (PT)	2021	Permitting	ES	PT	1900	1000	111,9	1,09
2.4	Interconnection between Codrongianos (IT), Lucciana (Corsica, FR) and Suvereto (IT) [currently known as "SACOI 3"]	2024	Permitting	IT	FR	100	100	750	7
2.7	Interconnection between Aquitaine (FR) and the Basque country (ES) [currently known as "Biscay Gulf"]	2027	Permitting	FR	ES	2200	2200	1750	10,2
3.4	Interconnection between Wurmlach (AT) and Somplago (IT)	2022	Permitting	AT	IT	150	150	92	1,6
1.3.1	Interconnection between Endrup (DK) and Klixbüll (DE)	2023	Permitting	DK_W	DE	500	500	210	2
1.7.1 + 1.7.5	1.7.1 Interconnection between Cotentin (FR) and the vicinity of Exeter (UK) [currently known as "FAB"] + 1.7.5 Interconnection between the vicinity of Dunkerque(FR) and the vicinity of Kingsnorth (UK) [currently known as "Gridlink"]	2025	Permitting	FR	UK	1400	1400	850	7,6
1.9.1	Ireland — United Kingdom interconnection between Wexford (IE) and Pembroke, Wales (UK) [currently known as "Greenlink"]	2023	Permitting	IE	UK	500	500	396	8
1.10.1 + 1.10.2	1.10.1 Interconnection between Blythe (UK) and Kvilldal (NO) [currently known as "North Sea Link"] + 1.10.2 Interconnection between Peterhead (UK) and Simadalen (NO) [currently known as "NorthConnect"]	2024	Permitting	UK	NO	1400	1400	1850	15,4
3.1.1 & 3.1.2	Interconnection between St. Peter (AT) and Isar (DE)	2028	Permitting	AT	DE	2000	2000	375	3

PCI	Name of the PCI - Electricity	Commissioning	Status	A	B	A>B (MW)	B>A (MW)	Cost (M€)	OPEX (m€/y)
3.9.1	Interconnection between Žerjavenec (HR)/ Hévíz (HU) and Cirkovce (SI)	2021	Permitting	HU	SI	1200	1200	132,5	0,12
2.13.1	Interconnection between Woodland (IE) and Turleenan (UK) [currently known as "North-South interconnector"]	2023	Permitting	IE	UK	900	950	349	0,6
3.21	Interconnection between Salgareda (IT) and Divača — Bericevo region (SI)	2028	Permitting /Under consideration	IT	SI	1000	1000	755	4
4.8.1 + 4.8.3	4.8.1 Interconnection between Tartu (EE) and Valmiera (LV) + 4.8.3 Interconnection between Tsirguliina (EE) and Valmiera (LV)	2024	Planned not yet permitting	EE	LV	0	0	1875	16,95
4.8.10	Interconnection between Lithuania and Poland [currently known as "Harmony Link"]	2025	Planned not yet permitting	LT	PL	1000	1000		
2.13.2	Interconnection between Srananagh (IE) and Turleenan (UK) [currently known as "RIDP1"]	2030	Planned not yet permitting	IE	UK	750	570	396,2	0,79
2.27.1 + 2.27.2	2.27.1 Interconnection between Aragón (ES) and Atlantic Pyrenees (FR) [currently known as "Pyrenean crossing 2"] + 2.27.2 Interconnection between Navarra (ES) and Landes (FR) [currently known as "Pyrenean crossing 1"]	2030	Planned not yet permitting	ES	FR	3000	3000	1170	6,03
1.15	Interconnection between the Antwerp area (BE) and the vicinity of Kemsley (UK) [curently known as "Nautilus"]	2028	Under consideration	BE	UK	1400	1400	1000	8
1.16	Interconnection between Netherlands and United Kingdom	2030	Under consideration	NL	UK	2000	2000	850	6
1.14	Interconnection between Revsing (DK) and Bicker Fen (UK) [currently known as "Viking Link"]	2023	Under construction	DK_W	UK	1400	1400	1970	16

PCI	Name of the PCI - Electricity	Commissioning	Status	A	B	A>B (MW)	B>A (MW)	Cost (M€)	OPEX (m€/y)
3.17 + 3.16.1	3.16.1. Interconnection Hungary – Slovakia between Gabčikovo (SK) and Gönyű (HU) and Veľký Ďur (SK) + 3-17 Interconnection Hungary – Slovakia between Sajóivánka (HU) and Rimavská Sobota (SK)	2021	Under construction	HU	SK	350	1850	82	1,48
1.8.1	Interconnection between Wilster (DE) and Tonstad (NO)	2021	Under construction	DE	NO	1400	1400	1850	15
3.7.1	Interconnection between Maritsa East 1 (BG) and N. Santa (EL)	2023	Under construction	BG	GR	1350	800	224,4	3
4.2.1	Interconnection between Kilingi-Nõmme (EE) and Riga CHP2 substation (LV)	2021	Under construction	EE	LV	479	479	200	0,8145
3.22.1	Interconnection between Resita (RO) and Pancevo (RS)	2024	Under construction	RO	RS	844	600	173	1,15
3.11.3	Internal line between Prestice and Kocin (CZ)	2029	Permitting	DE	CZ	500	500	461,95	0,08
3.11.4	Internal line between Kocin and Mirovka (CZ)	2028	Permitting	DE	CZ				0
3.1.4	Internal line between Westtirol and Zell-Ziller (AT)	2025	Under consideration	DE	AT	600	600	298,8	2,3904
3.8	Internal line between Dobrudja and Burgas (BG)	2022	Under construction	RO	BG	600	600	174	1,4
3.8	Internal line between Cernavoda and Stalpu (RO)	2022	Under construction	RO	BG				0
3.8	Internal line between Gutinas and Smardan (RO)	2024	Permitting	RO	BG				0
3.22	Internal line between Portile de Fier and Resita (RO)	2025	Under construction	RO	HU	617	335		1,15
3.11.1	Internal line between Vernerov and Vitkov (CZ)	2024	Permitting	DE	CZ	500	500	259,6	0,2016

PCI	Name of the PCI - Electricity	Commissioning	Status	A	B	A>B (MW)	B>A (MW)	Cost (M€)	OPEX (m€/y)
3.10.1	Interconnection between Hadera (IL) and Kofinou (CY)	2024	Permitting	IL	CY	2000	2000	5765	53,5
3.10.2	Interconnection between Kofinou (CY) and Korakia, Crete (EL)	2024	Permitting	GR	CY				
3.10.3	Interconnection between Korakia, Crete and Attica region	2024		GR	GR				
3.14	Internal line between Krajnik and Baczyna (PL)	2024	Under construction	DE	PL	1500	500	270,69	1,798
4.10.2	Internal line between Keminmaa and Pyhänselkä (FI)	2024		FI	SE	800	800	50	0,15
4.5.2	Internal line between Stanisławów and Ostrołęka(PL)	2024	Under construction	PL	LT	500	1000	335	1
4.4	Internal line between Ekhyddan and Nybro/Hemsjö (SE)	2025	Permitting	SE	LT	0	0	381	0,697
All projects						37790	36684	28447	230,5

Source: JRC 2021

Annex 3. NTCs in 2020 considered in the electricity TEN-E and the Baseline scenarios

Country A	Country B	2020 Baseline NTCs (MW)		2020 TEN-E NTCs (MW)	
		A => B	A <= B	A => B	A <= B
AL	GR	254	254	254	254
AL	ME	438	458	438	458
AL	MK	0	0	0	0
AL	RS	254	254	254	254
AT	CH	1200	1200	1200	1200
AT	CZ	900	800	900	800
AT	DE	4900	4900	4900	4900
AT	HU	800	800	800	800
AT	IT	335	145	335	145
AT	SI	950	950	950	950
BA	HR	1108	1000	1108	1000
BA	ME	500	500	500	500
BA	RS	600	600	600	600
BE	DE	0	0	1000	1000
BE	FR	1600	2600	1600	2600
BE	GB	0	0	1000	1000
BE	LU	680	180	680	180
BE	NL	1501	1501	1501	1501
BG	GR	688	533	688	533
BG	MK	400	100	400	100
BG	RO	575	567	575	567
BG	RS	446	308	446	308
BG	TR	700	300	700	300
CH	DE	4000	2333	4000	2333
CH	FR	1408	3227	1408	3227
CH	IT	4505	1910	4505	1910
CY	GR	0	0	0	0
CZ	DE	3200	2800	3200	2800
CZ	PL	696	1117	696	1117
CZ	SK	2100	1200	2100	1200
DE	DK	2100	1975	3500	3075
DE	FR	3000	1800	3000	1800
DE	GB	0	0	0	0
DE	LU	2300	2300	2300	2300
DE	NL	2449	2449	3949	3949
DE	NO	0	0	0	0
DE	PL	0	1000	500	2500
DE	SE	615	615	615	615
DK	PL	0	0	0	0
DK	SE	2490	1980	2490	1980
DK	GB	0	0	0	0
DK	NL	0	0	700	700

Country A	Country B	2020 Baseline NTCs (MW)		2020 TEN-E NTCs (MW)	
DK	NO	1640	1640	1640	1640
EE	FI	1016	1016	1016	1016
EE	LV	900	900	900	900
ES	FR	1628	2063	3528	3563
ES	PT	3910	4166	3910	4166
FI	NO	72	120	72	120
FI	SE	2300	2700	2300	2700
FR	IT	3486	1160	4686	2160
FR	GB	2000	2000	3000	3000
FR	IE	0	0	0	0
FR	LU	380	0	380	0
GB	IE	500	500	500	500
GB	NI	450	80	450	80
GB	NL	1076	1076	1076	1076
GB	NO	0	0	0	0
GR	IT	500	500	500	500
GR	MK	408	417	408	417
GR	TR	250	176	250	176
HR	HU	1000	1200	1000	1200
HR	RS	600	600	600	600
HR	SI	1533	1533	1533	1533
HU	RO	900	875	900	875
HU	RS	1000	1000	1000	1000
HU	SI	0	0	0	0
HU	SK	1000	1300	1000	1300
IE	NI	300	300	300	300
IT	ME	0	0	600	600
IT	SI	680	805	680	805
IT	MT	208	0	208	0
IT	TN	0	0	0	0
LT	LV	1200	1500	1200	1500
LT	PL	0	0	500	500
LT	SE	700	700	700	700
ME	RS	500	600	500	600
MK	RS	509	708	509	708
NL	NO	700	700	700	700
NO	SE	3695	3995	3695	3995
PL	SK	550	500	550	500
PL	SE	600	600	600	600
RO	RS	683	800	683	800

Source: JRC 2021

Annex 4. NTCs in 2030 considered in the electricity PCIs and the Baseline scenarios

Country A	Country B	2030 TEN-E NTCs (MW)		2030 (F) TEN-E NTCs (MW)	
		A => B	A <= B	A => B	A <= B
AL	GR	254	254	254	254
AL	ME	438	458	438	458
AL	MK	500	500	500	500
AL	RS	500	500	500	500
AT	CH	1700	1700	1700	1700
AT	CZ	1000	1200	1000	1200
AT	DE	4900	4900	7500	7500
AT	HU	1200	800	1200	800
AT	IT	900	700	1050	850
AT	SI	1200	1200	1200	1200
BA	HR	1250	1250	1250	1250
BA	ME	800	750	800	750
BA	RS	1100	1200	1100	1200
BE	DE	1000	1000	1000	1000
BE	FR	2800	4300	2800	4300
BE	GB	1000	1000	2400	2400
BE	LU	680	180	680	180
BE	NL	3400	3400	3400	3400
BG	GR	750	400	2100	1200
BG	MK	500	500	500	500
BG	RO	500	900	1100	1500
BG	RS	446	308	446	308
BG	TR	1200	500	1200	500
CH	DE	5600	3300	5600	3300
CH	FR	1408	3700	1408	3700
CH	IT	5150	2850	6000	3700
CY	GR	0	0	2000	2000
CZ	DE	3200	2800	4200	3800
CZ	PL	696	1117	696	1117
CZ	SK	2100	1200	2100	1200
DE	DK	3500	3485	4000	3985
DE	FR	4500	4500	4500	4500
DE	GB	0	0	1400	1400
DE	LU	2300	2300	2300	2300
DE	NL	5000	5000	5000	5000
DE	NO	1400	1400	2800	2800
DE	PL	500	2500	2000	3000
DE	SE	1315	1300	1315	1300
DK	PL	0	0	0	0
DK	SE	2490	1980	2490	1980
DK	GB	0	0	1400	1400
DK	NL	700	700	700	700

Country A	Country B	2030 TEN-E NTCs (MW)		2030 (F) TEN-E NTCs (MW)	
DK	NO	1700	1640	1700	1640
EE	FI	1016	1016	1016	1016
EE	LV	900	900	1379	1379
ES	FR	2200	2000	7400	7200
ES	PT	4200	4166	6100	5166
FI	NO	72	120	72	120
FI	SE	2400	2400	3200	3200
FR	IT	4400	2260	4500	2360
FR	GB	5500	5500	6900	6900
FR	IE	0	0	700	700
FR	LU	380	0	380	0
GB	IE	500	500	1000	1000
GB	NI	450	280	450	280
GB	NL	1076	1076	3076	3076
GB	NO	1400	1400	2800	2800
GR	IT	500	500	500	500
GR	MK	1200	1200	1200	1200
GR	TR	660	580	660	580
HR	HU	2000	2000	2000	2000
HR	RS	600	600	600	600
HR	SI	2000	2000	2000	2000
HU	RO	965	783	1300	1400
HU	RS	1000	1000	1000	1000
HU	SI	1200	1200	2400	2400
HU	SK	2000	2000	2350	3850
IE	NI	1250	1200	1250	1200
IT	ME	1200	1200	1200	1200
IT	SI	640	895	1640	1895
IT	MT	208	200	208	200
IT	TN	600	600	600	600
LT	LV	1200	1500	1200	1500
LT	PL	500	500	2500	2000
LT	SE	700	700	700	700
ME	RS	700	700	700	700
MK	RS	750	750	750	750
NL	NO	700	700	700	700
NO	SE	3695	3995	3695	3995
PL	SK	990	990	990	990
PL	SE	600	600	600	600
RO	RS	756	1200	1600	1800

Source: JRC 2021

Annex 5. KPI variability with climatic years

Table 24. KPI indicator variability with climate years

Min/avg/max	2030 Future TEN-E	2030 TEN-E	delta
Average number of congestion hours	2023 / 2112 / 2199	2396 / 2523 / 2601	-17.7% / -16.3% / -15.3%
total yearly trade in EU and UK	1274 / 1310 / 1356	1044 / 1078 / 1106	20.5% / 21.5% / 22.8%
Overall transmission usage (%)	30.0% / 30.9% / 31.8%	33.3% / 34.6% / 35%	-11.9% / -10.8% / -9.9%
Weighted average wholesale electricity generation price	66.5 / 69.9 / 78.4	67.7 / 78.5 / 96.5	-28.6% / -10.0% / -1.0%
Price divergence	3.6 / 6.0 / 15.7	11.3 / 19.0 / 36.6	-87.8% / -68.4% / -50.6%
Change in congestion charges			-19 663 /-8 064 /-952

Source: JRC 2021

Annex 6. Gas PCI projects assumed as completed for the 2020 scenarios

PCI	Description	From	To	GWh/d	Year
5.2	PCI Twinning of Southwest Scotland onshore system between Cluden and Brighouse Bay (United Kingdom)	GB	IE	12,1	2016
5.16	PCI Extension of the Zeebrugge LNG terminal	LNG	BE	472	2020
5.13	PCI New interconnection between Pitgam (France) and Maldegem (Belgium)	FR	BE	270	2016
5.14	PCI Reinforcement of the French network from South to North on the Arc de Dierrey pipeline between Cuvilly, Dierrey and Voisines (France)	FR	FR	-	2016
5.7.1	Val de Saône pipeline between Etrez and Voisines (FR)	FR	FR	-	2018
5.7.2	Gascogne-Midi pipeline (FR)	FR	FR	-	2018
5.11	Reverse flow interconnection between Italy and Switzerland at Passo Gries interconnection point	IT	CH	429	2018
8.1.1	Interconnection Estonia - Finland [currently known as "Balticconnector"]	EE	FI	48	2020
8.1.1	Interconnection Estonia - Finland [currently known as "Balticconnector"]	FI	EE	48	2020
8.2.3	Capacity enhancement of Klaipeda-Kiemenai pipeline in Lithuania	LT	LT	-	2016
6.3	PCI Slovakia – Hungary Gas Interconnection between Vel'ké Zlievce (SK) – Balassagyarmat border (SK/HU) - Vecsés (HU)	HU	SK	52	2015
6.3	PCI Slovakia – Hungary Gas Interconnection between Vel'ké Zlievce (SK) – Balassagyarmat border (SK/HU) - Vecsés (HU)	SK	HU	127	2015
7.1.1 (1st PCI ist)	Gas pipeline from the EU to Turkmenistan via Turkey, Georgia, Azerbaijan and the Caspian [currently known as the combination of the “Trans Anatolia Natural Gas Pipeline” (TANAP), the “Expansion of the South-Caucasus Pipeline” SCP-(F)X) and the “Trans-Caspian Gas Pipeline” (TCP)]	GE	TR	490	2018
6.5.5	Compressor station 1 at the Croatian gas transmission system	HR	HU	13,6	2019
6.24.1	6.24.1 ROHU(AT)/BRUA – 1st phase, including: - Development of the transmission capacity in Romania from Podișor to Recas, including, a new pipeline, metering station andthree new compressor stations in Podisor, Bibesti and Jupa	RO	BG	43,15	2020
5.10		CH	DE	240	2018
?	Ruse Giurgiu	RO	BG	1,6	-
		BG	RO	8	-
6.24.1	6.24.1 ROHU(AT)/BRUA – 1st phase, including: - Development of the transmission capacity in Romania from Podișor to Recas, including, a new pipeline, metering station andthree new compressor stations in Podisor, Bibesti and Jupa	RO	HU	64,50	2020

Source: JRC 2021

Annex 7. Gas projects from the full 4th PCI list

PCI	TYNDP 2020 Code	Cluster/PCI	From	To	(GWh/d)	Year	Status
5.3	LNG-A-30	5.3 Shannon LNG Terminal and connecting pipeline (IE)	LNG	IE	86,00	2022	Advanced
5.3	LNG-A-30	5.3 Shannon LNG Terminal and connecting pipeline (IE)	LNG	IE	64,00	2025	Advanced
5.3	LNG-A-30	5.3 Shannon LNG Terminal and connecting pipeline (IE)	LNG	IE	100,00	2029	Less-Advanced
5.19	TRA-A-31	5.19 Connection of Malta to the European gas network — pipeline interconnection with Italy at Gela	IT	MT	56,00	2024	Advanced
5.19	TRA-A-31	5.19 Connection of Malta to the European gas network — pipeline interconnection with Italy at Gela	MT	IT	56,00	2024	Advanced
6.2.1	TRA-F-190	6.2 Interconnection between Poland, Slovakia and Hungary with the related internal reinforcements, including the following PCIs:	SK	PL	174,59	2021	FID
6.2.1	TRA-F-190	6.2 Interconnection between Poland, Slovakia and Hungary with the related internal reinforcements, including the following PCIs:	PL	SK	143,96	2021	FID
6.2.13	TRA-N-524	6.2 Interconnection between Poland, Slovakia and Hungary with the related internal reinforcements, including the following PCIs:	HU	SK	102,00	2022	Less-Advanced
6.2.13	TRA-N-524	6.2 Interconnection between Poland, Slovakia and Hungary with the related internal reinforcements, including the following PCIs:	SK	HU	26,00	2022	Less-Advanced
6.5.1	LNG-F-82	6.5 Cluster Krk LNG terminalwith connecting and evacuation pipelines towards Hungary and beyond, including the following PCIs:	LNG	HR	109,20	2027	FID
6.5.1	LNG-F-82	6.5 Cluster Krk LNG terminalwith connecting and evacuation pipelines towards Hungary and beyond, including the following PCIs:	LNG	HR	81,50	2020	FID
6.5.1	TRA-F-90	6.5 Cluster Krk LNG terminalwith connecting and evacuation pipelines towards Hungary and beyond, including the following PCIs:	HR	HU	81,51	2020	FID
6.5.5	TRA-F-334	6.5 Cluster Krk LNG terminalwith connecting and evacuation pipelines towards Hungary and beyond, including the following PCIs:	HR	HU	13,60	2019	FID
6.8.1	TRA-F-378	6.8 Cluster of infrastructure development and enhancement enabling the Balkan Gas Hub, including the following PCIs:	GR	BG	90,00	2020	FID
6.8.1	TRA-F-378	6.8 Cluster of infrastructure development and enhancement	BG	GR	90,00	2020	FID

PCI	TYNDP 2020 Code	Cluster/PCI	From	To	(GWh/d)	Year	Status
		enabling the Balkan Gas Hub, including the following PCIs:					
6.8.1	TRA-F-378	6.8 Cluster of infrastructure development and enhancement enabling the Balkan Gas Hub, including the following PCIs:	GR	BG	60,00	2025	FID
6.8.1	TRA-F-378	6.8 Cluster of infrastructure development and enhancement enabling the Balkan Gas Hub, including the following PCIs:	BG	GR	60,00	2025	FID
6.8.2	TRA-F-298	6.8 Cluster of infrastructure development and enhancement enabling the Balkan Gas Hub, including the following PCIs:	RS	BG	19,36	2024	FID
6.8.2	TRA-F-298	6.8 Cluster of infrastructure development and enhancement enabling the Balkan Gas Hub, including the following PCIs:	BG	RS	19,36	2024	FID
6.8.2	TRA-F-298	6.8 Cluster of infrastructure development and enhancement enabling the Balkan Gas Hub, including the following PCIs:	BG	TR	58,08	2021	FID
6.8.2	TRA-F-298	6.8 Cluster of infrastructure development and enhancement enabling the Balkan Gas Hub, including the following PCIs:	BG	BG	13,78	2021	FID
6.8.3	TRA-F-137	6.8 Cluster of infrastructure development and enhancement enabling the Balkan Gas Hub, including the following PCIs:	RS	BG	51,00	2022	FID
6.8.3	TRA-F-137	6.8 Cluster of infrastructure development and enhancement enabling the Balkan Gas Hub, including the following PCIs:	BG	RS	51,00	2022	FID
6.9.1	LNG-N-62	6.9	LNG	GR	253,10	2020	Advanced
6.20.2	UGS-A-138	6.20 Cluster increase storage capacity in South-Eastern Europe, including one or more of the following PCIs:	storage	BG	48,90	2025	Advanced
6.20.2	UGS-A-138	6.20 Cluster increase storage capacity in South-Eastern Europe, including one or more of the following PCIs:	BG	Storage	51,07	2025	Advanced
6.20.3	UGS-N-385	6.20 Cluster increase storage capacity in South-Eastern Europe, including one or more of the following PCIs:	storage	GR	44,00	2023	Less-Advanced
6.20.3	UGS-N-385	6.20 Cluster increase storage capacity in South-Eastern Europe, including one or more of the following PCIs:	GR	storage	55,00	2023	Less-Advanced
6.20.4	UGS-A-233	6.20 Cluster increase storage capacity in South-Eastern Europe,	RO	Storage	18,92	2021	Advanced

PCI	TYNDP 2020 Code	Cluster/PCI	From	To	(GWh/d)	Year	Status
		including one or more of the following PCIs:					
6.20.4	UGS-A-233	6.20 Cluster increase storage capacity in South-Eastern Europe, including one or more of the following PCIs:	RO	Storage	15,78	2024	Advanced
6.20.4	UGS-A-233	6.20 Cluster increase storage capacity in South-Eastern Europe, including one or more of the following PCIs:	storage	RO	18,92	2021	Advanced
6.20.4	UGS-A-233	6.20 Cluster increase storage capacity in South-Eastern Europe, including one or more of the following PCIs:	storage	RO	15,78	2024	Advanced
6.20.6	UGS-N-371	6.20 Cluster increase storage capacity in South-Eastern Europe, including one or more of the following PCIs:	RO	Storage	34,00	2024	Less-Advanced
6.20.6	UGS-N-371	6.20 Cluster increase storage capacity in South-Eastern Europe, including one or more of the following PCIs:	storage	RO	45,00	2024	Less-Advanced
6.23	TRA-N-112	6.23 Hungary – Slovenia - Italy interconnection (Nagykanizsa (HU) — Tornyiszentmiklós (HU) —Lendava (SI) – Kidričevo (SI) – Ajdovščina (SI) – Šempeter (SI) – Gorizia (IT))	SI	HU	12,90	2023	Less-Advanced
6.23	TRA-N-112	6.23 Hungary – Slovenia - Italy interconnection (Nagykanizsa (HU) — Tornyiszentmiklós (HU) —Lendava (SI) – Kidričevo (SI) – Ajdovščina (SI) – Šempeter (SI) – Gorizia (IT))	HU	SI	12,90	2023	Less-Advanced
6.23	TRA-N-112	6.23 Hungary – Slovenia - Italy interconnection (Nagykanizsa (HU) — Tornyiszentmiklós (HU) —Lendava (SI) – Kidričevo (SI) – Ajdovščina (SI) – Šempeter (SI) – Gorizia (IT))	SI	HU	36,10	2025	Less-Advanced
6.23	TRA-N-112	6.23 Hungary – Slovenia - Italy interconnection (Nagykanizsa (HU) — Tornyiszentmiklós (HU) —Lendava (SI) – Kidričevo (SI) – Ajdovščina (SI) – Šempeter (SI) – Gorizia (IT))	HU	SI	36,10	2025	Less-Advanced
6.24.1	TRA-F-358	6.24 Cluster phased capacity increase on the (Bulgaria) — Romania — Hungary — (Austria) bidirectional transmission corridor (currently known as "ROHUAT/BRUA") to enable a capacity at the Romania-Hungary interconnection of 1.75 bcm/a in the 1stphase, 4.4 bcm/a in the 2ndphase, and including new resources from the Black Sea in the 2nd phase:	RO	HU	47,75	2020	FID
6.24.1	TRA-F-358	6.24 Cluster phased capacity increase on the (Bulgaria) —	RO	BG	43,15	2020	FID

PCI	TYNDP 2020 Code	Cluster/PCI	From	To	(GWh/d)	Year	Status
		Romania — Hungary — (Austria) bidirectional transmission corridor (currently known as "ROHUAT/BRUA") to enable a capacity at the Romania-Hungary interconnection of 1.75 bcm/a in the 1stphase, 4.4 bcm/a in the 2ndphase, and including new resources from the Black Sea in the 2nd phase:					
6.24.4	TRA-A-1322	6.24 Cluster phased capacity increase on the (Bulgaria) — Romania — Hungary — (Austria) bidirectional transmission corridor (currently known as "ROHUAT/BRUA") to enable a capacity at the Romania-Hungary interconnection of 1.75 bcm/a in the 1stphase, 4.4 bcm/a in the 2ndphase, and including new resources from the Black Sea in the 2nd phase:	HU	RO	78,12	2022	Advanced
6.24.4	TRA-A-1322	6.24 Cluster phased capacity increase on the (Bulgaria) — Romania — Hungary — (Austria) bidirectional transmission corridor (currently known as "ROHUAT/BRUA") to enable a capacity at the Romania-Hungary interconnection of 1.75 bcm/a in the 1stphase, 4.4 bcm/a in the 2ndphase, and including new resources from the Black Sea in the 2nd phase:	RO	HU	75,88	2022	Advanced
6.26.1	TRA-A-86	6.26	HR	SI	40,76	2021	Advanced
6.26.1	TRA-A-86	6.26	SI	HR	162,00	2023	Advanced
6.26.1	TRA-A-86	6.26	HR	SI	121,24	2023	Advanced
6.26.1	TRA-N-361	6.26	AT	SI	105,20	2023	Less-Advanced
6.26.1	TRA-N-361	6.26	SI	AT	166,50	2023	Less-Advanced
6.26.1	TRA-N-390	6.26	HR	SI	121,24	2023	Less-Advanced
6.26.1	TRA-N-390	6.26	HR	SI	40,76	2021	Less-Advanced
6.26.1	TRA-N-390	6.26	SI	HR	162,00	2023	Less-Advanced
6.27	LNG-N-947	6.27 LNG Gdansk (PL)	LNG	PL	138,00	2025	Less-Advanced
7.1.1	TRA-A-339	7.1 PCI Cluster of integrated, dedicated and scalable transport infrastructure and associated equipment for the transportation of a minimum of 10 bcm/a of new sources of gas from the Caspian	TM	AZ	505,00	2023	Advanced

PCI	TYNDP 2020 Code	Cluster/PCI	From	To	(GWh/d)	Year	Status
		Region, crossing Azerbaijan, Georgia and Turkey and reaching EU markets in Greece and Italy, and including the following PCIs:					
7.1.1	TRA-A-339	7.1 PCI Cluster of integrated, dedicated and scalable transport infrastructure and associated equipment for the transportation of a minimum of 10 bcm/a of new sources of gas from the Caspian Region, crossing Azerbaijan, Georgia and Turkey and reaching EU markets in Greece and Italy, and including the following PCIs:	TM	AZ	505,00	2022	Advanced
7.1.1	TRA-N-1138	7.1 PCI Cluster of integrated, dedicated and scalable transport infrastructure and associated equipment for the transportation of a minimum of 10 bcm/a of new sources of gas from the Caspian Region, crossing Azerbaijan, Georgia and Turkey and reaching EU markets in Greece and Italy, and including the following PCIs:	GE	TR	150,70	2024	Less-Advanced
7.1.3	TRA-F-51	7.1 PCI Cluster of integrated, dedicated and scalable transport infrastructure and associated equipment for the transportation of a minimum of 10 bcm/a of new sources of gas from the Caspian Region, crossing Azerbaijan, Georgia and Turkey and reaching EU markets in Greece and Italy, and including the following PCIs:	TR	GR	350	2020	FID
7.1.3	TRA-F-51	7.1 PCI Cluster of integrated, dedicated and scalable transport infrastructure and associated equipment for the transportation of a minimum of 10 bcm/a of new sources of gas from the Caspian Region, crossing Azerbaijan, Georgia and Turkey and reaching EU markets in Greece and Italy, and including the following PCIs:	GR	TR	331	2020	FID
7.1.3	TRA-F-51	7.1 PCI Cluster of integrated, dedicated and scalable transport infrastructure and associated equipment for the transportation of a minimum of 10 bcm/a of new sources of gas from the Caspian Region, crossing Azerbaijan, Georgia and Turkey and reaching EU markets in Greece and Italy, and including the following PCIs:	GR	IT	509	2020	FID

PCI	TYNDP 2020 Code	Cluster/PCI	From	To	(GWh/d)	Year	Status
7.1.3	TRA-F-51	7.1 PCI Cluster of integrated, dedicated and scalable transport infrastructure and associated equipment for the transportation of a minimum of 10 bcm/a of new sources of gas from the Caspian Region, crossing Azerbaijan, Georgia and Turkey and reaching EU markets in Greece and Italy, and including the following PCIs:	GR	AL	40	2020	FID
7.1.3	TRA-F-51	7.1 PCI Cluster of integrated, dedicated and scalable transport infrastructure and associated equipment for the transportation of a minimum of 10 bcm/a of new sources of gas from the Caspian Region, crossing Azerbaijan, Georgia and Turkey and reaching EU markets in Greece and Italy, and including the following PCIs:	IT	GR	158	2020	FID
7.3.1	TRA-A-330	7.3 PCI Cluster infrastructure to bring new gas from the East Mediterranean gas reserves, including:	CY	GR	110,00	2025	Advanced
7.3.1	TRA-A-330	7.3 PCI Cluster infrastructure to bring new gas from the East Mediterranean gas reserves, including:	GR	CY	30	2025	Advanced
7.3.3	TRA-A-10	7.3 PCI Cluster infrastructure to bring new gas from the East Mediterranean gas reserves, including:	IT	GR	160	2022	Advanced
7.3.3	TRA-A-10	7.3 PCI Cluster infrastructure to bring new gas from the East Mediterranean gas reserves, including:	GR	IT	250	2025	Advanced
7.5	LNG-A-1146	7.5 Development of gas infrastructure in Cyprus [currently known as "Cyprus Gas2EU"]	LNG	CY	40	2022	Advanced
8.2.1	TRA-A-342	8.2 Cluster infrastructure upgrade in the Eastern Baltic Sea region, including the following PCIs:	LV	LT	54	2023	Advanced
8.2.1	TRA-A-342	8.2 Cluster infrastructure upgrade in the Eastern Baltic Sea region, including the following PCIs:	LT	LV	63	2023	Advanced
8.2.4	UGS-F-374	8.2 Cluster infrastructure upgrade in the Eastern Baltic Sea region, including the following PCIs:	storage	LV	84,00	2019	FID
8.2.4	UGS-F-374	8.2 Cluster infrastructure upgrade in the Eastern Baltic Sea region, including the following PCIs:	LV	Storage	8,50	2025	FID
8.3.1	TRA-A-394	8.3 Cluster infrastructure, including the following PCIs:	NO	DK	306,80	2022	Advanced
8.3.2	TRA-A-271	8.3 Cluster infrastructure, including the following PCIs:	PL	DK	91,10	2022	Advanced

PCI	TYNDP 2020 Code	Cluster/PCI	From	To	(GWh/d)	Year	Status
8.3.2	TRA-A-271	8.3 Cluster infrastructure, including the following PCIs:	DK	PL	306,80	2022	Advanced
8.5	TRA-F-212	8.5 Poland-Lithuania interconnection [currently known as "GIPL"]	LT	PL	58,30	2021	FID
8.5	TRA-F-212	8.5 Poland-Lithuania interconnection [currently known as "GIPL"]	PL	LT	73,90	2021	FID

Source: JRC 2021

Annex 8. Entry/Exit tariffs and capacities for pipeline interconnections

Pipeline identification	Capacity [MW]	Entry tariff [Euro/MWh]	Exit tariff [Euro/MWh]
AT->DE	13,938	0.69	0.58
AT->HU	6,379	0.46	0.19
AT->IT	47,867	0.88	0.78
AT->SI	9,071	0.46	0.56
AT->SK	10,271	0.43	0.19
AZ->TR	26,696	0.00	0.00
BE->DE	12,063	0.66	0.26
BE->FR	25,833	0.33	0.25
BE->GB	33,475	0.00	0.00
BE->LU	2,033	0.00	0.00
BE->NL	16,375	0.27	0.18
BG->GR	11,127	0.00	0.00
BG->MK	849	2.37	1.10
BG->RO	329	0.59	0.73
BG->RS	19,398	0.00	0.00
BG->TR	22,295	0.01	0.33
BY->LT	13,558	0.58	1.00
BY->PL	50,029	0.58	1.00
CH->DE	7,200	0.69	0.41
CH->FR	4,167	0.43	0.41
CH->IT	26,475	0.87	0.41
CZ->DE	46,051	0.60	0.50
CZ->PL	1,167	1.04	0.78
CZ->SK	51,946	0.43	0.53
DE->AT	15,083	0.22	0.67
DE->BE	16,688	0.15	0.66
DE->CH	13,614	0.41	0.69
DE->CZ	77,534	0.13	0.61
DE->DK	6,938	0.53	0.63
DE->FR	25,238	0.43	0.69
DE->LU	1,600	0.02	0.69
DE->NL	20,967	0.27	0.61
DE->PL	15,826	1.04	0.57
DK->DE	3,792	0.63	0.85
DK->SE	3,667	0.00	0.00
DZ->ES	30,488	0.53	0.10
DZ->IT	47,929	1.64	0.20
EE->FI	2,000	0.00	0.00
EE->LV	0	0.00	0.00
ES->FR	9,350	0.43	0.98
ES->PT	6,000	0.39	0.98
FI->EE	2,000	0.00	0.00
FR->BE	11,250	0.00	0.00
FR->CH	10,850	0.41	1.02
FR->ES	6,875	0.53	2.54
GB->BE	27,154	0.00	0.00
GB->IE	19,842	0.00	0.00
GR->AL	1,667	0.00	0.00
GR->BG	8,189	0.70	1.06

Pipeline identification	Capacity [MW]	Entry tariff [Euro/MWh]	Exit tariff [Euro/MWh]
GR->IT	31,625	0.00	0.00
GR->TR	13,792	0.00	0.00
HR->HU	3,963	0.00	0.00
HR->SI	13,821	0.11	0.61
HU->HR	3,263	1.12	0.51
HU->RO	5,426	0.59	0.51
HU->RS	5,917	0.86	0.51
HU->SK	6,417	0.00	0.00
HU->UA	8,625	0.55	0.51
IT->AT	8,054	0.13	0.13
IT->CH	18,413	0.41	0.40
IT->GR	13,250	0.00	0.00
IT->MT	2,333	0.00	0.00
IT->SI	1,179	0.34	0.89
LT->LV	5,436	0.58	0.42
LT->PL	2,429	0.00	0.00
LV->EE	2,625	0.00	0.00
LV->LT	4,980	0.58	0.58
LY->IT	20,792	1.54	0.00
MT->IT	2,333	0.00	0.00
NL->BE	33,118	0.15	0.38
NL->DE	25,488	0.65	0.38
NL->GB	20,583	0.00	0.00
NO->BE	20,333	0.13	1.20
NO->DE	79,344	0.64	1.20
NO->FR	23,750	0.38	1.20
NO->GB	62,463	0.00	0.00
NO->NL	40,167	0.27	1.20
PL->DE	38,817	0.57	0.58
PL->LT	3,079	0.00	0.00
PL->SK	5,998	0.00	0.00
PL->UA	5,650	0.55	0.64
PT->ES	3,333	0.53	0.09
RO->BG	32,273	0.48	0.78
RO->HU	7,818	0.46	0.78
RO->MD	1,755	1.36	0.78
RO->UA	16,659	0.00	0.00
RS->BA	749	0.16	2.43
RS->BG	2,932	0.00	0.00
RU->DE	108,875	0.55	1.15
RU->EE	1,488	0.58	1.00
RU->FI	9,167	1.58	1.00
RU->LV	7,438	0.58	0.20
RU->TR	74,050	0.01	0.00
RU->UA	317,507	0.00	0.00
SI->AT	6,938	0.00	0.00
SI->HR	15,738	1.12	0.29
SI->HU	2,042	0.00	0.00
SI->IT	892	0.85	0.54
SK->AT	65,433	0.13	0.94
SK->CZ	16,683	0.31	0.77
SK->HU	6,374	0.00	0.00

Pipeline identification	Capacity [MW]	Entry tariff [Euro/MWh]	Exit tariff [Euro/MWh]
SK->PL	7,275	0.00	0.00
SK->UA	17,333	0.55	0.94
TR->BG	24,042	0.61	0.30
TR->GR	16,608	0.91	0.30
UA->HU	21,525	0.46	1.15
UA->MD	5,699	1.36	0.85
UA->PL	5,650	1.04	0.20
UA->RO	46,421	0.00	0.00
UA->SK	94,900	0.68	0.20

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