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Interaction gas-electricity toolbox

Identifying and quantifying the interaction gas-electricity

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Contents

Abstract

Regulation (EU) No 2017/1938 on the Security of Gas Supply introduces the concept of critical gas-fired power plants which can be designated by Member States of the European Union to be prioritised over certain categories of protected customers during gas supply crises when curtailment of gas customers is unavoidable. This report aims at identifying all possible interaction mechanisms between gas and electricity systems, providing a checklist to support EU Member States for correctly addressing the interaction gas-electricity within risk assessments. Further, the report aims at developing a set of indicators that could be used to identify and quantify the interaction gas-electricity in different Member States of the European Union, in particular the criticality of gas-fired power plants in the sense of Reg. (EU) No 2017/1938. These indicators help to understand the interaction gas-electricity within the European Union on a high level and to screen it for regions in which the interdependency gas-electricity is of increased relevance. Such regions arguably deserve further attention by application of more sophisticated analysis tools.

Foreword

This report is part of the Administrative Arrangement "Support to the implementation of the new Regulation (EU) No 2017/1938 on Security of Gas Supply, repealing Regulation 994/2010)" (acronym: RSGS III). It aims at identifying all possible ways gas and electricity infrastructures could depend on each other, and at developing a set of indicators that could be used to identify and quantify the interaction gas-electricity in different Member States of the European Union and in particular the criticality of gas-fired power plants in the sense of Reg. (EU) No 2017/1938. A preceding literature review was an important first step and feeds directly into this and upcoming deliverables. In a later deliverable, a full methodology will be proposed with which regions with large interdependency gas-electricity identified using this toolbox can be analysed in more detail with advanced modelling techniques.

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1 Introduction

Regulation (EU) No 2017/1938 concerning measures to safeguard the security of gas supply and repealing Regulation (EU) No 994/2010 (European Parliament and the Council, 2017) – in the following simply referred to as the Regulation – introduces the concept of critical gas-fired power plants (GFPPs) which can be designated by Member States (MSs). The critical GFPPs could be prioritised over certain categories of protected customers during gas supply crises when curtailment of gas is unavoidable. For quick reference, we show the article 11(7) and part of the article 13(1) of the Regulation concerning the criticality of the GFPPs in the text boxes 1 and 2, respectively.

Box 1. Article 11(7) of the Regulation (EU) No 2017/1938

During an emergency and on reasonable grounds, upon a request of the relevant electricity or gas transmission system operator a Member State may decide to prioritise the gas supply to certain critical gas-fired power plants over the gas supply to certain categories of protected customers, if the lack of gas supply to such critical gas-fired power plants either:

(a) could result in severe damage in the functioning of the electricity system; or

(b) would hamper the production and/or transportation of gas.

Member States shall base any such measure on the risk assessment.

Critical gas-fired power plants as referred to in the first subparagraph shall be clearly identified together with the possible gas volumes that would be subject to such a measure and included in the regional chapters of the preventive action plans and emergency plans. Their identification shall be carried out in close cooperation with transmission system operators of the electricity system and the gas system of the Member State concerned.

Box 2. Article 13(1) of the Regulation (EU) No 2017/1938

In exceptional circumstances and upon a duly reasoned request by the relevant electricity or gas transmission system operator to its competent authority, the gas supply may also continue to certain critical gas-fired power plants as defined pursuant to Article 11(7) in the Member State providing solidarity if the lack of gas supply to such plants would result in severe damage in the functioning of the electricity system or would hamper the production and/or transportation of gas.

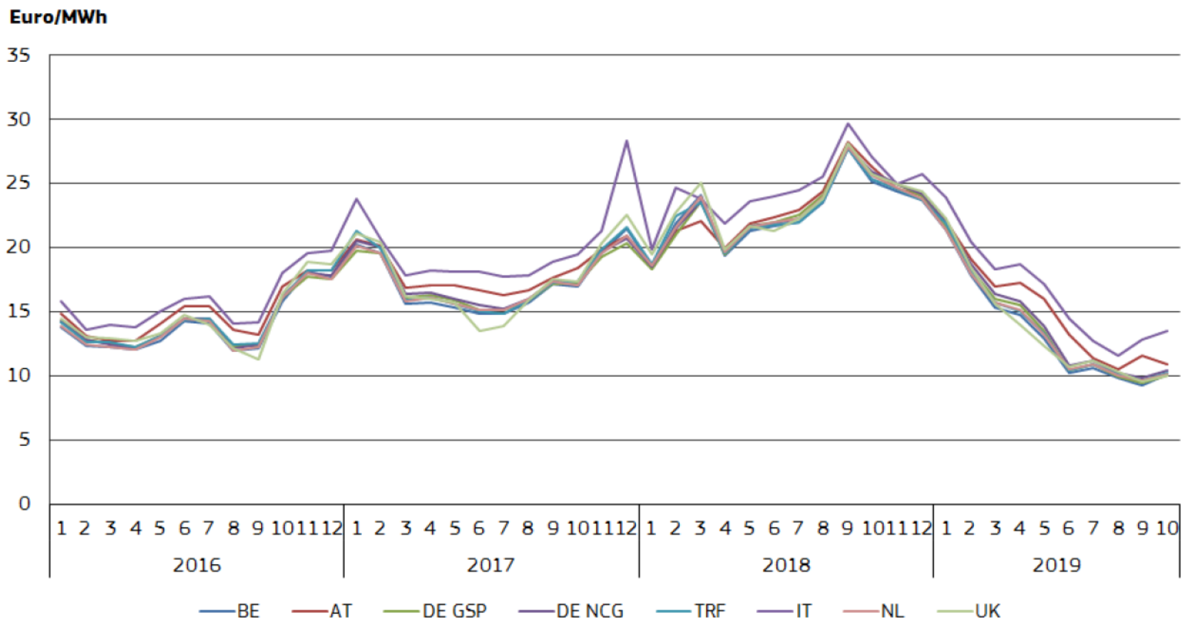
In both the articles 11(7) and 13(1) of the Regulation, the gas-electricity interaction is underlined by the fact that the gas interruption for the critical GFPP may result in severe damage in the functioning of the electricity system. The gas-electricity nexus has been growing in the last decade for several reasons that were previously identified in the preceding literature review (Jung et al., 2020):

- Economic factors: Increased availability of natural gas (e.g. in the USA) (Pambour et al., 2018; Zlotnik et al., 2016), and decreased natural gas prices (Carter et al., 2016; Pambour et al., 2018; Zlotnik et al., 2016), e.g. see Figure 1; low capital investment costs (Correa-Posada et al., 2017);
- Increased electricity consumption (Pambour et al., 2018);
- Political factors: Meeting environmental targets such as reduction of greenhouse gas emissions and climate protection, natural gas thereby playing a role as "transition technology" on the way to carbon neutrality (Carter et al., 2016; Correa-Posada et al., 2017; Deane et al., 2017; Hu et al., 2017; Pambour et al., 2018; Saldarriaga-Cortés et al., 2019);
- Technological factors: Short response times of gas-fired generators (Carter et al., 2016; Correa-Posada et al., 2017; Hu et al., 2017; Qadrdan et al., 2017), which is related to political factors (climate protection policies) as rapid response and short ramping times are also beneficial in terms of flexibility in order to compensate intermittent production of renewable energy sources (RES) (Correa-Posada et al., 2017; Deane et al., 2017; Pambour et al., 2018; Qadrdan et al., 2017); high efficiency (Correa-Posada et al., 2017), enabling massive deployment of RES.

The strength of gas-electricity interaction changes over time and across MSs as the generation mix is evolving towards a renewable-based paradigm and electricity demand is increasing. Within the context of strong dependency of the electricity system on gas-fired generation, the MSs with a large fleet of GFPPs may be interested in identifying which plant(s) are critical for the operation of the joint gas-electricity system. When the GFPP could be prioritised over protected customers, as established in the Regulation, the European Commission Directorate-General for Energy (DG ENER) would like to be able to assess if such a designation done by the MSs can be considered reasonable. To this end, this report describes a "toolbox", consisting of two principal sets of tools:

1. Identification of all major interaction mechanisms that exist between gas and electricity infrastructures (including GFPPs). This can be used in risk assessments as a form of checklist in order to ensure that the interdependency between gas and electricity systems as a source of risk is properly accounted for.
2. Development of a set of pointers that can be used to quantify the "interaction strength" of electricity infrastructures on gas-fired generation in the different MSs. This is done here using high-level statistical indicators only. In a follow-up report, a more sophisticated method based on modelling will be proposed that can be used if the situation in a region from the European Union (EU) needs to be investigated in greater detail.

Figure 1. Wholesale day-ahead gas prices on gas hubs in the EU.



Source: Quarterly Report on European Gas Markets (vol. 13, issue 3, third quarter of 2019) of the Market Observatory for Energy.

At this point, the question here is whether we can identify critical GFPPs, which is relevant for only a subset of MSs, by using high-level statistical indicators. To the best of our knowledge, this outcome is not possible by only resorting to high-level statistics since assessing the criticality of a certain power plant would need to account for the real operation of the joint gas-electricity system. To do that, we need to model the physics behind each system, especially topological constraints and other technical and economic constraints defining the joint system of a particular country or region. In addition to the modelling of the joint system, we must analyse scenarios relevant to the security of supply to be able to pinpoint a given power plant as critical.

A part of the information relevant to the first set of tools, which is the identification of all major interaction mechanisms, can directly be inferred from the previous literature review (Jung et al., 2020). We also consider a similar identification approach done by Artelys (2019). In addition, national preventive action plans (PAPs)[1] prepared by MSs in accordance with the Regulation may provide essential information and clarify existing dependencies between the gas and electricity sectors within the EU. To define the set of pointers, experience gained within the literature review can partially be used as well.

Regarding the PAPs (the ones already published to this date), the role of gas in electricity generation is explicitly addressed in the PAPs of Germany, the Netherlands, Belgium, Ireland, and Malta, and to a lesser degree in the PAPs of Poland and Spain. Table 1 presents a summary of the contents of these PAPs on the gas-electricity

[1] Publicly available preventive action plans can be found in https://ec.europa.eu/energy/topics/energy-security/secure-gas-supplies/commissions-opinions-preventive-action-plans-and-emergency-plans-submitted-member-states-2019_es

interaction. Most of these PAPs highlighted the growing role of GFPPs as a source of flexibility to accommodate renewable generation. Communication and coordination between the gas and electricity transmission system operators are promoted by the PAPs of Germany, the Netherlands, Ireland, and Poland. Finally, the matter of critical GFPPs is discussed only in the PAPs of Germany, the Netherlands, and Poland. Germany has regulated the concept of "systemically relevant" GFPPs in Section 13f of the Energy Industry Act and the transmission system operator for electricity can designate GFPPs with a nominal capacity above 50 MW as systemically relevant, however, unlike the definition of critical GFPP in the Regulation, this does not imply that the GFPPs should be prioritised over protected customers. The Netherlands lists four criteria to determine if a power plant is considered critical: their share in total generation capacity, their use to balance the electricity grid, their black start capability, and their criticality for continued operation of vital infrastructures. Finally, Poland is the only country providing a list of critical GFPPs and combined heat and power plants.

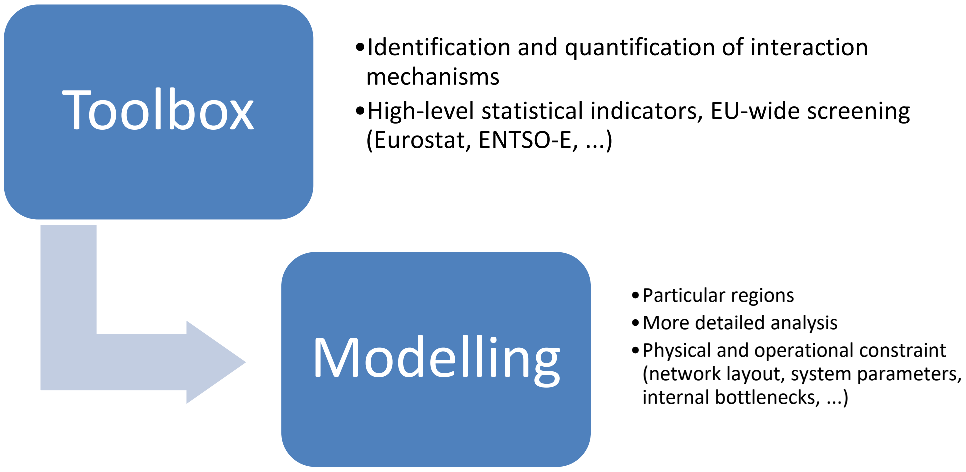
Figure 2 illustrates the conceptualisation of the toolbox presented here, which will eventually be just the first step in a cascade of methods that can successively be used in order to go into more detail for regions of interest. Upcoming work will address sophisticated modelling techniques that are necessary to study the interaction gas-electricity in more detail. This naturally comes with an increase of data requirements and (numerical) effort. Model-based approaches may lead to generate another set of pointers on the topic of critical GFPPs. Such pointers should aim at allowing the European Commission to assess whether critical GFPPs identified in some risk assessments, as established in Article 7 of the Regulation, realistically fall in such a category.

Table 1. Summary of the contents of the PAPs of some MSs with regard to the gas-electricity interaction.

Member State	Contents on the gas-electricity interaction in the PAP
Belgium	- Illustrative example in case of blackout - Local power outage could impact one of the electricity-driven compressor stations, but without impact on the Belgian market - Addition of three recent electrically-driven compressor could stress even more the strength of gas and electricity sectors
Germany	- Important role of GFPPs in the electricity supply in periods of low renewable energy or in case of grid congestion (particularly in southern Germany) - Brief description of the tense supply situation in February 2012 in terms of security of electricity supply due to a gas supply bottleneck - Concept of "systemically relevant" gas-fired power plants
Ireland	- Summary of the preventative measures for tackling the gas-electricity interactions is presented - Fuel switching is described as a non-market-based measure to ensure gas security of supply
Malta	- Strong dependency of the electricity sector on gas-fired generation because of the strong dependence of electricity production on natural gas
Poland	- Agreement of cooperation in October 2018 between the gas and electricity transmission system operators - It provides the list of Polish critical GFPPs and combined heat and power plants
Spain	- Recommendation about the integration of gas and electricity markets due to the limited interconnection with the rest of European markets - Under a gas shortage, agents may promote a gas reduction in gas-fired generators in the electricity market
The Netherlands	- Four criteria are listed to determine whether a GFPP is critical - The selection of critical GFPPs is the result of a continuous collaboration between gas and electricity transmission system operators

Source: JRC, 2022.

Figure 2. Cascade of methods approach, from EU-wide screening tools to more detailed analyses in particular regions.



Source: JRC, 2022.

It is suggested to use the simple methods provided by this toolbox to get a broad overview over the whole EU, and then to activate more sophisticated modelling techniques for regions only in the case of need. Due to their simplicity, the methods proposed in this toolbox can also be used to continuously monitor the situation on a EU-wide level.

This report is structured as follows: Section 2 introduces the points of interactions of the joint gas-electricity system and elaborates on both the concept of critical GFPPs and the aspects relevant to perform a criticality assessment; Section 3 presents a set of indicators characterising the dependence of the electricity system on natural gas; Section 4 illustrates the importance of model-based approaches and describes some modelling options with commercial and open source software. Finally, Section 5 concludes the report with a summary of this work and the main takeaways.

2 Points of interaction

Identification of all possible ways in which gas and electricity systems interact is essential for assessing the risk transfer between both systems. One part of the toolbox to develop is an identification of all the possible interaction points between gas and electricity systems that should be considered during the risk management cycle. The results could be used as a "checklist" to ensure a comprehensive consideration of aspects regarding the interaction gas-electricity on national and EU-regional level.

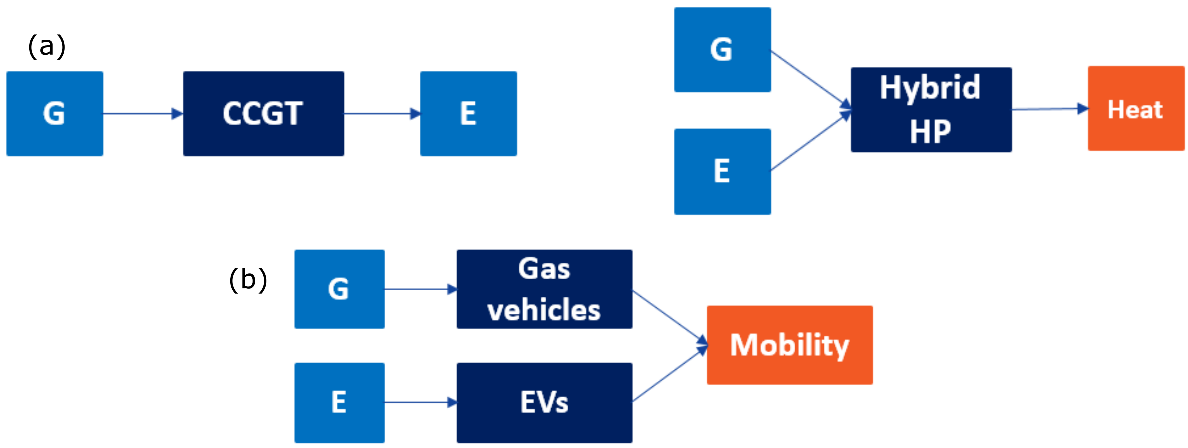
Gas-fired electricity generation arguably represents the main interaction between gas and electricity systems in most MSs, with a rising share of electricity being produced from burning natural gas. However, other forms of interaction exist, as elaborated in the following.

2.1 Overview

A recent study by Artelys (2019) developed a screening method for the European Network of Transmission System Operators (ENTSOs) to identify scenarios that need to consider effects of the interaction gas-electricity more thoroughly within the Ten Year Network Development Plan (TYNDP) assessment process. The study also contains a mapping of all direct and indirect potential interactions between gas and electricity systems and proposes a set of indicators measuring the interdependence of gas and electricity systems.

The Artelys study (Artelys, 2019) characterises possible interactions between gas and electricity systems as *direct* or *indirect*, as illustrated in Figure 3. Following Artelys' definition, an interaction is direct if both energy carriers (gas and electricity) are an input or an output of the interaction. For example, a GFPP constitutes a direct interaction as gas is an input and electricity is an output. Direct interactions dynamically link the gas and electricity sectors. An indirect interaction links the gas and electricity via a third sector, for example mobility, in which a user could make a choice between two different drive technologies, like gas-driven (e.g. CNG) and electric-driven cars (battery electric vehicles, BEVs). Thus, an indirect interaction often involves some form of competition between the two energy carriers, while a direct interaction would be exposed by mobility in form of a vehicle or transport system that could make use of both energy carriers at the same time and dynamically switch between both (some forms of hybrid vehicles).

Figure 3. Examples for (a) direct and (b) indirect interactions.



Source: Artelys (2019).

The direct interactions identified by Artelys (2019) are:

1. Conversion
    a. Gas-to-power
        i. Open cycle gas turbines (OCGT) and Combined cycle gas turbines (CCGT)
        ii. Gas combined heat and power plants (CHP)
    b. Power-to-gas

i. Power-to-hydrogen (P2H)

ii. Power-to-gas (hydrogen or methane injection into the natural gas network)

2. Assistance

   a. Electricity-driven gas compressors

   b. Hybrid heating technologies

      i. Industrial gas furnaces with electric boilers

      ii. Hybrid heating (residential, district)

   c. Hybrid transport

Indirect interactions identified by Artelys comprise:

3. Competition

   a. Mobility

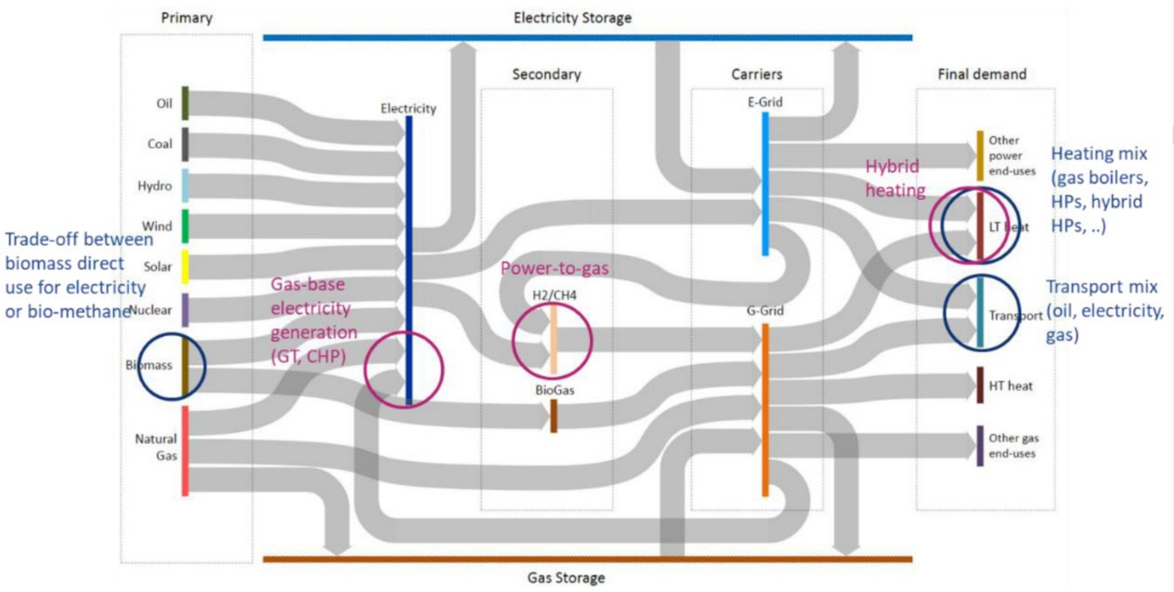
   b. Heat

   c. Biogas

Conversion between energy carriers (1) as well as electricity-driven gas compressors (2a) represent an actual interdependence between both sectors. Hybrid heating and hybrid transport may be related to the competition between the two energy carriers (e.g. electric mobility competing with natural gas vehicles, gas heating versus electric heat pumps, the use of hydrogen generated by P2H as replacement of methane). Hybrid heating solutions can also unravel synergies between gas and electricity, as can P2H and power-to-methane (P2CH4) technologies with grid injection.

It is unclear as to how P2H – without injection into the natural gas grid – should represent a direct interaction between natural gas and electricity systems. About hybrid transport as direct interaction, it is hard to imagine a transport system that is able to directly use natural gas from the gas network and alternatively electricity from the electricity grid. This could only play a role if extending the scope beyond natural gas to the complete gas sector or even petrol sector, in which plugin-hybrid electric vehicles (PHEV) or hybrid trains, able to use either electricity (using batteries or the overhead catenary) or diesel and dynamically switch between both, could represent a direct interaction between sectors.

Figure 4. Direct and indirect interaction between gas and electricity systems identified by (Artelys, 2019).



Source: Artelys (2019).

In the view of Artelys (2019), assistance provided by the electricity grid to the gas grid consists mainly of electricity needed to drive gas compressors and for hybrid heating and hybrid transport solutions. Note that gas compressors do not only exist in dedicated gas-driven compressor stations, but also in underground gas storage (UGS) facilities (necessary at least for injection of gas). LNG terminals do also rely on electricity driven pumps to push the LNG out of the tanks and for compressing it before re-gasification. Moreover, many valves and other components in UGS facilities may be electricity driven; losing power would render the facility non-operable, which may lead to close operation in safe mode with the help of auxiliary diesel generators, stopping gas injection into the network.

Beyond Artelys' analysis, there are further possible points of interaction worth mentioning. Depending on the technology applied, many end-user gas appliances and gas meters need electricity to operate, making electricity supply critical also for essential end-user gas applications such as heating. This might be considered by Artelys (2019) in the competition aspect between gas and electricity end uses and hybrid heating and transport applications. Households are protected customers by definition. But also, commercial end users might need gas to operate and might not always represent a priority electricity load.

Almost all components (of both the gas and the electricity system) require electricity to function properly, even if electricity can be provided from alternative sources (e.g. oil/diesel backup generators) for a limited amount of time or for unlimited time, provided a flawless transport chain for backup fuel can be maintained. Such facilities, which include also control centres and SCADA/ICT systems, will be on a priority list of specially protected customers that may not be disconnected by the electricity operator as long as other means to stabilize the grid can be exhausted. In principle, these facilities are not treated differently to any other electricity customer defined as essential service such as hospitals, government buildings, data centres and the like and do not induce a form of "dynamic interaction" as they do not represent a big load as such.

Loads of a meaningful size that can induce a more "dynamic" interaction between gas and electricity are arguably represented only by large electric compressors in compressor stations (covered by Artelys in Figure 4 in Point 2a), to a lesser degree also those compressors existing in UGS facilities (for injection[2]) and pumps in LNG terminals. Here, the performance of the gas system directly depends on the availability of a larger amount of electric energy. This dependency might differ a lot between facilities, as capacity to store backup fuel, accessibility to additional backup fuel and the volumes actually kept in place can vary a lot between facilities and different national rules. Especially compressors in LNG terminals that might be necessary to inject regasified LNG into the natural gas grid require attention; e.g. there are cases in which LNG terminals cannot run in "island mode" (in case of a blackout).

2.2 Direct points of interaction

The list of direct points of interaction is presented in the following:

- Gas-fired power plants (OCGT/CCGT);
- Gas-fired combined heat and power plants (CHP);
- Power-to-gas (injection to natural gas network);
- Electricity-driven compressor stations;
- UGS facilities;
- LNG terminals.

Potential direct end uses:

- Agriculture (e.g. heating requirements of chicken farms);
- Industrial gas furnaces with electric boilers;
- Hybrid heat pumps (residential, district).

As previously discussed, specific details of facilities significantly influence the "strength" of the interaction. For example, the existence of backup systems makes a considerable difference for the assessment, and there is a large variety of possible system configurations, which makes it impossible to provide a generalised assessment.

[2] As the injection period of UGS facilities is naturally different from the season in which the peak demand occurs, the electricity demand by compressors in UGS facilities will probably not contribute to major risk scenarios.

A possible derating of the facility's capabilities when operating on alternative or backup fuel could be another factor, as well as the actual amount of reserve fuel kept on-site.

Appendix 1 contains a list of points of interaction between gas and electricity systems, enriched by an indication of data elicitation needs, that could be used as a checklist, for example by MSs, for identifying and assessing risks.

2.3 Backup systems and alternative fuel sources

Regarding backup electricity generators and alternative or backup fuel sources of GFPPs, it needs to be stressed that they are not able to fully eradicate the interdependency (and the risk stemming from it), merely mitigate it. While diversification and redundancy of fuel and power sources is certainly beneficial to improve reliability of service, its usefulness might be limited by several factors:

- On-site storage capacity of alternative fuel / backup fuel / batteries;
- Volumes of alternative fuel / backup fuel actually kept on-site (driving operational costs);
- Flaws / risks in the transport chain to acquire additional alternative fuel / backup fuel, especially during crises that may affect many sectors and large regions;
- The facility not being able to work at 100% of its designed performance (derated state) when running on alternative fuel / backup fuel.

The conclusion is that a facility might still depend on its main power or fuel source when counting on its best, non-derated and reliable operation.

2.4 Critical gas-fired power plants

Being the main subject of this study, some dedicated elaborations about the criticality exhibited by GFPPs are certainly in place.

According to Regulation (EU) No 2017/1938, critical GFPPs can be designated by MS so that they can be prioritised over certain categories of protected customers during gas supply crises when curtailment of gas is unavoidable. It is desirable to possess a number of pointers that help justifying such designations. This can – in a first step – include country-wide indicators such as those developed in Section 3 to assess the criticality of the whole nation-wide gas-fired generation sector, while more detailed analyses will presumably have to rely on computer-aided modelling approaches of various depth in a second step of the toolbox (see Section 4).

A number of pieces of information could be relevant to assess the criticality of GFPPs:

- Its relevance for meeting the MS's electricity supply (generation adequacy);
- Fuel-switching capability, availability and accessibility of alternative fuel / backup fuel;
- The plant's relevance for blackstarting the electricity system after a blackout;
- To a lesser degree: Provision of grid services (fore mostly provision of reserve capacity; backup for intermittency of RES);
- The plant's relevance for maintaining security constraints (feasibility under contingencies);
- Availability of natural gas (i.e., number of pipelines from different sources, proximity of gas storage facilities, etc.).

All but the last point concern the electricity grid, as the power plant's role for stable and reliable electricity production is what makes it "critical" in the first place. How the different factors influence the criticality of GFPPs is tackled in the following.

Generation adequacy

One possible (and necessary) way for understanding the role of gas (and its lack) for electricity supply – or any other fuel used to generate electricity – by assessing its effects on generation adequacy. As already pointed out in the preceding literature review (Jung et al., 2020), methods for evaluating generation adequacy could be used for assessing the criticality of GFPPs, by analysing the effect of a lack of gas as fuel to generate electricity, for different regional extents and timeframes relating to feasible gas supply disruption scenarios.

Adequacy assessments often aggregate all generation capacity on a per country basis ("one node per country"), compare it to the demand forecast, and take into account only transmission capacity of cross-border interconnectors. Local grid structure and thus internal bottlenecks are not taken into account. Particularly the location of power plants within one country is ignored. To analyse regional differences[3] in the distribution of GFPPs and internal bottlenecks that could lead to gas-fired generators be more important in one region than the other, the spatial granularity of the underlying grid model has to be increased, for example by dividing larger countries into several nodes.

Fuel switching capabilities

Some GFPPs within the EU can use an alternative fuel to produce electricity if natural gas is temporarily not available, such as fuel oil or diesel. Also economic reasons can lead to the usage of alternative fuel. Fuel switching capability surely reduces the dependence of the power system on natural gas, but the extent to which the dependency is reduced depends on various factors. First, the rated power of the facility might be reduced when running on alternative fuel. Secondly, the alternative fuel is usually more expensive. Also transport and storage of alternative fuel comes with additional costs which the operator might want to avoid by limiting the amount of backup fuel stored on site. Different regulatory obligations and incentives exist in different countries. Availability and accessibility of the backup fuel might be limited as well, especially during nation-wide crises when energy carriers are scarce and transport chains could be blocked. At last, environmental protection policies could prevent the usage of alternative fuel systems, as it is the case, for example, in Belgium[4].

Blackstart capabilities

It is vital for any power system that it is able to recover from a system-wide or partial blackout. The recovery from a blackout follows a well-defined process in which the largest generators (with large rotating masses) play a pivotal role. If GFPPs are part of a countries' list of "black start machines", they are clearly important for the system's security, and sufficient supply of natural gas needs to be guaranteed if needed, which could warrant their designation as "critical".

In case of a system-wide blackout, it must be ensured that the gas system is still able to provide gas to at least the gas-fired black start plants. Key facilities in the gas system are equipped with backup systems to be able to temporarily operate without external electricity supply. As nowadays modern appliances in the vast majority of households need electricity to operate, the amount of gas available in the gas system could even be higher than normal[5]. Within the recovery phase, actions in the gas and electricity system should be coordinated, because as the end consumers are gradually resupplied with electricity, their gas consumption will be re-established as well.

Grid services

In power system operations, it is essential that production is adjusted to the demand in real time. As both demand and RES are variable and uncertain, and on top of that, unexpected failures may occur, the grid operator has to rely on reserve capacity that is booked in advance to ensure the balance between demand and production can be kept at all times. This is expected to only have a very limited impact on the dependency of the power system on natural gas, as usually a large number of generators is participating in the provision of reserves and the amount of needed reserves is not very large when compared to the total production capacity of the electricity system of a country. The aspect could however gain importance in a future power system that almost solely consists of RES and GFPPs, that is, if GFPPs would become the dominating group of thermal units needed to compensate the naturally occurring fluctuations of RES and demand and are providing most of the reserves. Here, a lack of a greater portion of conventional generating capacity could lead to a situation where the provision of reserves could be endangered. On the other hand, it is foreseeable that the introduction of different storage, power-to-gas and power-to-x technologies as well as new concepts in the field of demand response will help to prevent this scenario from materialising.

Connectivity in the gas grid / availability of gas

The availability and accessibility of gas may also play a role for the criticality of a GFPP. Unlike previous aspects which solely concerned the power grid, this point is about the gas side of the interaction.

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[3] Consider for example the situation of GFPPs in southern Germany, which triggered to introduce the concept of "systemically relevant power plants" in the German Energy Industry Act and the Preventive Action Plan (BMWi, 2019).

[4] Preventive Action Plan Belgium, After Regulation (EU) 2017/1938 of the European Parliament and of the Council of 25 October 2017 concerning measures to safeguard security of gas supply, July 2019.

[5] Ibidem.

All off-take nodes in a gas transmission network are characterised by a minimum delivery pressure, below which delivery of flows is stopped. GFPPs generally are among the off-take nodes that need the highest delivery pressures, particularly most modern CCGTs. If grid pressure is lower, it is technically impossible to operate the plant. A stable pressure within the gas system around the GFPP is thus essential for a reliable operation. Pressure decreases along the pipeline from the source to the sink. Because of that, compressor stations need to be installed in regular intervals along the pipeline to increase pressure again. Generally speaking, high pressure can best be ensured if the distance to a source (or compressor station) is as small as possible, and no significant demand exists in intermediate nodes. On the other hand, if a GFPP exists far away from the next source, the leeway between normal system pressure and minimum operating pressure of the GFPP might be smaller. In such cases, it might be more difficult in gas scarcity situations to ensure the right gas pressure at the location of the GFPP. The interaction between gas and electricity systems is stronger, as small changes in the state of one system can already have a large effect on the other.

On a higher level, the number and capacity of countries' entry points are of interest, which include cross-border entry points as well as production sites and LNG terminals. In general, diversification helps to ensure a stable supply of gas, as do large gas storage capacities and production sites within the country. Also, the internal transmission capacity and the redundancy of pipelines are of interest in order to bring gas where it is needed if the amount of gas is limited. In addition, the distribution of GFPPs across the country might play a role. A concentration in only one area or a small number of power plants increases the dependency on a functioning gas system.

A high share of a country's gas consumption used for electricity production also indicates a strong interaction. If other uses, for example for industrial purposes, are small, a gas scarcity situation might necessitate an even earlier cut of gas supply to GFPPs. If now gas-fired generation also plays an important role in the country's electricity mix, the interaction gas-electricity is certainly strong.

Examples

Only few MSs have already dealt with critical GFPPs in their Preventive Action Plans (PAPs). Notably, Germany already defined a list of "systemically relevant" plants, located mainly in the country's southern parts, which are deemed important for maintaining system stability[6]. The designation as systemically relevant ensures the delivery of gas to these power plants in times of grid congestion or low RES feed-in. Their gas demand is accounted for within the estimate of "Dmax" (estimated 1-in-20-year daily peak gas demand) within the infrastructure standard as foreseen by the gas security of supply regulation[7]. Germany also devoted the 2018 edition of the Inter-State and Inter-Departmental Crisis Management Exercise (germ. Länder- und Ressortübergreifende Krisenmanagementübung, LÜKEX) to a gas shortage situation in Southern Germany[8].

[6] Preventive Action Plan for Gas for the Federal Republic of Germany, pursuant to Art. 8 of REGULATION (EU) no. 2017/1938 of the European Parliament and of the Council of 25 October 2017 concerning measures to safeguard the security of gas supply and repealing Regulation (EU) No 994/2010, June 2019.

[7] Regulation (EU) No 2017/1938 of the European Parliament and of the Council of 25 October 2017 concerning measures to safeguard the security of gas supply and repealing Regulation (EU) No 994/2010.

[8] https://www.bbk.bund.de/EN/Topics/Crisis_management/LUEKEX/LUEKEX_18/LUEKEX_18_start.html

3 Indicators for the dependence of the electricity system on natural gas

While the data availability on the usage of electricity by the gas system – in terms of both country-wide figures and in terms of electricity consumption of single facilities – is limited, sufficient data is publicly available on the gas volumes used for electricity production, which can be used to construct simple indicators measuring the dependency of the electricity system on natural gas. At the same time, gas-fired electricity production must still be considered the dominating form of interaction between gas and electricity systems in the EU. In this section, we will propose a number of simple statistical indicators, fulfilling the purpose on measuring the strength of this form of interaction.

There has been an increasing trend towards gas-fired electricity production in the last decades (Correa-Posada et al., 2017; Zlotnik et al., 2016). As mentioned in the introduction, the main drivers for this trend, which were identified in the preceding literature review (Jung et al., 2020), are economic, political, and technological factors. In this section, we are interested in analysing the degree of both gas-electricity dependency and criticality of GFPPs per Member State (MS) by means of country-wide indicators (or indices). Several reliable sources provide data at a coarse granularity, typically yearly or monthly, per MS. Therefore, we base our analysis on data collected by:

- EUTOSTAT, which is the European Statistical Office (Eurostat, 2020), and
- ENTSO-E, which is the European Network of Transmission System Operators for electricity (ENTSO-E, 2020a).

The set of indicators can serve two main purposes. On the one hand, they can help to identify countries with a high level of gas-electricity dependency for which a more thorough analysis (with finer resolution) is required to assess the security of gas supply. On the other hand, the indicators can help to quantify the degree of criticality gas-fired electricity production is representing for different countries, with regards to shortages of gas supply. All in all, the computation of these indicators could be viewed as part of a screening phase to identify regions in which GFPPs could potentially be designated as critical (in the sense of Regulation (EU) No 2017/1938), and for which a more thorough analysis (including advanced modelling techniques) could be worthwhile.

We split the set of indicators for the dependence of the electricity system on natural gas into two groups:

- Energy-balance-based indicators. In Section 3.1, we compute two indices with the energy and consumption balances of the EUROSTAT service to describe the interaction strength between gas and electricity sectors. We also analyse a compound index by combining the two indicators.
- Capacity-based indicators. Section 3.2 first provides an index based on the installed electric generating capacity of the country, its corresponding installed capacity for GFPPs, and its annual peak demand. Later, we propose a more advanced indicator wherein more technical metrics are accounted for under severe conditions, which are available in ENTSO-E winter outlook data (ENTSO-E, 2020c). The technical metrics include imports and exports, reserves, and forced outage rates.

The main limitation of these indicators is their granularity. As a result, we may not be able to pinpoint individual critical GFPPs within a country. To do that, we would need network-related data, which may not be disclosed due to their sensitive nature, and finer data resolution. Obtaining such data, if at all possible, can require considerable effort. It makes sense to conduct detailed analyses based on such data only for a preselected set of regions and subsystems. Insofar, coarse data such as those used in this study could undoubtedly give a first idea of the criticality of the interaction gas-electricity in different countries. This knowledge would allow in a later stage to further analyse the security of electricity and gas supply.

We could also analyse the proportion of protected customers in relation to the total gas demand and compare it to the proportion of gas devoted to electricity generation. The Regulation (EU) No 2017/1938 (European Parliament and the Council, 2017) defines protected customers as certain customers, including households and customers providing essential social services are particularly vulnerable and may need protection against the negative effects of disruption of gas supply. Each country is requested to provide its definition of protected customers in their respective Prevention Action Plans. Under certain conditions, critical GFPPs may be prioritised over those protected customers, even under an emergency situation. Although an indicator incorporating these aspects may provide another interesting dimension to the gas-electricity dependence, the Preventive Action Plans of some countries lack such information while others are still pending for submission at the time of writing.

3.1 Energy-balance-based indicators

The EUROSTAT service (Eurostat, 2020) is the statistical office of the European Union and provides high quality statistics and data of European countries. Specifically, EUROSTAT maintains a wide range of statistical indicators of the energy sector. Table 2 lists the pertinent ones for analysing the interaction gas-electricity.

Table 2. EUROSTAT indicators relevant for the interaction gas-electricity (Eurostat, 2020).

Symbol	Description	Unit	EUROSTAT table code/field code
$\boldsymbol{P_{it}^{E,G}}$	Production of electricity by natural gas	GWh	nrg_bal_peh/G300
$\boldsymbol{P_{it}^{E}}$	Total production of electricity	GWh	nrg_bal_peh/TOTAL
$\boldsymbol{C_{it}^{E}}$	Final consumption of electricity	GWh	nrg_cb_e/FC
$\boldsymbol{C_{it}^{G,E}}$	Transformation input for electricity and combined heat and power generation	TJ	nrg_cb_gas/TI_EHG_MAPE_E + nrg_cb_gas/TI_EHG_MAPCHP_E + nrg_cb_gas/TI_EHG_APE_E + nrg_cb_gas/TI_EHG_APCHP_E
$\boldsymbol{C_{it}^{G}}$	Inland consumption of natural gas	TJ	nrg_cb_gas/IC_OBS

Source: JRC, 2022.

Based on yearly EUROSTAT data, it is possible to define a set of indexes characterising the strength of dependency of the electricity sector on the gas sector. By considering certain ratios, the role of gas in the production of electricity and the role of electricity production in the total demand of gas can be understood.

First, we can compute the share of electric energy that is produced by means of natural gas in the final electricity production of country i in year t, as the ratio $P_{it}^{E,G}/P_{it}^{E}$. To better reflect the influence of electricity imports, we modify this ratio to obtain the share of electric energy that is produced by means of natural gas in the final electricity consumption of country i in year t as follows:

$$I_{it}^{1} = \frac{P_{it}^{E,G}}{C_{it}^{E}} \ . \qquad (1)$$

Second, we compute the share of consumption of natural gas used for electricity production:

$$I_{it}^{2} = \frac{C_{it}^{G,E}}{C_{it}^{G}} \ . \qquad (2)$$

As can be seen in Section 3.1.1, both indicators are highly positively correlated. Therefore, it makes sense to convert the indicators discussed so far into a compound indicator for the interaction strength gas-electricity. The goal is the definition of a compound indicator that is as accurate as possible taking into account all available information. It is possible to define a compound indicator I_{it}^{3}, which takes into account the EUROSTAT-based indicators I_{it}^{1} and I_{it}^{2}. One possibility to construct a compound indicator is the geometric mean:

$$I_{it}^{3} = \sqrt{I_{it}^{1} I_{it}^{2}} \ . \qquad (3)$$

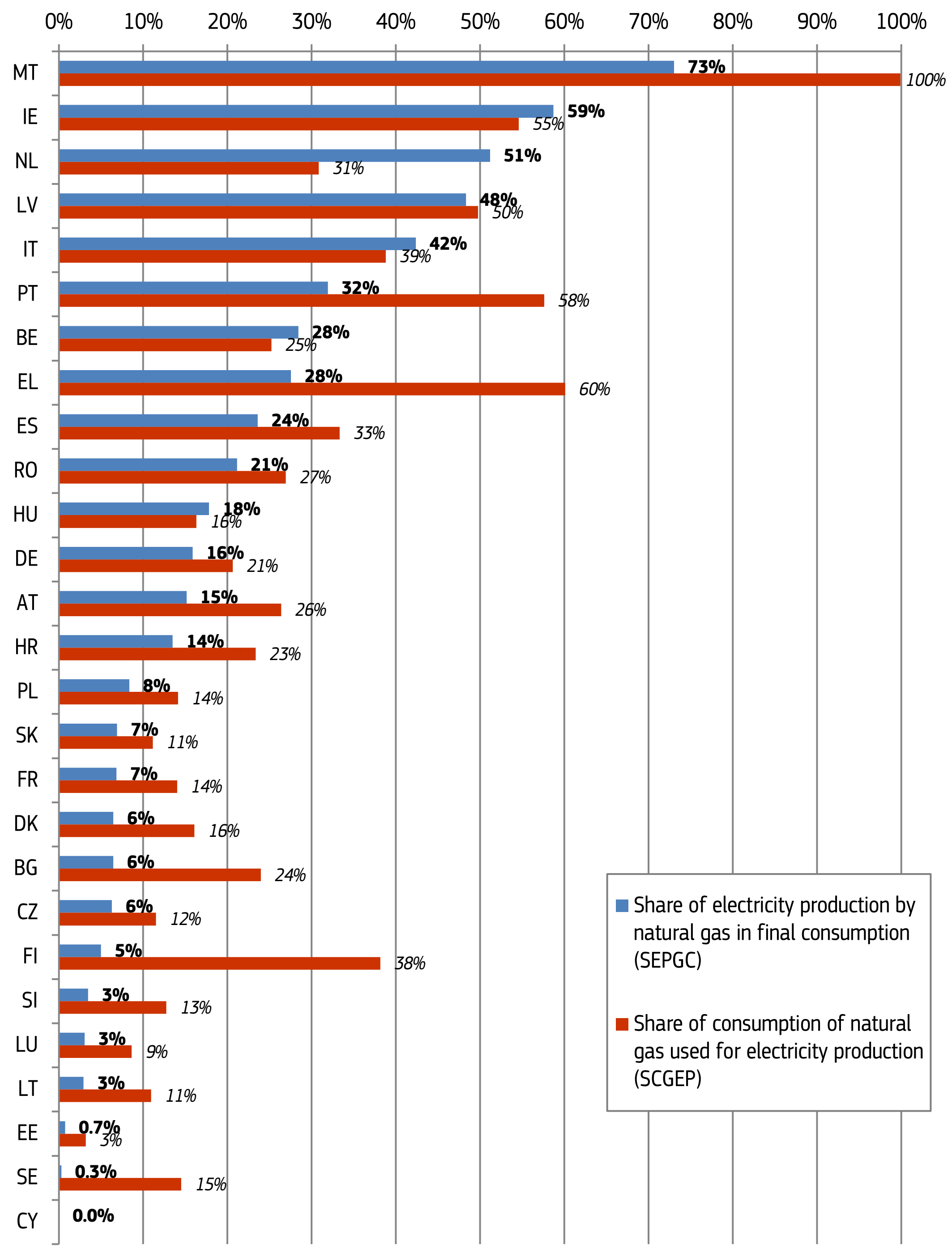
The index in Equation 3 is largest if the production of electricity by gas plays a big role in both the electricity production mix and in the consumption of gas in a country. If one constituent is considered more important than others for the question of criticality, a weighted mean could also be constructed.

This approach could be deemed simple, as it does not consider existing gas-fired generating capacities, put in contrast to other conventional generating capacities. In Section 3.2, we improve it by defining a compound indicator which takes into account gas-fired generating capacities in relation to generating capacities of other fuel types and to the peak demand.

3.1.1 Results

Figure 5 shows the two indexes I_{it}^1 and I_{it}^2 for the EU-27 in 2018, i.e., the last year for which a complete dataset is available. In many EU MSs, a large share of electricity production is provided by GFPPs. According to EUROSTAT data from 2018, Malta is leading with a share of 73% of electric energy produced by natural gas (see Figure 5), followed by Ireland (59%) and the Netherlands (51%).

Figure 5. Share of electricity produced by natural gas in the final electricity consumption (SEPGC) and share of consumption of natural gas used for electricity production (SCGEP) in EU-27 countries in the year 2018.

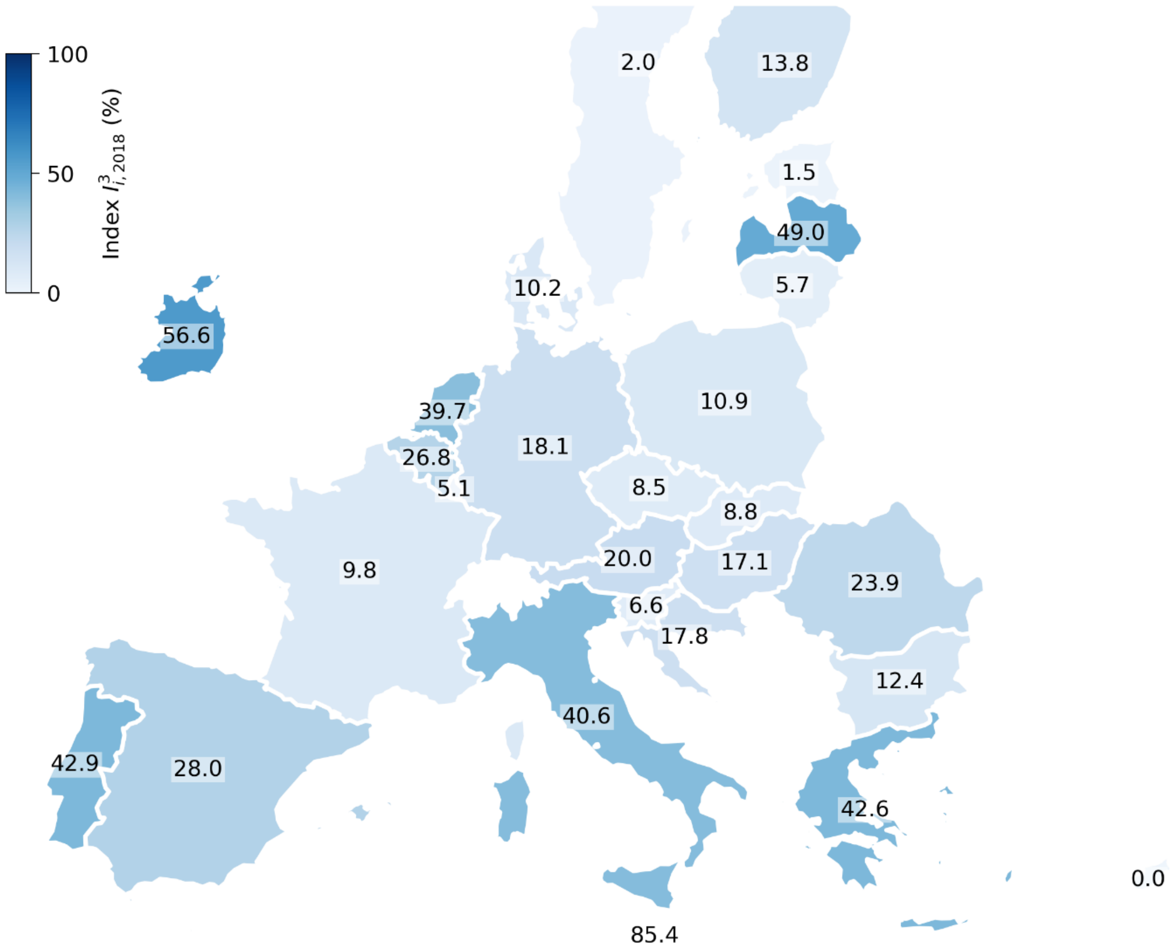


Source: JRC, 2022, based on Eurostat data (2020).

Regardless of the share of electricity produced by natural gas, the consumption of natural gas can either be dominated by producing electricity, as it is for example the case in Malta (see Figure 5), or by other uses, such as industrial or residential. Thus, the share of gas used for electricity production, compared to the overall consumed quantity, is another important indicator for assessing the dependency of the electricity sector on natural gas, primarily because consumption might be bound to other uses of higher priority, i.e., that of protected customers.

Figure 6 illustrates the compound indicator I_{it}^{3} of EU MSs for the year 2018. The top five countries with the highest degree of dependency of the electricity sector on the gas sector are Malta (85%), Ireland (57%), Latvia (49%), Portugal (43%) and Greece (43%), followed very close by Italy and the Netherlands with a value of the index around 40%.

Figure 6. Energy-balance-based compound indicator for the degree of dependency of the electricity sector on the gas sector across the EU-27 Member States in the year 2018.



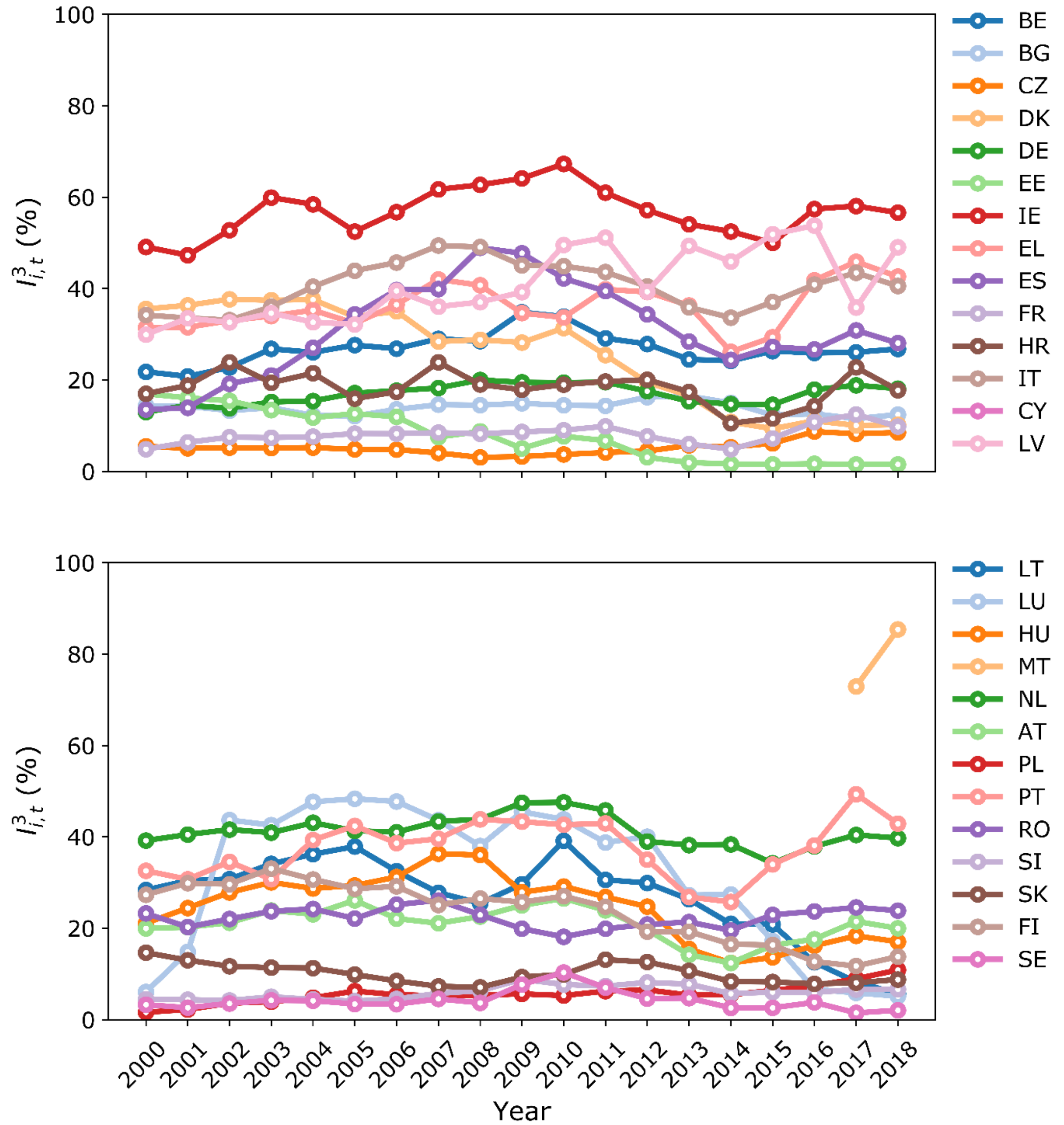
Source: JRC, 2022, based on Eurostat data (2020).

3.1.2 Evolution of indicators

Now we focus on the compound indicator $I_{i,t}^{3}$ to analyse the time evolution of the degree of dependency of the interaction gas-electricity. The evolution may show the trend of a country regarding its energy policy and the importance of the electricity system on the gas sector. Figure 7 illustrates the volatility of the index $I_{i,t}^{3}$ from the beginning of the 21st century until 2018. For the sake of clarity, this figure is divided into two plots. In the upper plot, we show the evolution of 14 EU MSs, whereas in the lower plot, we depict the remaining 13 EU MSs.

The highest values of the indicator can be observed for Malta for the last two years when it reaches 73% and 85%, respectively. In 2018, the countries with a high dependency of the electricity sector on gas are Ireland, Latvia, Portugal, Greece, Italy, and the Netherlands. We can observe that the index is stable throughout the observation period for the Netherlands. The remaining five countries follow an irregular evolution over time, but in general there is an increase of the energy-balance-based compound indicator compared to the values achieved in 2000. The countries with the higher growth of the indicator in absolute terms in 2018 with respect to the year 2000 are: Malta, Latvia, Spain, Greece, and Portugal. There are also countries in which the indicator remained steady over time, such as the Netherlands, Croatia, or Austria. In contrast, we can clearly observe a reduction of this compound indicator for other countries, e.g. Denmark, Lithuania, or Estonia, which translates to a decreasing degree of dependency of the electricity sector on the gas sector for these countries. Most of the countries experience a drop of the degree of dependency in the period 2010-2014 because of the decrease in total gas demand, and in particular in electricity generation from GFPPs.

Figure 7. Time evolution of the energy-balance-based compound indicator in the period 2000-2018 in the EU-27 countries.



Source: JRC, 2022, based on Eurostat data (2020).

3.2 Capacity-based indicators

ENTSO-E (ENTSO-E, 2020a) collects and provides publicly available data related to the operation of the electricity sector of EU Member States via the ENTSO-E Transparency Platform. This platform includes load, generation and transmission data, among other system operation data. For instance, we can obtain the generation capacities per production type and year, the actual and forecast electricity demand per hour, the cross-border physical flows, among others. Another relevant contribution of ENTSO-E is the release of a series of outlooks, namely the summer and winter outlooks, the mid-term adequacy report, and the Ten-Year Network Development Plan (TYNDP).

Our goal is to use data collected by ENTSO-E to identify the criticality of natural gas supply for the production of electricity in European countries by accounting for information about the installed gas-fired capacity and its role for maintaining the adequacy of the national electricity systems. Generation adequacy studies can be used to identify critical GFPPs or, at least, for identifying the whole gas-to-power sector of a country as "critical". The key idea of the capacity-based indicators is to take into account available generator capacities in the absence of the fleet of GFPPs, i.e., in a scenario in which natural gas is not available to produce electricity.

We could have developed even more advanced indicators if more data were available. For instance, we disregard whether the GFPPs consider fuel-switching capabilities (in that case, performance and endurance of backup systems could be considered). In addition, we do not account for the cross-border capacities of gas and electricity systems, or whether there is an abundance of gas (e.g. in transit countries). Also, additional constraints for distribution and transport, imposed by internal bottlenecks, are not taken into account. However, we believe that, despite of some shortcomings, we have a reasonably good estimate of the country-wide criticality of the interaction gas-electricity despite neglecting such aspects.

In Section 3.2.1, we compute an indicator based on the installed capacities by production type and the electricity peak demand for a given year. In Section 3.2, we improve the indicator by considering more information about the electricity system and devise an indicator that also accounts for reserves, cross-border capacities, forced outage rates of power plants, and other aspects. Finally, Section 3.2.3 presents a probabilistic indicator to take into account the inherent stochasticity of several parameters, such as the unplanned outages, net load, or other uncertain parameters related to the nature of the data source.

3.2.1 Solely capacity-based indicator

First, we compute a solely capacity-based indicator for country i and year t with the relevant information shown in Table 3, i.e., the total installed capacity (including renewable energy sources), the installed capacity of the fleet of GFPPs, and the peak electricity demand. Thus, the indicator can be formulated as follows:

$$I_{it}^{4} = \frac{D_{it}^{P}}{P_{it}^{T} - P_{it}^{G}} \ . \qquad (4)$$

The larger the value of the index, the more does the electricity system depend on natural gas. If the index is 1, the non-gas-fired generation capacity would just be enough to cover the peak electricity demand, that is, only if there were no (planned or unplanned) outages. If the index is greater than 1, then gas-fired generation can be regarded as critical, as without it the country's generation adequacy could not be maintained under peak load. However, this index does not account for planned (for reasons such as maintenance) and unplanned outages, reserves, etc. The index also ignores whether the system is operated under normal or severe conditions, and does not distinguish firm and intermitted generation (renewable energy sources). A variant could be considered that takes into account only the firm generating capacity (provided this data is available), excluding intermittent renewable energy sources, as this would arguably provide a more accurate indicator for the dependence of electricity on gas, because one cannot depend on the availability of a renewable energy source. So the indicator proposed above is only meaningful as long as the share of RES in a country is not too high.

Table 3. ENTSO-E indicators relevant for the interaction gas-electricity (ENTSO-E, 2020a).

Symbol	Description	Unit
$\boldsymbol{P_{it}^{T}}$	Total installed capacity	MW
$\boldsymbol{P_{it}^{G}}$	Installed capacity of the production type 'Fossil Gas'	MW
$\boldsymbol{D_{it}^{P}}$	Hourly peak electricity demand	MW

Source: JRC, 2022.

3.2.2 Deterministic compound indicator under severe conditions

Now, we present an indicator based on the ENTSO-E Winter Outlook (ENTSO-E, 2020c) to estimate the critical percentage of power generation capacity of GFPPs in each European country for maintaining the electricity supply, taking the data from a particular peak load day as a test case. Unlike the indicators in previous sections, we account for more information about the system state of a critical period thanks to comprehensive data provided in the ENTSO-E Winter Outlook report (ENTSO-E, 2020c). The analysis of this report is based on qualitative and quantitative data submitted by each transmission system operator (TSO) via a questionnaire. This report comprises, among other aspects, the following data for each country:

— The peak dates at reference point[9] in time in a given day of the week of the winter season;

— average forced outage rate (FOR) for normal and severe conditions;

— net generating capacity per technology;

— planned outages per technology;

— system service reserve for normal and severe conditions;

— non-usable capacity per fuel for normal and severe conditions;

— simultaneous importable and exportable capacity.

ENTSO-E defines normal and severe conditions as:

— 'Normal conditions' correspond to normal demand in the system (i.e. normal weather conditions resulting in normal wind production or hydro output and average outage level);

— 'Severe conditions' correspond to extreme weather conditions in terms of demand (higher than in normal conditions) and in terms of reduced generation output (i.e. severe conditions resulting in lower wind or restrictions in classical generation power plants).

In addition, ENTSO-E defines the terms 'non-usable capacity' and 'importable/exportable capacity' as:

— 'Non-usable capacity' is the aggregated reduction of the net generating capacities due to various causes, including, but not limited to: temporary limitations due to constraints (e.g. power stations that are mothballed or in test operation, heat extraction for CHPs); limitations due to fuel constraints management; limitation reflecting the average availability of the primary energy source; power stations with output power limitation due to environmental and ambient constraints, etc.;

— 'Importable/exportable capacity' is the transmission capacity for exports/imports to/from countries and areas expected to be available. It is calculated taking into account the mutual dependence of flows on different profiles due to internal or external network constraints and may therefore differ from the sum of NTCs on each profile of a control area or country.

The power generation of GFPPs is also available, as the data are provided with a breakdown of the production technologies. Then, assuming a total gas cut for each country and taking into account the data for the remaining capacity, it is possible to calculate the remaining generation capacity after a total gas cut. Hence, a critical percentage of GFPPs for maintaining the electricity supply in each country can be estimated. Table 4 lists the mathematical symbols used for the derivation of the criticality index.

[9] ENTSO-E defines reference point as 'the dates and times for which power data are collected. Reference points are characteristic enough of the entire period studied to limit the data to be collected to the data at the reference points'.

Table 4. ENTSO-E Winter Outlook data relevant for the derivation of the criticality index (ENTSO-E, 2020c).

Symbol	Description	Unit
AC_{it}^{G}	Available capacity of GFPPs	GW
C_{it}^{G}	Generating capacity of GFPPs	GW
EXP_{it}	Export capacity	GW
FOR_{it}^{G}	Forced outage rate of GFPPs	%
IMP_{it}	Import capacity	GW
NUC_{it}^{G}	Non-usable capacity of GFPPs	GW
PO_{it}^{G}	Planned outages of GFPPs	GW
RC_{it}^{s}	Remaining capacity under severe conditions	GW

Source: JRC, 2022.

Although power generation by gas represents only a part of a country's electricity demand, reducing electricity production by GFPPs can substantially decrease the capacity of the power system. If the remaining generation capacity after a gas disruption is not sufficient to meet electricity demand, a shortfall in electricity supply will arise.

As proposed in (Rqiq and Yusta, 2020), the index for assessing the adequacy of the power system of each country i in year t in case of gas shortages is estimated as

$$I_{it}^{5} = \begin{cases} -\frac{RC_{it}^{s,gascut}}{AC_{it}^{G}} 100 & \text{if } RC_{it}^{s,gascut} < 0 \; and \; -\frac{RC_{it}^{s,gascut}}{AC_{it}^{G}} < 1 \,, \\ 100 & \text{if } RC_{it}^{s,gascut} < 0 \; and \; -\frac{RC_{it}^{s,gascut}}{AC_{it}^{G}} \geq 1 \,, \\ 0 & \text{if } RC_{it}^{s,gascut} \geq 0 \,, \end{cases} \tag{5}$$

where

$$RC_{it}^{s,gascut} = RC_{it}^{s} + IMP_{it} - EXP_{it} - AC_{it}^{G} \tag{6}$$

$$AC_{it}^{G} = C_{it}^{G} - PO_{it}^{G} - NUC_{it}^{G} - FOR_{it}^{G}(C_{it}^{G} - PO_{it}^{G} - NUC_{it}^{G}) \,. \tag{7}$$

For each country, the available gas-fired capacity is calculated by subtracting their planned and unplanned outages as well as their non-operating capacity from the net electricity generating capacity supplied with gas, as stated in Equation 7. The remaining capacity of the power system, RC_{it}^{s}, is obtained from the ENTSO-E dataset as the difference between the reliably available generation capacity and the net weekly peak load under severe conditions.

In Equation 6, we compute the remaining electricity generating capacity in the event of a gas outage, i.e. $RC^{s,gascut}$. In this case, the gas supply to GFPPs is completely disrupted, thus decreasing the remaining electricity generating capacity. In Equation 6, we also account for imports and exports, which adds the cross-border dimension that previous indicators lack. Depending on the severity of the outage, the power system may have trouble meeting electricity demand. Then, the index of GFPP criticality (Equation 5) is estimated as the ratio between the remaining system capacity after a gas shortage and the available capacity of the GFPPs, in case the remaining capacity is negative; that is to say, it is a relative measure of the electric supply deficit caused by the shortage of GFPPs.

This index has been used previously by Rqiq and Yusta (2020) to analyse the impact of gas shortages on the European power system under severe conditions of high demand and low availability of resources. Two different strategies are compared based on whether the European countries cooperate or not when assuming an interruption of gas supply. The study suggests that cooperation among countries could lead to a reduction of the electricity not served.

3.2.3 Probabilistic compound indicator

Many uncertainties can be identified when computing the previous indicator under severe conditions: (i) the forced outage rate (FOR) for each of the technologies, which is an average value, (ii) the non-usable capacity of all technologies and non-usable gas capacity, and (iii) the electricity demand, which is used to compute the remaining capacity. For this reason, we have assumed all those quantities as uncertain and then we run a Monte Carlo simulation for N samples wherein each sample j is drawn from the following distributions:

$$FOR_{it}^{G,j} \sim U\left((1-v^F)FOR_{it}^G, (1+v^F)FOR_{it}^G\right) \tag{8}$$

$$NUC_{it}^{G,j} \sim U\left((1-v^N)NUC_{it}^G, (1+v^N)NUC_{it}^G\right) \tag{9}$$

$$NUC_{it}^{j} \sim U\big((1-v^N)NUC_{it}, (1+v^N)NUC_{it}\big) \tag{10}$$

$$Load_{it}^{j} \sim \big(1-\mathcal{N}(\mu_t, \sigma_t)\big) \cdot Load_{it}. \tag{11}$$

Note that FOR_{it}^G, NUC_{it}^G, NUC_{it}, and $Load_{it}$ are average values provided by the ENTSO-E winter outlook report (ENTSO-E, 2020c), v^F is the variability of the FOR, v^N is the variability of the non-usable capacity, and μ_t and σ_t are the mean and standard deviation of the load forecast error. We assume that the load forecast error follows a normal distribution whereas the FOR and non-usable capacity both follow a uniform distribution $U(x)$.

It can be argued that the deviation from average values of the FOR and non-usable capacity may be too small. For this reason, in the numerical results, we consider that the variability of the FOR is small (around 1%) and we compare three different values for the variability v^N of the non-usable capacity.

3.2.4 Results

Next, we analyse the results for each of the proposed indicators for estimating the strength of dependency of the gas-electricity interactions in the EU MSs.

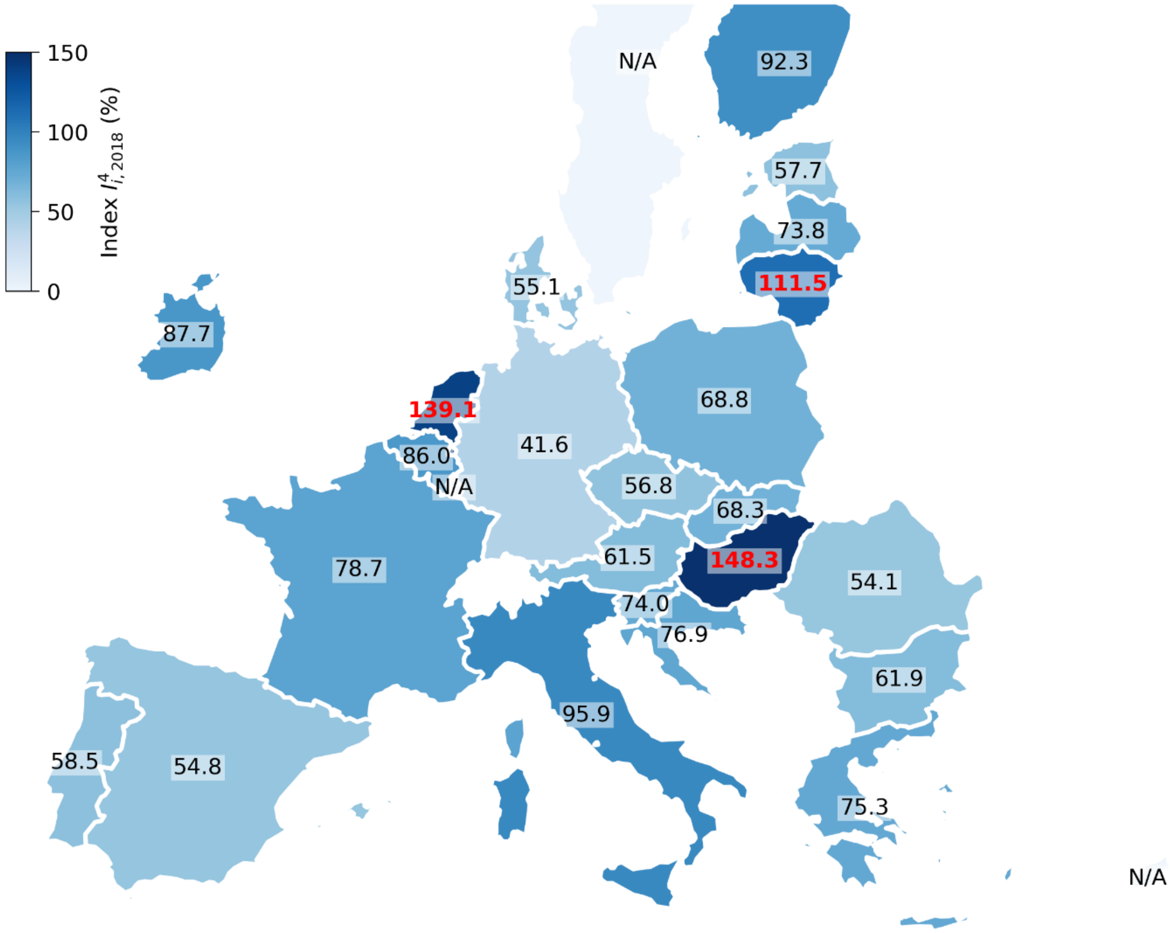
Solely capacity-based indicator

Figure 8 provides the solely capacity-based indicator I_{it}^4 across the EU-27 for the year 2018. Countries in which the gas-electricity interaction is critical, i.e. the index is above 100%, are Hungary, the Netherlands, and Lithuania because their share of GFPPs is substantially high (greater than 40% of the total installed capacity). Note that the indicator for Luxembourg has been precluded in the figure because it is especially high, reaching almost 400%. According to the ENTSO-E Transparency Platform, Luxembourg reported 298 MW of total installed capacity, of which 81 MW corresponds to the production type categorised as fossil gas. In addition, its peak demand amounted to 815.75 MW on 6 February 2018 in the time interval 11:00-12:00. Note that Luxembourg shares a bidding zone with Germany and mainly relies on imports.

The solely capacity-based indicator can also identify countries in which the gas-electricity sector is prone to be critical, such as Italy, Finland, Ireland and Belgium whose values are above 85%, and, in the case of Italy and Finland very close to 100%. The index for the remaining countries ranges between 40-85%[10]. According to this index, the countries with the lowest interaction between the gas and electricity sectors are Germany, Romania, Spain, Denmark, and Czechia. However, this index excludes reserves, cross-border exchanges, planned and unplanned outages, and so on, from its calculation, which may distort the resulting strength of the gas-electricity interaction.

[10] We do not report any values of the index for Cyprus, Malta and Sweden. Data for Cyprus and the GFPP capacity for Sweden are missing from ENTSO-E Transparency Platform. Malta is not even a member of ENTSO-E because it does not have a TSO.

Figure 8. Solely capacity-based indicator for the degree of dependency of the electricity sector on the gas sector across the EU-27 Member States in the year 2018. Index values greater than 100% are highlighted in red.



Source: JRC, 2022, based on data from ENTSO-E Transparency Platform.

Deterministic compound indicator under severe conditions

Let us focus on the Winter Outlook Report 2016/2017 (ENTSO-E, 2020c). In January 2017, Europe experienced an exceptional cold spell, thus affecting the energy consumption in both electricity and gas sectors. On the one hand, electricity peak demand occurred on 18 January 2017 with 581 GW, as can be seen in Table 5. This table summarises some statistics of the actual load across European countries in the year 2017 that can be downloaded from the ENTSO-E Transparency Platform. On the other hand, the peak gas demand took place on the same day, 18 January 2017, according to the Winter Review 2016/2017 (ENTSO-G, 2020) by the European Network of Transmission System Operators for Gas (ENTSO-G). Figure 9 shows the total gas demand daily profile and we can see that the gas demand on that day reached 25 521 GWh/d. The average demand during the 14-day peak period (from 14 January to 27 January) was 23 999 GWh/d. The European peak simultaneity for gas consumption during the peak day on 18 January 2017 was 94%. Therefore, on 18 January 2017, a peak gas demand coincided with a peak electricity demand in Europe, making it the ideal testbed for the proposed index.

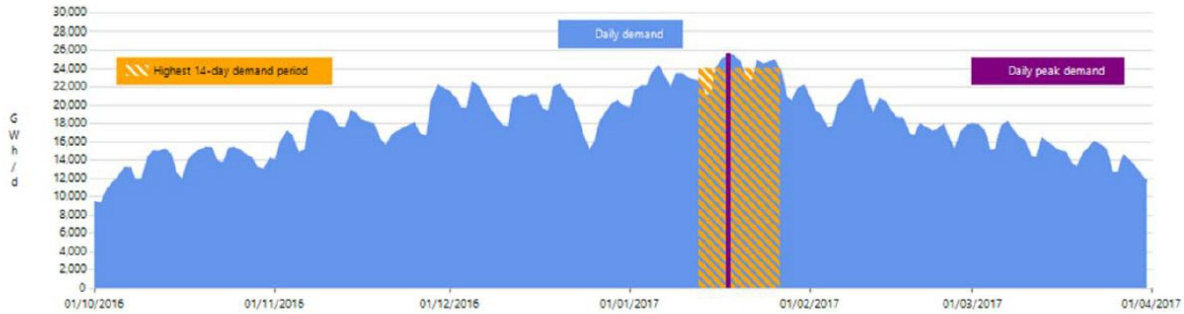
In the Winter Review 2016/2017 by ENTSO-G (ENTSO-G, 2020), it is stated that natural gas consumption for power generation reached its highest level in the last seven years in January 2017 due to the combined effect of low availability of nuclear plants and limited renewable generation. Total electricity generated by gas amounted to 65 TWh in the EU in January 2017, the highest since January 2010. On the other hand, the electricity produced from gas in the winter of 2016/2017 was 316 TWh_e, representing 20% of the generation mix (ENTSO-G, 2020).

Table 5. Country values (MW) on the days of highest and lowest ENTSO-E load values.

	18.01.2017 18:00–19:00	11.06.2017 05:00–06:00		18.01.2017 18:00–19:00	11.06.2017 05:00–06:00		18.01.2017 18:00–19:00	11.06.2017 05:00–06:00
AL	1 340	524	**FI**	12 004	7 024	**ME**	567	237
AT	11 279	4 951	**FR**	93 910	31 729	**MK**	1 272	471
BA	2 041	907	**GB**[3]	62 083	22 124	**NL**	17 658	9 510
BE	13 270	6 792	**GR**	8 323	4 021	**NO**	19 576	9 968
BG	7 059	2 868	**HR**	2 890	1 422	**PL**	23 684	11 421
CH	9 724	5 531	**HU**	6 253	3 369	**PT**	8 308	4 156
CY	711	369	**IE**	4 404	2 093	**RO**	8 491	4 449
CZ	10 399	4 661	**IS**	2 234	1 997	**RS**	6 814	2 503
DE	77 860	36 241	**IT**	52 336	22 774	**SE**	22 013	10 010
DK	5 373	2 357	**LT**	1 749	893	**SI**	2 134	1 116
EE	1 264	577	**LU**	776	440	**SK**	4 433	2 421
ES	39 783	21 475	**LV**	1 100	532	**TR**	38 162	23 486
						*	**581 276**	**265 419**

Source: Statistical factsheet 2017 (ENTSO-E, 2020b).

Figure 9. Total gas demand (GWh/d) daily profile in winter 2016/2017. Daily demand is represented by blue, the highest 14-day demand period is highlighted in yellow, and the daily peak demand is indicated in purple.



Source: ENTSO-G, Winter Review 2016-17 (ENTSO-G, 2020).

We can adopt three different approaches depending on the importable and exportable capacities when the electricity system is in a critical situation:

— Domestic approach: We neglect the importable and exportable capacity from the computation of this indicator. Then, the adequacy assessment is performed under domestic conditions only. In this case, we disregard the cross-border dimension since there could be countries that rely partially on imports to reach adequacy (and for that, other countries borrow part of their capacity to others), which would distort the resulting criticality index.

— Selfish approach: The importable capacity is introduced in the estimation to alleviate the possible deficit of generating capacity, while the exportable capacity is set to zero. In this case, imports from neighbouring electricity systems may support meeting the domestic demand.

— Generous approach: The exportable capacity is only considered in the estimation. Some countries may be able to fulfil generation adequacy even under a complete disruption of the gas-fired generation fleet. However, the criticality index may be worsen for other countries.

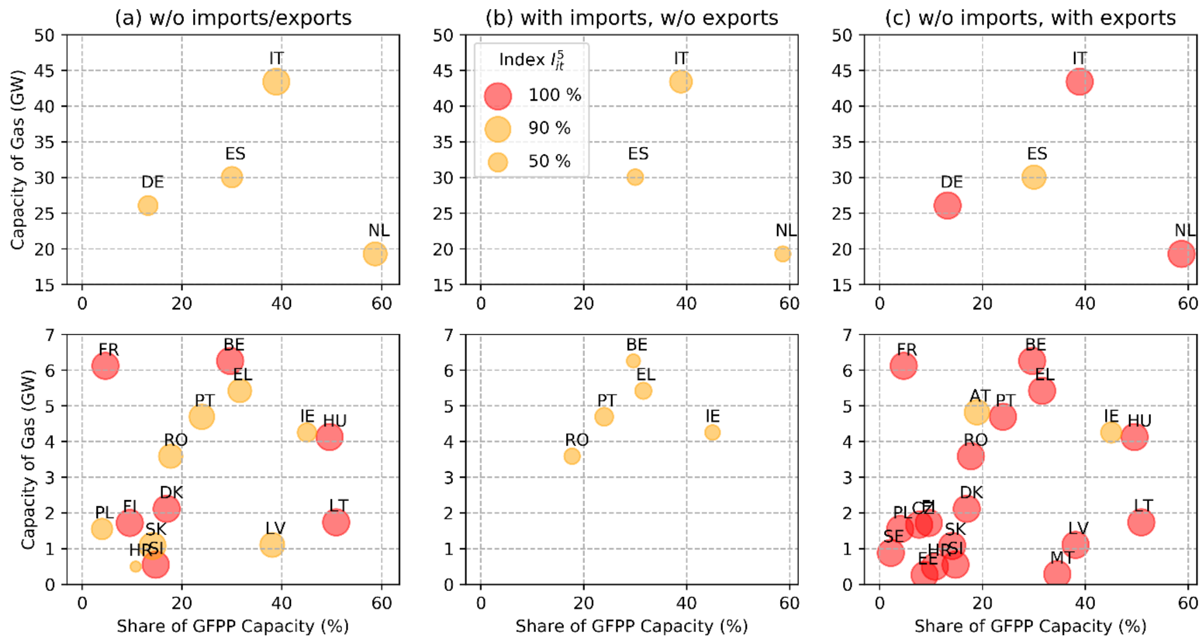
Figure 10 presents the results for the deterministic compound indicator under severe conditions for each MS plotted against the capacity of the fleet of GFPPs and the share of GFPP capacity in the electricity mix for the three approaches: (a) the two leftmost plots show results when imports and exports are neglected, (b) the plots in the middle column show the results when a selfish approach is considered, and (c) the two rightmost plots show the results under the assumption of a generous approach, i.e., only exportable capacity is accounted for. Note that the capacity of the fleet of GFPPs (in absolute values) may give an idea of the gas consumption due to electricity generation.

In Figure 10, we can observe quite different results for this indicator. The heterogeneity of national demand profiles and supply sources is leading to vastly different index values. A value of 100% (red circle) indicates that electricity demand cannot be met even if the full capacity of GFPP were available. The additional capacity deficit beyond the unavailability of GFPPs is presented in Table 6.

Under the severe load and power generation conditions of the ENTSO-E Winter Outlook (ENTSO-E, 2020c), it is clear that some countries would be unable to meet their electricity demand if a complete cut of gas supply occurred. When the cross-border flows are ignored (see Figure 10.(a)), this applies to seven EU MSs, namely Belgium, France, Hungary, Lithuania, Denmark, Finland, and Slovenia. Other countries also show high values for the index, making it necessary for all these countries to address the challenges of potential gas supply crises that coincide with severe conditions in the power system. For instance, Italy, Spain, the Netherlands, and Germany, which have a high capacity of GFPPs, or Ireland, which has a high share of GFPP capacity in the electricity mix.

Under a selfish approach wherein the importable capacity is included in the calculations, we clearly see in Figure 10.(b) that the global situation in the EU MSs would substantially improve. More countries would now be able to cover their electricity demand. Although the problem still remains for eight countries, the critical GFPP index takes lower values compared to the above approach. The insufficient available generation capacity is now partially compensated by the energy imported from neighbouring countries. The latter demonstrates the benefits of increasing the interconnector capacities in the European system to manage crisis situations. This approach would be in line with the current EU regulation (Regulation (EU) No 2017/1938) where cross-border cooperation is promoted among MSs.

Figure 10. Deterministic capacity-based compound indicator (%) under severe conditions for EU-27 countries as function of gas-fired generation capacity (GW) and the share of gas-fired generation in the electricity mix (%). Results for the three approaches are shown: (a) without imports or exports, (b) selfish approach, i.e., with imports but without exports, and (c) generous approach, i.e., without imports and with exports. Note that the circle size represents the value of the compound indicator and a red circle highlights that the index reaches the value of 100%.



Source: JRC, 2022.

In contrast, under a generous approach in which the full exportable capacity is taken into consideration in the computations while imports are neglected, most of the countries reach 100% of criticality, as observed in Figure 10.(c). The index for Spain increases from 60.9% when accounting only for domestic conditions to 79.2%. This result can be explained due to the low exportable capacity of Spain compared to its total net generating capacity, which is around 4.3% for the severe conditions reported on 18 January 2017. Similarly, the index for Ireland increases from 49.7% to 59.9% (not reaching 100%) due to its low exportable capacity. Bulgaria is not even critical under the disruption of the gas-fired generation units because its gas capacity amounts to 0.8 GW only (around 6% of the total net generating capacity of 12.71 GW), the exportable capacity is also low (1.33 GW), and the remaining capacity for severe conditions is estimated to be 1.8 GW.

Table 6. Deterministic capacity-based compound indicator (%) under severe conditions and additional capacity deficit (%) for three approaches: (a) without imports or exports, (b) selfish approach, i.e., with imports but without exports, and (c) generous approach, i.e., without imports and with exports.

Country code	w/o imports/exports		with imports, w/o exports		w/o imports, with exports	
	I_{it}^{5}	Additional capacity deficit	I_{it}^{5}	Additional capacity deficit	I_{it}^{5}	Additional capacity deficit
FI	100.0	306.2	0	0	100.0	625.2
SI	100.0	73.4	0	0	100.0	741.1
FR	100.0	58.5	0	0	100.0	339.9
HU	100.0	40.2	0	0	100.0	180.1
LT	100.0	15.9	0	0	100.0	235.3
DK	100.0	13.0	0	0	100.0	363.1
BE	100.0	9.9	25.8	0	100.0	113.4
SK	98.8	0	0	0	100.0	473.4
IT	97.9	0	69.7	0	100.0	11.0
PT	88.0	0	46.7	0	100.0	60.6
LV	83.5	0	0	0	100.0	165.1
RO	79.0	0	35.6	0	100.0	25.4
NL	77.6	0	33.7	0	100.0	21.4
EL	76.0	0	39	0	100.0	11.0
PL	61.5	0	0	0	100.0	144.9
ES	60.9	0	36.4	0	79.2	0
DE	52.7	0	0	0	100.0	26.9
IE	49.7	0	31.8	0	59.9	0
HR	16.2	0	0	0	100.0	458.5
BG	0	0	0	0	0	0
CZ	0	0	0	0	100.0	143.4
EE	0	0	0	0	100.0	827.9
CY	0	0	0	0	0	0
LU(*)	0	0	0	0	0	0
MT	0	0	0	0	100.0	12.0
AT	0	0	0	0	87.4	0
SE	0	0	0	0	100.0	1842.1

(*) Note that simultaneous importable/exportable capacities border between Luxembourg and Germany are considered unlimited because of the common bidding zone.

Source: JRC, 2022.

Probabilistic compound indicator under severe conditions

As stated previously, we run Monte Carlo simulations for 500 samples in which the FOR and the non-usable capacity are each drawn from a uniform distribution with a certain variability around the average values reported by the ENTSO-E Winter Outlook (ENTSO-E, 2020c). We take a 1% of variability for the FOR since we assume that the failure rate of the elements of the transmission system is very low and the reported average values are good estimates. For the non-usable capacity, we assume three different scenarios of variability, i.e. 1%, 5%, and 10%. For the electricity demand, we use the average given by the ENTSO-E Winter Outlook (ENTSO-E, 2020c), corrected by the load forecast error, which is sampled from a normal distribution. The load forecast error depends on the country and the year. Those parameters can easily be computed with the actual and forecast load given by ENTSO-E[11].

We focus our analysis on the year 2017 under the domestic approach, in which imports and exports are precluded for the computation of the indicator. Table 8 classifies the EU MSs based on whether the average value of the probabilistic indicator for the 500 samples is 100%, 0%, or lies between 0% and 100% for the three values of the non-usable capacity. The countries where the gas-electricity interaction is in all cases critical (i.e. the indicator is above 100%) are Finland, Slovakia, Hungary, and Lithuania, regardless of the variability of the non-usable capacity. On the opposite site, there are some countries where the gas-electricity interaction is weak, which is the case for Luxembourg, Estonia, Bulgaria, Cyprus, Czechia, and Sweden.

Table 7. Descriptive statistics for the probabilistic index under the three scenarios of non-usable capacity variability per EU member state.

	Non-usable capacity variability											
	1%				**5%**				**10%**			
	Mean	**Std**	**Min**	**Max**	**Mean**	**Std**	**Min**	**Max**	**Mean**	**Std**	**Min**	**Max**
BE	100	0	100	100	100	0	100	100	99.7	0.9	96.1	100
DK	100	0	100	100	100	0.1	99.2	100	98.2	3.7	85.3	100
FI	100	0	100	100	100	0	100	100	100	0	100	100
FR	100	0	100	100	100	0	100	100	98	5	78.9	100
HU	100	0	100	100	100	0	100	100	100	0	100	100
LT	100	0	100	100	100	0	100	100	100	0	100	100
SI	100	0	100	100	100	0	100	100	100	0	100	100
SK	98.4	1.5	95.1	100	95	6	80.1	100	90.6	11.6	60.2	100
IT	97.9	0.9	96.4	99.4	96.9	3.2	90.4	100	95.1	5.6	82.9	100
PT	88	1.2	85.9	90.2	88	6.2	77.2	98.9	87	10.9	66.3	100
LV	83.4	0.6	82.5	84.4	83.4	2.8	78.7	88.2	83.4	5.6	73.9	93
RO	78.9	1.5	76.4	81.6	78.9	7.4	66	92	78.5	14.5	52.9	100
NL	77.6	0.4	76.8	78.4	77.6	2.2	73.5	81.8	77.5	4.4	69.2	85.9
EL	76	0.7	74.8	77.3	75.9	3.7	69.9	82.2	75.7	7.4	63.7	88.4
PL	61.7	7.6	48.2	74.7	59.5	33.6	0	100	55.9	42	0	100
ES	60.9	1	59	62.7	60.8	5.1	51.5	70.1	60.7	10.2	42.1	79.2
DE	52.7	2.8	47.8	57.5	52.7	14.2	28.1	76.8	52.7	28.4	3.3	100
IE	49.7	0.3	49.1	50.3	49.6	1.7	46.7	52.6	49.6	3.5	43.8	55.5
HR	16.2	0.6	15.1	17.3	16.3	3.1	10.8	21.5	16.3	6.2	5.4	26.8
AT	0	0	0	0	0.4	0.9	0	3.8	2.2	3.9	0	13.3
BG	0	0	0	0	0	0	0	0	0	0	0	0
CY	0	0	0	0	0	0	0	0	0	0	0	0
CZ	0	0	0	0	0	0	0	0	0	0	0	0
EE	0	0	0	0	0	0	0	0	0	0	0	0
LU	0	0	0	0	0	0	0	0	0	0	0	0
SE	0	0	0	0	0	0	0	0	0	0	0	0

Source: JRC, 2022.

Table 7 provides numerical results for the probabilistic index under the three scenarios of non-usable capacity variability per MS. In particular, we can compare the mean and the standard deviation, as well as the lowest and highest value of the index throughout the 500 samples. As expected, the mean for the three different scenarios tends to the same value of the deterministic index since we use uniform and normal distributions to

[11] Note that we do not report any probabilistic index for Malta because we could not retrieve information about its actual and forecast load. Malta is not a member of ENTSO-E because it does not have a TSO.

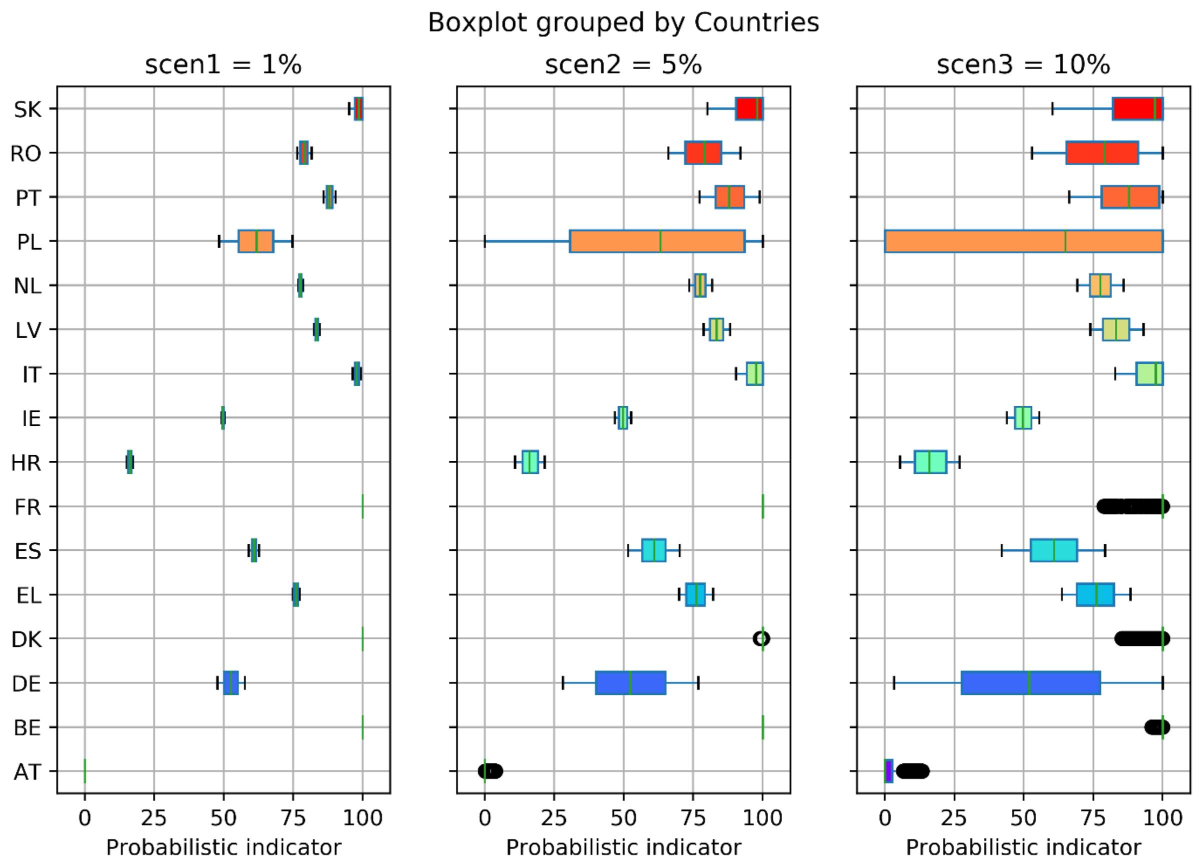
represent the random variables. However, we notice an increase of the standard deviation for some countries (e.g., Poland or Germany) when increasing the non-usable capacity variability to 5 and 10%. This is more clearly visible in the boxplot in Figure 11. This means that the strength of the gas-electricity interaction strongly depends on this random variable. For other countries such as Austria, France or Denmark, the criticality of the gas-electricity system is not sensitive to the non-usable capacity.

Table 8. Categorization of countries in terms of the average of the probabilistic indicator under the three scenarios of non-usable capacity variability.

Criterion	**Non-usable capacity variability**		
	1%	**5%**	**10%**
Mean of the indicator $I_{it}^5 = 100\%$	BE, FR, FI, SI, HU, LT, DK	BE, FR, FI, SI, HU, LT	FI, SI, HU, LT
Mean of the indicator $I_{it}^5 \in (0, 100)\%$	IT, PT, LV, RO, NL, EL, ES, PL, IE, DE, SK	DK, IT, PT, LV, RO, NL, EL, ES, PL, IE, DE, SK, AT	BE, DK, FR, IT, PT, LV, RO, NL, EL, ES, PL, IE, DE, SK, AT
Mean of the indicator $I_{it}^5 = 0\%$	AT, LU, EE, BG, CY, CZ, SE	LU, EE, BG, CY, CZ, SE	LU, EE, BG, CY, CZ, SE

Source: JRC, 2022.

Figure 11. Boxplot of the probabilistic indicator for EU member states with a standard deviation greater than zero for each scenario of non-usable capacity variability (1%, 5% and 10%).



Source: JRC, 2022.

3.3 Comparison of indicators

To wrap up, the energy-balance-based and capacity-based indicators computed in the previous sections are shown in Table 9. Capacity-based indicators are upper bounded by 100% (i.e. index $I_{i,2018}^{4}$ is limited to 100% for Hungary, the Netherlands, and Lithuania) and a red scale is applied to the cells to highlight values reaching this limit. Needless to say that one should be careful when analysing these results and keep in mind the meaning of each indicator. On the one hand, the energy-balance-based indicators show the share of electric energy produced by gas in the final electricity consumption ($I_{i,2018}^{1}$), the share of consumption of natural gas used for electricity generation ($I_{i,2018}^{2}$), and the geometric mean of these two indicators ($I_{i,2018}^{3}$), respectively. On the other hand, the capacity-based indicator $I_{i,2018}^{4}$ shows the country's generation adequacy after a complete gas interruption under peak load conditions, whereas the index $I_{i,2017}^{5}$ represents a relative measure of the electric supply deficit caused by the shortage of GFPPs under severe conditions accounting for planned and unplanned outages, non-usable capacity, reserves and, depending on the scenario (i.e. domestic, selfish, or generous), imports or exports.

Table 9. Energy-balance-based and capacity-based indicators computed in previous sections.

Country code	Energy-balance-based indicators			Capacity-based indicators			
	$I_{i,2018}^{1}$	$I_{i,2018}^{2}$	$I_{i,2018}^{3}$	$I_{i,2018}^{4}$	$I_{i,2017}^{5}$		
					Domestic	Selfish	Generous
BE	28	25	27	86	100	26	100
BG	6	24	12	62	0	0	0
CZ	6	12	9	57	0	0	100
DK	6	16	10	55	100	0	100
DE	16	21	18	42	53	0	100
EE	1	3	2	58	0	0	100
IE	59	55	57	88	50	32	60
EL	28	66	43	75	76	39	100
ES	24	33	28	55	61	36	79
FR	7	14	10	79	100	0	100
HR	14	23	18	77	16	0	100
IT	42	39	41	96	98	70	100
CY	0	0	0	-	0	0	0
LV	48	50	49	74	84	0	100
LT	3	11	6	100	100	0	100
LU	3	9	5	-	0	0	0
HU	18	16	17	100	100	0	100
MT	73	100	85	-	0	0	100
NL	51	31	40	100	78	34	100
AT	15	26	20	62	0	0	87
PL	8	14	11	69	62	0	100
PT	32	58	43	59	88	47	100
RO	21	27	24	54	79	36	100
SI	3	13	7	74	100	0	100
SK	7	11	9	68	99	0	100
FI	5	38	14	92	100	0	100
SE	0	15	2	69	0	0	100

Source: JRC, 2022.

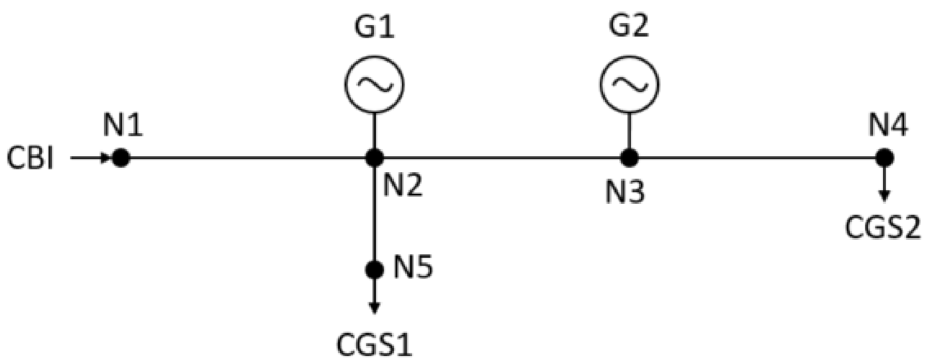
Some countries with a low or moderate dependence of the electricity system on gas-fired generation when looking at the energy-balance-based indicators, such as Lithuania or Hungary, show a critical gas-electricity interaction when it comes to the capacity-based indicators (except under a selfish approach). All indicators for other countries, such as Italy or Greece, lead to the same direction with regard to the interaction strength of the gas-electricity system. We can also observe that the deterministic compound indicator under a selfish approach (i.e. only imports are accounted for in the computation of this index) generally follows a similar pattern than the energy-balance-based indicators. However, we can spot some exceptions, such as the case of Malta, in which the energy-balance-based indicators suggest a high dependence of its electricity system on gas, but its capacity-based indicators under the domestic and selfish approaches do not identify such dependence as critical under a complete gas shortage. All in all, although the indicators may signal a strong dependence of the electricity and gas systems, we need to resort to modelling-based approaches for a clearer picture of their interaction strength.

4 Modelling approaches for more detailed analyses

Energy-balance-based and capacity-based indicators can give us a rough estimate of the strength of the country-wide gas-electricity interaction and how it evolves over time. If the indicator suggests that the electricity and gas systems may lead to a critical situation in a certain country, we need to resort to mathematical programming for an in-depth analysis of the combined system, regardless of the degree of modelling detail. In addition, disregarding the structure and physical behaviour of electricity and gas transmission networks makes it rather impossible to identify single critical GFPPs of a country or region and accordingly rank GFPPs by their criticality, which are the main goals of the coming deliverables.

In the following illustrative example, we show the importance of accounting for the network topology, even when the critical GFPP is already identified as such. Let us consider a natural gas network made of five nodes and four pipelines, as depicted in Figure 12. Node 1 (N1) is a cross-border import station (CBI), nodes 2 and 3 represent GFPPs (G1 and G2, respectively), and the customers connected at nodes 4 and 5 are considered protected customers (CGS1 and CGS2). Also, let us assume that the second GFPP (G2) located at Node 3 is critical for the security of the electricity supply.

Figure 12. Natural gas network for the illustrative example.



Source: JRC, 2022.

Several pressure-related constraints are enforced in the natural gas system: (i) the pressure at node 1 is limited to 55 bar-g, (ii) the minimum delivery pressure at each GFPP is set to 30 bar-g, and (iii) the minimum delivery pressure at each CGS is set to 16 bar-g. Note that the gas offtakes of GFPPs must be curtailed if the minimum pressure constraint is violated and, in the worst case, they must be shutdown. We run a steady-state hydraulic simulation by using the software encoord® SAInt (SAInt, 2020). Next, we analyse four scenarios whose results are shown in Table 10:

— **Scenario S0**. We consider a gas peak demand period in which the gas offtakes are 200 km^3/h for each GFPP, 500 km^3/h for CGS1 and 520 km^3/h for CGS2. In this scenario, the nodal pressures at three gas offtake stations (the two GFPPs and CGS2) fall below their minimum delivery pressures. Probably, the second GFPP G2 needs to be shut down because its pressure (17.9 bar-g) is far below the limit of 30 bar-g. However, this GFPP is critical for the operation of the electricity system and the supply of gas to the CGS2 needs to be secured because it is a protected customer. Therefore, actions must be taken for a secure and reliable operation of the gas system.

— **Scenario S1**. Now we assume that the GFPP G1, which is not designated as critical, is shut down. In this scenario, all pressure-related constraints are fulfilled except for the critical GFPP G2. This is not a desirable solution since it may cause a disruption of gas supply to this critical power plant. Therefore, we have two options from the perspective of the gas system: (i) shutting down the GFPP G2, or (ii) curtailing gas to the CGS2. However, we do not know the impact on the electricity system since the model is myopic to the consequences on the power system, i.e. the electricity topology is not included in the simulation.

— **Scenario S2**. We assume that GFPP G2 is shut down instead of the GFPP G1. This case would be feasible, but we are neglecting the consequences of this action on the electricity system.

— **Scenario S3**. In this scenario, gas offtake of CGS2 is curtailed in such a way that the minimum delivery pressure of GFPP G2 can be maintained. As a consequence, gas offtake of CGS2 is reduced by 26.8%. In other words, we prioritise the operation of the critical GFPP G2 over the protected customers. This scenario is feasible from both a joint gas-electricity perspective and a regulatory perspective.

This example illustrates the value of considering natural gas network topology and hydraulic modelling so that the nodal pressure profile can be traced in order to ensure gas supply. In addition, we highlight the need for coordination of gas and electricity systems and their joint modelling when it comes to analyse the operation of critical GFPPs, let alone the identification of these critical power plants. There are many criteria that the operators of both systems may consider in order to decide whether a GFPP should be designated as critical. However, it is clear that modelling gas and electricity system topologies matters to identify such GFPPs. Finally, we also illustrate an example on how critical GFPPs could be prioritised over protected customers.

Table 10. Gas flow and pressure at each node for all scenarios described in the illustrative example. Red cells indicate values violating minimum offtake constraints.

Variable	**S0**	**S1**	**S2**	**S3**
Q_1 (km^3/h)	1420	1220	1220	1286
Q_2 (km^3/h)	200	0	200	200
Q_3 (km^3/h)	200	200	0	200
Q_4 (km^3/h)	500	500	500	366
Q_5 (km^3/h)	520	520	520	520
P_1 (bar-g)	55.0	55.0	55.0	55.0
P_2 (bar-g)	29.4	37.9	37.9	35.5
P_3 (bar-g)	17.9	29.9	34.0	30.0
P_4 (bar-g)	6.4	24.8	29.7	27.4
P_5 (bar-g)	23.7	33.7	33.7	30.9

Source: JRC, 2022.

A fine space-time resolution allows for an accurate representation of the operation of both electricity and gas systems. However, one of the main caveats of using a modelling approach is the availability of data. The lack of available data may trigger two scenarios: (i) The mathematical model must rely on simpler formulations, thus avoiding the need of huge amounts of data, or (ii) we complement the data by estimates based on expert knowledge and statistics. Either way, according to our purposes, we need to take model-related decisions such as how to mathematically model the electricity and gas networks, whether to perform simulations of the operation of the combined system or, conversely, optimise it, what kind of software is suitable for such application, and so on. Therefore, it is desirable to compare the available options to model the electricity-gas interaction to studying security of supply questions in short-term (day-ahead), medium-term (year-ahead) and long-term planning horizons, such as the identification of the critical GFPP at country- or regional-level. Table 11 provides an overview of modelling approaches, which are further described in the following sections.

Table 11. Comparison of modelling approaches for the gas-electricity interaction.

Option	Suggested software	Approach	Model
Integrated system-wide optimisation of coupled gas and electricity networks	- Gas: Plexos - Electricity: Plexos	- Gas: Optimisation - Electricity: Optimisation	- Gas: Mass-balance model - Electricity: Unit commitment - Coupling: Integrated
Physical simulation of coupled gas and electricity networks	- Gas: SAInt - Electricity: SAInt or DIgSILENT	- Gas: Simulation - Electricity: Optimisation	- Gas: Dynamic simulation - Electricity: AC or DC OPF - Coupling: Integrated or iterative
Integrated optimisation coupled to network simulators to introduce additional constraints	- Gas: SAInt - Electricity: Plexos	- Gas: Simulation - Electricity: Optimisation	- Gas: Dynamic simulation - Electricity: Unit commitment - Coupling: Iterative
Integrated network-constrained optimisation of coupled gas and electricity networks	- Gas: Own model - Electricity: Plexos	- Gas: Optimisation - Electricity: Optimisation	- Gas: Steady-state simulation - Electricity: Unit commitment - Coupling: Iterative

Source: JRC, 2022.

4.1 Integrated system-wide optimisation of coupled gas and electricity networks

The PLEXOS Integrated Energy Modelling software (Plexos, 2020) is an "*object-oriented, rapid application development library that processes industrial-scale mathematical programming. In addition, its data-driven flexibility in the business logic and mathematics creates a dynamic formulation engine: it adapts to your data to deliver the right balance of detail and performance"*. PLEXOS is able to co-optimise coupled gas and electricity networks driven by the minimisation of total system costs. According to the gas applications outlined on the official website, the integrated optimisation of both markets can give insights about the following aspects:

- Value gas and electric storage options with dual fuel optimisation;
- evaluate gas and electric contingencies as well as the reliability impacts on the wider system;
- calculate least cost OPEX and CAPEX co-optimisation for expansion and retirement;
- create full end-to-end LNG modelling and co-optimise with electricity;
- identify emergence of gas constraints with generation retirements.

There are many problems from the power system sector that can be modelled with PLEXOS, such as economic dispatch and unit commitment problems, transmission expansion planning problems and market simulations. For our purposes, the electricity system can best be formulated as either an economic dispatch or a unit commitment problem by using a DC power flow model, especially to limit data requirements and numerical effort. On the other hand, the gas network could be represented as a mass-balance model as that is the only method PLEXOS is currently providing.

As a first step, a system-wide optimisation could be done where each country is represented by only one node, although large countries could also be split into several nodes reflecting their bidding zones. For example, Italy could be represented with up to six nodes. This approach cannot overcome the difficulties encountered with the indicators yet, i.e., it cannot identify single critical GFPPs, due to the coarse spatial granularity. To do that, we may need to focus on a specific country or region and co-optimise its integrated gas-electricity system with a finer spatial resolution (modelling the actual transmission grids). However, the use of PLEXOS could already lead to estimates about the criticality of GFPPs superior to the indicators developed in this report.

4.2 Physical simulation of coupled gas and electricity networks

In addition to the system-wide co-optimisation approaches presented in the previous section, there is a need for physical flow-based models to deal with security of supply questions. There are essentially two alternatives to describe the physical behaviour of coupled gas-electricity systems: (i) The use of the software encoord® SAInt (SAInt, 2020) for a co-simulation of the joint system, or (ii) the use of separate software for the gas and for the electricity system. Such a combination could for example consist of encoord® SAInt (SAInt, 2020) for modelling the gas system and DIgSILENT® PowerFactory (DIgSILENT, 2017) for modelling the power system.

The software encoord® SAInt (SAInt, 2020) is one of the few simulation tools currently available able to model the joint gas-electricity system. The gas system can be represented by using either a steady-state hydraulic model or a dynamic hydraulic model. The dynamic simulation mode allows for changes in the linepack, which may play a key role in security of supply questions. On the other hand, this software also integrates a power system module where the electricity system may be optimised by using a steady-state DC or AC load flow model. The user can choose from a co-simulation method and a combined simulation method.

DIgSILENT® PowerFactory (DIgSILENT, 2017) is a leading power system analysis software application for analysing generation, transmission, distribution, and industrial systems. The software encompasses a wide range of modelling approaches and analysis functions. The software can be coupled to encoord® SAInt (SAInt, 2020) by using their respective APIs via the Python programming language (Van Rossum and Drake Jr., 1995). This coupling between both tools may allow for a more accurate representation of both gas and electricity systems to perform scenario-based risk analysis as when solely relying on SAInt for modelling both systems. On the other hand, coupling both software comes with additional effort and using an integrated software environment to model the integrated gas-electricity system has clear benefits.

4.3 Integrated optimisation coupled to network simulators to introduce additional constraints

A close alternative to the coupling of gas-electricity sectors presented in the previous section is the linking between SAInt and PLEXOS. PLEXOS has a functionality by which external constraints can be introduced into their optimisation algorithms. The external constraints may be generated from simulating the gas system with hydraulic constraints by means of the software SAInt and, subsequently, a gas-constrained electricity system may be optimised by using PLEXOS. The optimisation of the power system in PLEXOS constrained by gas-related equations in SAInt may lead to more accurate results.

This approach has already been demonstrated by Pambour et al. (2018). In this work, they first ran the economic dispatch and unit commitment model set up in PLEXOS, then the gas fuel offtake is passed on to SAInt, and, finally, SAInt sent back to PLEXOS fuel offtake constraints to update the commitment and dispatch decisions. This coordination strategy was compared against a non-coordinated one in which the gas fuel offtake constraints were not reported back to PLEXOS. The analysis was conducted in a synthetic joint gas-electricity system. It was concluded that a coordinated gas-electricity system may lead to a reduction in curtailed gas during high stress periods, thus underlining the economic and reliability benefits of a coordinated strategy.

4.4 Integrated network-constrained optimisation of coupled gas and electricity networks

The ideal albeit time-consuming approach is the use of a full network-constrained optimisation of coupled gas and electricity sectors, which may for example be coded in the Python programming language by using the open-source package Pyomo (Hart et al., 2017). However, there is no need to implement another power system model since PLEXOS can give us, in principle, all the required functionalities. Therefore, our first recommendation for an integrated network-constrained optimisation is to implement a gas system operation model by using Python/Pyomo and this model may interact with PLEXOS by adding some gas-related constraints to its electricity system model, as already described in the previous subsection.

5 Conclusions

The current regulatory framework on the security of gas supply, namely Regulation (EU) No 2017/1938, introduces two main novelties. Firstly, the concept of critical gas-fired power plants (GFPPs) which can be designated by Member States (MSs) of the European Union. Second, its possible prioritisation over protected customers if the lack of gas supply to such plants would result in severe damage in the functioning of the electricity system or would hamper the production or transportation of gas.

Within this regulatory framework, this report provided two main sets of tools:

- The identification and description of all major interaction mechanisms that exist between gas and electricity infrastructures.
- A set of pointers or indicators for the dependence of the electricity system on gas-fired generation.

The first part, and in particular Annex 1, can be used as a checklist to ensure that the interplay between gas and electricity systems are sufficiently covered in risk assessments. The set of indicators developed in the second part can be used to quantify the interaction strength of electricity systems on gas-fired generation across MSs. This can be considered as the main form of interaction between gas and electricity systems. Furthermore, an initial attempt to find sufficient data that could be used to construct indicators for the dependence of the gas system on electricity failed. Thus, this study focused only on the dependence of electricity systems on natural gas.

We proposed two groups of high-level statistical indicators: (i) energy-balance-based indicators in which energy and consumption balances of the EUROSTAT service are used, and (ii) capacity-based indicators in which installed electric generating capacities and annual peak electricity demand from ENTSO-E are accounted for. A more sophisticated capacity-based indicator was devised by considering other technical metrics: forced outage rates, reserves, non-usable capacity, and imports/exports under severe conditions, as presented in the ENTSO-E Winter Outlook. These indicators help understanding the interaction strength of the electricity system on gas-fired generation within the European Union on a high level. They can be also used as screening tools to identify regions in which the interdependency gas-electricity is of increased relevance, which may further be analysed by more sophisticated modelling-based tools. An overview of sophisticated modelling approaches was also provided in this report. Further modelling-based results could be discussed in follow-up reports.

This report represents that part of the gas-electricity that analyses the gas-electricity interaction without going into actual modelling of the individual transmission systems. However, as illustrated in the report, disregarding the structure and physical behaviour of electricity and gas transmission networks makes it virtually impossible to identify single critical GFPPs of a country or region and accordingly rank GFPPs by their criticality. Also, the cross-border aspect cannot adequately be addressed without a modelling approach. Therefore, modelling is key to accurately identify such critical GFPPs, which will be addressed in upcoming reports.

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List of abbreviations and definitions

ACER	Agency for the Cooperation of Energy Regulators
BEV	Battery-electric vehicle
CC	Combined cycle
CCGT	Closed cycle gas turbine
CS	Compressor station
CHP	Combined heat and power plant
CNG	Compressed natural gas
DG ENER	European Commission Directorate-General for Energy
DSO	Distribution system operator
EC	European Commission
ENTSO-E	European Network of Transmission System Operators for Electricity
ENTSO-G	European Network of Transmission System Operators for Gas
EP	Emergency plan
EU	European Union
GFPP	Gas-fired power plant
GW	Gigawatt
GWh	Gigawatt-hour
HPP	Hydro power plant
JRC	Joint Research Centre
LNG	Liquefied natural gas
MS	Member state
MW	Megawatt
MWh	Megawatt-hour
NG	Natural gas
OCGT	Open cycle gas turbine
PAP	Preventive action plan
PHEV	Plugin-hybrid electric vehicle
PP	Power plant
RA	Risk assessment
RES	Renewable energy sources
SCGEP	Share of consumption of natural gas used for electricity production
SEPGC	Share of the final electricity consumption produced by natural gas
TJ	Terajoule
TSO	Transmission system operator
TYNDP	Ten Year Network Development Plan
UGS	Underground gas storage

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Annexes

Annex 1. Checklist gas-electricity interaction

Gas infrastructure

General statistics

Of general interest are metrics concerning the use of gas in the whole country:

- Countrywide yearly final gas consumption (mcm).
- Countrywide peak gas consumption (mcm/d).
- Countrywide yearly final gas consumption used for the production of electricity (mcm), compared to the total gas consumption.
- Countrywide peak gas consumption used for the production of electricity (mcm/d), compared to total peak gas consumption.

List of relevant gas facilities that rely on electricity to operate:

Gas-driven compressor stations

Electricity is necessary to operate specific components of compressor facilities. Missing external electricity supply might limit their operation or make it entirely impossible. Of particular interest:

- Name and approximate location (municipality) of facility.
- Grid connection: Pipeline branch on which the facility is located and electric circuit(s) that the facility is connected to.
- Minimum gas suction pressure.
- On-site equipment (e.g. pumps, valves, SCADA) requiring electricity supply to operate but that can be operated manually in the lack of electricity supply.
- On-site electrically operated equipment (e.g. pumps, valves, SCADA) for which manual control is either impossible or considerably limiting the operation of the facility in the absence of electricity supply.
- Resulting de-rating factor of the facility due to lack of electricity; i.e.: decrease in power or capacity, or in any other relevant operation attribute.

Backup power generators and uninterruptible power supply:

- Capability of backup power generators and uninterruptible power supply: electric capacity and to what extend this capacity is able to cover the power demand of the facility.
- Type of backup fuel (e.g. diesel, heavy-fuel oil).
- Storage of backup fuel:
    - Volumetric capacity of on-site storage tanks for backup fuel.
    - Actual quantity of backup fuel typically kept on site at all times (might be less than volumetric capacity of storage tanks).
    - Any additional requirements to use backup fuel (e.g. electric preheating of heavy fuel oil).
- Time (grace period) during which the facility could continue to operate without external electricity supply (solely on backup fuel) with only the backup fuel stored on-site (without additional deliveries) at maximum power capacity.
- Accessibility: Ability to ship additional backup fuel to the site when running out of backup fuel when facing longer crises.
    - Is there any well designed plan to provide continuous supply of replacement fuel after the exhaustion of the replacement fuel stored on site?
    - If such a plan exists, does it consider possible contingencies affecting the supply chain of the replacement fuel?

  - Could the supply of replacement fuel be disrupted under some likely conditions?

Electrically driven compressor stations

Here, electricity is not only necessary to operate specific components, but the whole facility is relying on external power supply for doing the actual work. Missing external electricity supply could only partially be compensated by backup generators. Of particular interest:

- Name and approximate location (municipality) of facility.
- Grid connection: Pipeline branch on which the facility is located and electric circuit(s) that the facility is connected to.
- Minimum gas suction pressure.
- Electric grid connection: Electric circuit(s) or substation(s) where the facility gets its power from.
- Power consumption at different derating levels.

Backup power generators and uninterruptible power supply:

- Capability of backup power generators and uninterruptible power supply: electric capacity and to what extend this capacity is able to cover the power demand of the facility.
- Type of backup fuel (e.g. diesel, heavy-fuel oil).
- Storage of backup fuel:
  - Volumetric capacity of on-site storage tanks for backup fuel.
  - Actual quantity of backup fuel typically kept on site at all times (might be less than volumetric capacity of storage tanks).
  - Any additional requirements to use backup fuel (e.g. electric preheating of heavy fuel oil).
- Time (grace period) during which the facility could continue to operate without external electricity supply (solely on backup fuel) with only the backup fuel stored on-site (without additional deliveries) at maximum power capacity.
- Accessibility: Ability to ship additional backup fuel to the site when running out of backup fuel when facing longer crises.
  - Is there any well designed plan to provide continuous supply of replacement fuel after the exhaustion of the replacement fuel stored on site?
  - If such a plan exists, does it consider possible contingencies affecting the supply chain of the replacement fuel?
  - Could the supply of replacement fuel be disrupted under some likely conditions?

Gas storage facilities

Even without electricity as main driver, electricity might be necessary to operate specific components of storage facilities which might limit or make impossible their operation. As crises usually take place during withdrawal period (winter), we focus on this mode of operation. Of particular interest:

- Name and approximate location (municipality) of facility.
- Grid connection: Pipeline branch to which the facility is connected.
- On-site equipment (e.g. pumps, valves, SCADA) requiring electricity supply to operate but that can be operated manually in the lack of electricity supply.
- On-site electrically operated equipment (e.g. pumps, valves, SCADA) for which manual control is either impossible or considerably limiting the operation of the facility in the absence of electricity supply.
- Resulting de-rating factor of the facility due to lack of electricity (mostly decreased send-out capacity).

Backup power generators and uninterruptible power supply:

- Capability of backup power generators and uninterruptible power supply: Electric capacity and to what extend this capacity is covering the power demand of the facility during the withdrawal period.

- Type of backup fuel (e.g. diesel, heavy-fuel oil).
- Storage of backup fuel:
  - Volumetric capacity of on-site storage tanks for backup fuel.
  - Actual quantity of backup fuel typically kept on site at all times (might be less than volumetric capacity of storage tanks).
  - Any additional requirements to use backup fuel (e.g. electric preheating of heavy fuel oil).
- Time (grace period) during which the facility could continue to operate without external electricity supply (solely on backup fuel) with only the backup fuel stored on-site (without additional deliveries) at maximum power capacity.
- Accessibility: Ability to ship additional backup fuel to the site when running out of backup fuel when facing longer crises.
  - Is there any well designed plan to provide continuous supply of replacement fuel after the exhaustion of the replacement fuel stored on site?
  - If such a plan exists, does it consider possible contingencies affecting the supply chain of the replacement fuel?
  - Could the supply of replacement fuel be disrupted under some likely conditions?

District heating facilities

Even without electricity as main driver, electricity might be necessary to operate specific components of district heating facilities which might limit or make impossible their operation. Of particular interest:

- Name and approximate location (municipality) of facility.
- Grid connection: Pipeline branch to which the facility is connected and electric circuit(s) that the facility is connected to.
- Delivery gas pressure to be able to produce power (bar-g).
- Gas consumption at maximum power production (mcm/d).
- On-site equipment (e.g. pumps, valves, SCADA) requiring electricity supply to operate but that can be operated manually in the lack of electricity supply.
- On-site equipment (e.g. pumps, valves, SCADA) for which manual control is either impossible or considerably limiting the operation of the facility in the absence of electricity supply.
- Resulting de-rating factor of the facility due to lack of electricity.

Backup power generators and uninterruptible power supply:

- Capability of backup power generators and uninterruptible power supply: Electric capacity and to what extend this capacity is covering the power demand of the facility.
- Type of backup fuel (e.g. diesel, heavy-fuel oil).
- Storage of backup fuel:
  - Volumetric capacity of on-site storage tanks for backup fuel.
  - Actual quantity of backup fuel typically kept on site at all times (might be less than volumetric capacity of storage tanks).
  - Any additional requirements to use backup fuel (e.g. electric preheating of heavy fuel oil)
- Time (grace period) during which the facility could continue to operate without external electricity supply (solely on backup fuel) with only the backup fuel stored on-site (without additional deliveries) at maximum power capacity.
- Accessibility: Ability to ship additional backup fuel to the site when running out of backup fuel when facing longer crises.

- Is there any well designed plan to provide continuous supply of replacement fuel after the exhaustion of the replacement fuel stored on site?
- If such a plan exists, does it consider possible contingencies affecting the supply chain of the replacement fuel?
- Could the supply of replacement fuel be disrupted under some likely conditions?

Some district heating facilities might have fuel-switching capabilities, although it might alter their heat capacity.

- Capability on alternative fuel: Heat capacity using alternative fuel instead of gas.
- Time (grace period) during which the facility can operate on alternative fuel using only the quantity of fuel stored on-site (without additional deliveries) at maximum heat capacity.
- Storage of alternative fuel:
    - Volumetric capacity of on-site storage tanks for alternative fuel.
    - Actual quantity of alternative fuel typically kept on site at all times (might be less than volumetric capacity of storage tanks).
    - Any additional requirements to use alternative fuel (e.g. electric preheating of heavy fuel oil).
- Accessibility: Ability to ship additional alternative fuel to the site when running out of alternative fuel when facing longer crises.
    - Is there any well designed plan to provide continuous supply of replacement fuel after the exhaustion of the replacement fuel stored on site?
    - If such a plan exists, does it consider possible contingencies affecting the supply chain of the replacement fuel?
    - Could the supply of replacement fuel be disrupted under some likely conditions?

Gas-fired power plants (in their role as gas consumer)

Some gas-fired power plants might have fuel-switching capabilities, although it might alter their heat capacity. Of particular interest:

- Name and approximate location (municipality) of facility.
- Grid connection: Pipeline branch to which the facility is connected and electric circuit(s) that the facility is connected to.
- Delivery gas pressure to be able to produce power (bar-g).
- Gas consumption at maximum power production (mcm/d).
- Capability on alternative fuel: Power capacity using alternative fuel instead of gas.
- Time (grace period) during which the facility could operate on alternative fuel using only the quantity of fuel stored on-site (without additional deliveries) at maximum power capacity.
- Storage of alternative fuel:
    - Volumetric capacity of on-site storage tanks for alternative fuel.
    - Actual quantity of alternative fuel typically kept on site at all times (might be less than volumetric capacity of storage tanks).
    - Any additional requirements to use alternative fuel.
- Accessibility: Ability to ship additional alternative fuel to the site when running out of alternative fuel when facing longer crises.
    - Is there any well designed plan to provide continuous supply of replacement fuel after the exhaustion of the replacement fuel stored on site?
    - If such a plan exists, does it consider possible contingencies affecting the supply chain of the replacement fuel?
    - Could the supply of replacement fuel be disrupted under some likely conditions?

Liquefied Natural Gas (LNG) regasification terminals

Even without electricity as main driver, electricity might be necessary to operate specific components of LNG regasification terminals which might limit or make impossible their operation. Of particular interest:

- Name and location of facility.
- Grid connection: Pipeline branch to which the facility is connected and electric circuit(s) that the facility is connected to.
- On-site equipment (e.g. low-pressure and high-pressure pumps, valves) requiring electricity supply to operate but that can be operated manually in the lack of electricity supply.
- On-site electrically operated equipment (e.g. low-pressure and high-pressure pumps, valves) for which manual control is either impossible or considerably limiting the operation of the facility in the absence of electricity supply.
- Resulting de-rating factor of the facility due to lack of electricity (mostly decreased send-out capacity).

Power Plants on-site:

- Is there any Power Plant on-site?
- If there is any, what is its role?
- Does it have the capability to work in island mode and continue providing electricity to the entire site in case of a disruption of external power supply?

Backup power generators and uninterruptible power supply:

- Capability of backup power generators and uninterruptible power supply: Electric capacity and to what extend this capacity is covering the power demand of the facility.
- Type of backup fuel (e.g. diesel, heavy-fuel oil).
- Storage of backup fuel:
    - Volumetric capacity of on-site storage tanks for backup fuel.
    - Actual quantity of backup fuel typically kept on site at all times (might be less than volumetric capacity of storage tanks).
    - Any additional requirements to use backup fuel (e.g. electric preheating of heavy fuel oil).
- Time (grace period) during which the facility could continue to operate without external electricity supply (solely on backup fuel) with only the backup fuel stored on-site (without additional deliveries) at maximum power capacity.
- Accessibility: Ability to ship additional backup fuel to the site when running out of backup fuel when facing longer crises.
    - Is there any well designed plan to provide continuous supply of replacement fuel after the exhaustion of the replacement fuel stored on site?
    - If such a plan exists, does it consider possible contingencies affecting the supply chain of the replacement fuel?
    - Could the supply of replacement fuel be disrupted under some likely conditions?

Electricity infrastructure

General statistics

- Countrywide yearly final electricity consumption (MWh).
- Countrywide peak electricity consumption (MW).
- Countrywide yearly total electricity production (MWh).
- Countrywide yearly gas-fired electricity production (MWh).
- Countrywide total installed electricity-generating capacity (MW).

- Countrywide installed gas-fired electricity generating capacity (MW), as compared to the total generating capacity, and to which extent it is able to cover peak demand.

Note that the installed gas-fired generating capacity might exceed the actual gas-fired electricity production, which is why it is important to know both.

Gas-fired power plants (in their role as power producer)

- Grid connection: Name and approximate location (municipality).
- Electric circuit(s) that the facility is connected to.
- Type of the facility: Combined heat and power or sole power producer.
- Possible operational modes: Capacity to produce only heat (MW_{th}), capacity to produce only power (MW_e) and capacity to produce heat and power in cogeneration mode (MW_{th}, MW_e).

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