Artelys | OPTIMIZATION SOLUTIONS

Investigation on the interlinkage between gas and electricity scenarios and infrastructure projects assessment

Full report

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1 Introduction and objectives of the focus study

Context

As the electricity and gas systems interact continuously through a wide range of technologies, ranging from gas-to-power technologies (e.g. CCGTs) to power-to-gas technologies (e.g. electrolysis and methanation), via hybrid technologies (e.g. hybrid heat-pumps), a closer cooperation between electricity and gas systems can help achieving climate goals in a more cost-efficient way by exploiting the synergies between the two systems.

Even if substantial uncertainties remain regarding the evolution of the interlinkages between the electricity and gas sectors (level of electrification of end-uses, uptake of biomethane, role of power-to-gas, deployment of electric and gas mobility, etc.), the planning of electricity and gas infrastructure developments should involve a certain degree of coordination to allocate financial resources in an efficient way.

Regulation (EU) No 347/2013

Regulation (EU) No 347/2013 states that the “basis for the discussion on the appropriate allocation of costs should be the analysis of the costs and benefits of an infrastructure project on the basis of a harmonised methodology for energy-system-wide analysis, in the framework of the 10-year network development plans prepared by the European Networks of Transmission System Operators”.

To achieve this goal, Regulation (EU) No 347/2013 has tasked the ENTSOs with the development of a “consistent and interlinked electricity and gas market and network model including both electricity and gas transmission infrastructure”.

Overview of the interlinked model submitted by the ENTSOs

On 21 December 2016, the ENTSOG and ENTSO-E (hereafter the ENTSOs) have submitted the required interlinked model to the European Commission and the Agency for the Cooperation of Energy Regulators (ACER) for approval [1].

The key element of the model submitted by the ENTSOs is the joint development of scenarios that constitute the basis for the cost-benefit analysis of gas and electricity infrastructure projects.

Once the scenarios have been commonly established, the submitted model proposes that each of the ENTSOs performs the cost-benefit analysis of infrastructure projects based on their specific tools and methodologies, as is illustrated by Figure 1.

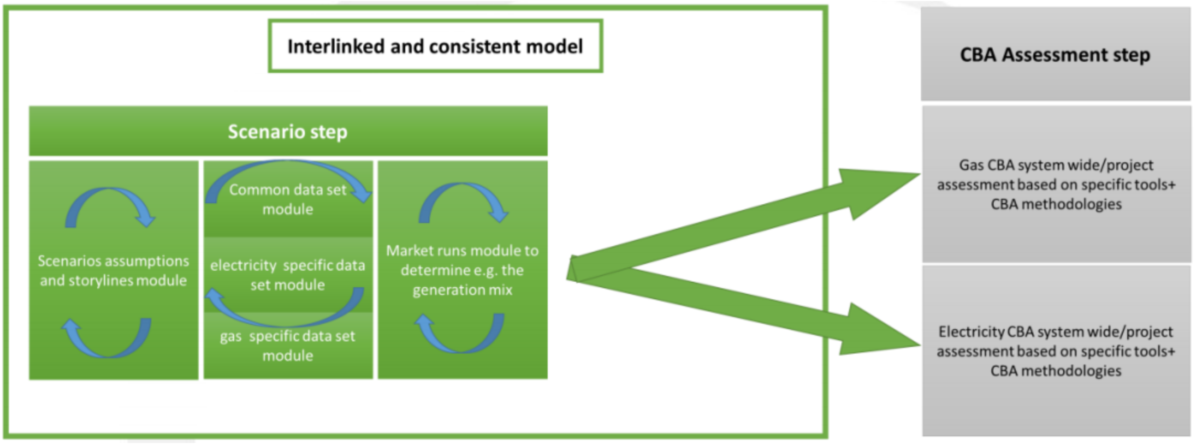


Figure 1 - Interlinked model and CBA steps. Source: [1]

The common development of the TYNDP scenarios by the ENTSOs ensure that the storylines are consistent and that a common database of input and assumptions is used by both associations (e.g. commodity and CO_2 prices).

The submitted model does not foresee any structural changes to the tools that are used in the sector-specific assessments, although it is the aim of the ENTSOs to continuously improve these tools for each new edition of their respective TYNDPs.

Overview of ACER's Opinion No 07/2017

In March 2017, ACER has published its opinion on the ENTSOs' draft consistent and interlinked electricity and gas market and network model [2]. ACER is of the view that the level of interlinkage between the modelling of the gas and electricity sectors is insufficient, and that the following phenomena should be investigated in further details:

- Interaction of the price formation process for the gas and electricity sectors;
- Interaction (potential competition and synergies) of electricity and gas infrastructure developments;
- Cross-sectoral influence of gas and electricity projects.

Objective of this focus study

The main objective of this focus study is to provide the ENTSOs with the elements allowing them to determine for which kind of projects a more thorough investigation of the impacts of interlinkages should be performed. In other terms, we aim at adding an intermediate layer between the green and grey areas shown on Figure 1. The intermediate layer is a screening process where:

- Projects that are assessed in a satisfactory manner with the current CBA methodologies are treated as usual
- Projects for which further interlinkages than those captured in the scenario building phase (green area) are of importance are detected and flagged for further investigation.

The objective of this study is to propose recommendations for the ENTSOs to develop the screening methodology described above. To achieve this objective, the focus study proceeds by first identifying all relevant interlinkages between the gas and electricity sectors, then qualitatively assess them via the definition and analysis of use-cases. The third step consists in a quantitative analysis of the use-cases to detect the cases where a more thorough investigation of gas and electricity interlinkages during the cost-benefit analysis would be valuable. Finally, the final task will be to propose recommendations for a screening process based on the quantitative results obtained in the third step.

Based on this work, the ENTSOs will develop a methodology to further analyse the impacts of interlinkages on the assessment of the projects that have been flagged by our proposed screening process.

Structure of this document

This document is a report of the work that has been done in this project. It is structured as follows:

- Section 2 provides a short literature review of the interactions between the gas and electricity sectors and of their potential evolutions, along to the way these interactions are modelled,
- Section 3 presents the results of Task 1, in which was done a generic mapping of all potential interactions between gas and electricity,
- Section 4 presents the results of Tasks 2 and 3 in which we have analysed qualitatively the interactions between gas and electricity and their potential effect on project assessment and quantified thresholds on parameters that might trigger interactions,
- Section 5 presents the results of Task 4 which summarizes the work performed and proposes recommendations on the screening methodology.
- Later sections are devoted to the appendices, references and glossary.

2 Gas and electricity interactions – A literature review

This section is devoted to the presentation of the European gas and electricity systems, of the different potential pathways towards the decarbonisation of the energy sectors and the corresponding roles gas and electricity may play in these scenarios, and of the way the interactions between gas and electricity are modelled in different contexts.

European gas and electricity systems – Key figures

As this focus study aims at assessing the potential impacts of interlinkages between the gas and electricity sectors on the assessment of projects, it can be useful to remind readers of key figures characterising the European gas and electricity systems. These order of magnitude will prove useful when analysing the potential impacts of interlinkages on project assessment in the subsequent tasks.

<u>European gas system</u>

In 2017, the European gas demand reached around 491 bcm, which corresponds to around 4800 TWh. The EU gas demand displays a strong seasonal behaviour as both production and consumption are around 1.5 times higher during wintertime (Q1 and Q4) than during warmer periods of the year (Q2 and Q3). On the other hand, gas imports do not exhibit such a strong seasonality. The EU gas system is characterised by a storage capacity of roughly 100 bcm. The storage units typically reach their maximum levels in October-November and minimum between February and April [3].

In Europe, gas is mainly used by industrial processes (around 1000 TWh in 2016), by the residential and commercial sectors for heating purposes (around 1800 TWh in 2016), and for power generation (around 1300 TWh of gas was used in power generation in 2016) [4].

Eurostat has Sankey diagram presenting the energy balance flows at the European level [4]. An example is provided below. We strongly encourage the reader to use this tool to obtain further insights on the structure of the European energy system and the role of the different energy vectors.

The following Sankey diagram shows the role of natural gas in the EU28 system in 2016, from import and production on the left, to final use on the right, via transformation steps in the middle (e.g. gas to electricity processes).

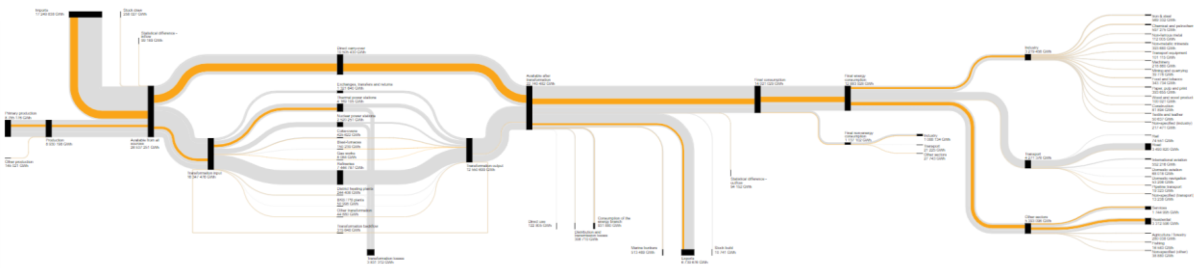


Figure 2 - Sankey diagram of the 2016 European energy flows (gas highlighted). Source: [4]

European electricity system

In 2017, the European electricity demand reached around 3700 TWh, of which around 770 TWh were produced by gas-fired power plants (CCGTs, OCGTs, CHPs) [5]. The European electricity system is undergoing a transition towards including more variable electricity generation technologies, such as wind turbines and solar panels.

The high level of interconnection between countries allows to dynamically adapt the output of the European generation portfolio according to external factors such as demand and weather patterns, and economic conditions. The total cross-border flows at the ENTSO-E level in 2017 reached around 450 TWh of imports and exports, the net position being very close from being balanced.

The following Sankey diagram shows the role of electricity in the EU28 system in 2016, from import on the left, to final use on the right, via transformation steps in the middle (e.g. RES, nuclear or fossil-based electricity generation).

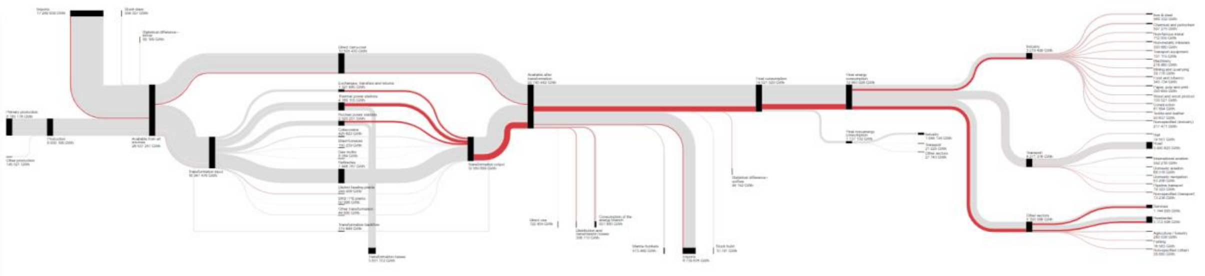


Figure 3 - Sankey diagram of the 2016 European energy flows (electricity highlighted). Source: [4]

The figures presented above represent the current situation of the gas and electricity systems. However, in order to meet the EU climate goals, and for the European energy system to transition towards a carbon-free energy system, the respective roles of the gas and electricity systems will change. The structure and importance of these changes are discussed below.

Potential impacts of decarbonisation on the gas and electricity sectors

The energy sector has a crucial role to play in order for the European Union to meet its ambitious decarbonisation objectives. The European Commission has recently been invited by the European Council to update its strategy for long-term EU greenhouse gas emissions reduction in accordance with the Paris Agreement by Q1 2019 [6]. This strategy is likely to rely on a total or close total decarbonisation of the electricity sector before 2050.

A successful decarbonisation strategy for the energy sector has to strongly involve energy efficiency measures and the use of renewable sources of energy in the electricity, heat, transport, and industrial sectors. Other carbon-neutral technologies such as nuclear power and CCS may also contribute to reaching the climate objectives, although the deployment of these solutions may subject to considerable political and/or technological uncertainties. In order to support the decarbonisation efforts, the role of infrastructure, and in particular of the gas infrastructure, may have to substantially change over the coming decades, depending on the pathway that will be selected to decarbonise the energy sector. We discuss a number of possible pathways (electrification of end-uses, green gas scenarios) and trends in the following paragraphs and shortly present their impacts in terms of infrastructure needs. Recent references include but are not restricted to [7], [8], [9], [10], [11].

Strong electrification of end-uses

One of the possible pathways towards decarbonisation of the energy sector is to electrify most of the end-uses. The set of end-uses that can electrified is substantial as it includes: heating and cooling in buildings (via district heating or heat pumps), mobility (passenger cars, delivery vans, trucks and vessels) and industry (hydrogen and synthetic methane production, heat production, etc.). A recent modelling work carried out by Eurelectric foresees that, at the EU level, direct electrification rates of more than 60% can be achieved in the transport and building sectors (compared to 1% and 34% in 2015 respectively), and a direct electrification rate of 50% can be reached in the industry [7].

Predicting the way the electricity and gas infrastructure would have to change in order to accompany a transition towards electrification is a challenging task. Relying solely on electricity for end-uses such as heating would result in a considerable pressure on the development of electricity transmission and distribution grids, and of electricity storage capacities. The gas infrastructure would have to develop in order to accommodate the power-to-gas and gas-to-power production, which will switch from using natural gas to using renewable gases. Estimating the importance of gas-to-power and power-to-gas generation has to take into account a number of factors such as the amount of deployed RES technologies, availability of electricity and gas storage, demand-response capacities, electricity and gas interconnection capacities, etc. and would require a specific modelling exercise. Finally, it is likely that not all end-uses would be electrified even in the most ambitious electrification scenarios. Gas could therefore have a role to play in mobility (e.g. heavy goods road transport) and industry (e.g. for the production of high-temperature heat, which is more difficult to generate with electricity).

Electricity and gas end-uses

Relying on a strong electrification of end-uses comes with its challenges, in particular in terms of electricity transmission and distribution infrastructure dimensioning. The pressure on these networks can be particularly acute during episodes with very cold temperatures as the demand for heat would have to be supplied by electricity only.

Maintaining gas end-uses would allow to reduce the strain on the electricity infrastructure, and, depending on the costs of equipment such as heat-pumps, might be a more cost-effective way of meeting the decarbonisation targets (see e.g. [8] in the gas of Germany). Analysing the costs of both strategies (relying on a strong electrification of end-uses or maintaining gas end-uses) is a complex exercise that has to take into account the latest projections of equipment costs (e.g. batteries, heat-pumps, etc.), the existing gas and electricity network and their respective expansion needs, etc.

End-uses that are eligible to directly consume gas (or other carriers but electricity) include mobility (where synthetic fuels are also an option), heating (either via direct gas heating or hybrid heat pumps) and industry.

A number of different scenarios can be elaborated, some involving a more important reliance on hydrogen, others favouring biomethane. The production of hydrogen and biomethane can either rely on power-to-gas installations or on the upgrading of biogas (as discussed above in the case of electrification). However, since the volumes of gas to be produced would be more important than in a scenario relying on strong electrification, the role of gas infrastructure would significantly differ from an electrification scenario, in particular at the distribution level since gas would have to be delivered to end-users.

An evolving technological landscape

Tackling the challenge of limiting the magnitude of climate change requires replacing carbon-emitting processes by carbon-neutral technologies by around 2050. As emphasised above, using energy more efficiently will be a key element of a successful decarbonisation pathway. The second key pillar will be the reliance of renewable energy, which will likely involve a number of technologies that are not yet mature and whose developments should be closely monitored. Besides energy efficiency, the following technologies are emerging as potential solutions to decarbonise the energy system:

- **Hydro, solar and wind** power generation will most probably remain the most important technologies in terms of overall generation volume of renewable electricity in Europe. The following figure presents the trend observed in Europe in terms of renewable electricity generation:

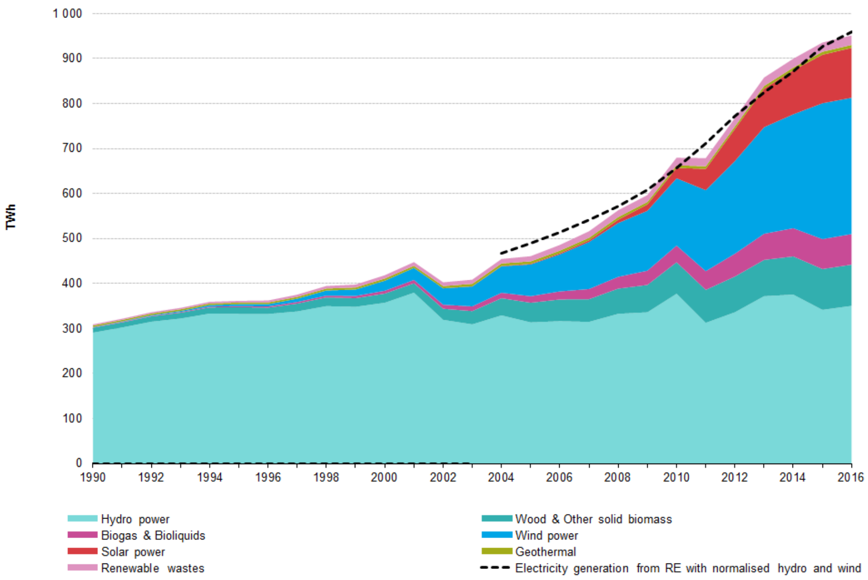


Figure 4 - Gross electricity generation from renewable sources at the EU28 level (Eurostat, nrg_105a)

- **Power-to-hydrogen** is likely to be the first power-to-X technology to emerge, as when coupled to cheap sources of electricity generation, the production of hydrogen by P2H2 facilities via electrolysis can become competitive with other sources of hydrogen (e.g. SMR, by-product of other industrial processes). Countries like Japan consider domestic power-to-hydrogen technologies to play a key role in their sourcing of hydrogen, together with the establishment of an international supply chains (Japan expects to scale up its hydrogen consumption from around 200 tonnes today to 300 000 tonnes in 2030 [12])
- **Power-to-methane** consists in combining hydrogen with carbon dioxide to produce methane. The required CO_2 can either be sourced by capturing emissions from other processes (e.g. power generation technologies such as biomass- or gas-fired plants combined with CCS) or via direct air capture technologies (see e.g. demonstrators such as H2020 project STORE&GO[1]). Without subsidies, the economic viability of P2CH4 technologies are expected to heavily depend on the price of CO_2 since the higher the CO2 price is, the more important the incentive to capture it becomes.

Other sources of renewable energy are available, either to produce renewable electricity (e.g. geothermal power, CSP, biomass), renewable gas (e.g. biomass) or even liquids (e.g. bioethanol), see e.g. [13] for a recent review of the prospects of such sources.

The sources of decarbonised gas and electricity are subsequently used in domestic, industrial and commercial applications by a portfolio of technologies that depend on the overall organisation of the energy sector (see above for a discussion of possible pathways towards a decarbonised energy system).

Interplay between gas and electricity infrastructure

In all pathways, ranging from scenarios assuming a strong electrification to scenarios relying on gas in a large number of end-uses, via scenarios where gas end-uses are only used as backups (e.g. hybrid heat-pumps), the impacts on the gas and electricity infrastructure will likely be important. Furthermore, the increasing level of interactions between the gas and electricity sectors that can be foreseen in all scenarios (e.g. gas-to-power, power-to-hydrogen, gas as seasonal storage, etc.) advocates for a coordinated planning of all system elements, including gas and electricity infrastructure [14].

Modelling interlinkages

Modelling techniques are one of the tools on which decision-makers rely to assess what is the most cost-efficient way to plan the development of infrastructure projects in order to meet pre-defined

[1] https://www.storeandgo.info/

policy objectives. The following paragraphs present recent references adopting an approach to gas and electricity planning that aims at capturing the synergies and interdependencies between these sectors.

Many multi-energy models have been used for policy development, including the MARKAL/TIMES family of models, top-down econometric models, general equilibrium models and more recently multi-energy market models.

At the European level, the Commission relies on several models to develop and assess the impacts of policy proposals: PRIMES, POTEnCIA, and METIS. While PRIMES and POTEnCIA focus on the generation of multi-energy scenarios, METIS is used to analyse the operations of the European energy system using an hourly time resolution.

In the US, the Illinois Institute of Technology has published a white paper on behalf of the Eastern Interconnection States' Planning Council (EISPC) and the National Association of Regulatory Utility Commissioners (NARUC) entitled "Long-term Electric and Natural Gas Infrastructure Requirements" [15]. In this paper, the authors recognise the importance of a joint approach to the operations and planning of gas and electricity sectors in the United States and mention that "An integrated gas-electric model is needed to allow detailed modelling of the physical delivery of gas from fields, through pipelines and storage to gas and electric demands. In the integrated model, gas and electric models are solved simultaneously allowing decision makers to trade-off gas investments, constraints and costs against other alternatives", and identify data exchange and consideration of sector-specific contracts/policies as the main difficulties to overcome.

A number of academic articles have been published on the topic of optimal expansion of electricity and gas transmission infrastructure, some of which being based on a detailed simulation of market operations, e.g. [16], others considering simulation techniques that are close to the ones to be used in this focus study, e.g. [17].

Recently, the European Climate Foundation has published a study using a joint model of gas and electricity to assess the potential role of infrastructure in the transition and to analyse security of supply [18], demonstrating that a joint approach can lead to substantial savings (avoided investments). Deane et al. implemented a similar type of model to assess security of supply in the EU [19].

At a more local level, a number of public authorities in France rely on a multi-energy modelling of gas electricity and heat to support their decisions to extend their gas, electricity and district heating infrastructure.

3 Task 1 - Generic mapping of all potential interactions between gas and electricity

This Section is devoted to presenting the objective (Section 3.1), methodology (Section 3.2) and results (Section 3.3) of the generic mapping of all potential interactions between gas and electricity.

3.1 Objective of this task

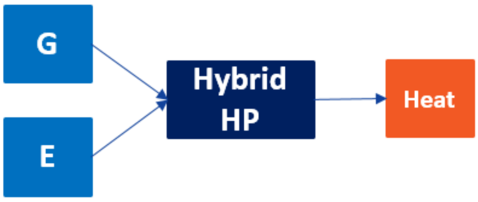
The objective of Task 1 is to present a generic and as exhaustive as possible mapping of all the potential interactions between the gas and electricity sectors. A characterisation of the interactions is introduced (direct and indirect interactions). Finally, the impacts of the interactions on the ENTSOs' Scenario Building exercise, gas and electricity prices, and gas and/or electricity infrastructure projects are qualitatively assessed.

3.2 Overview of the methodology

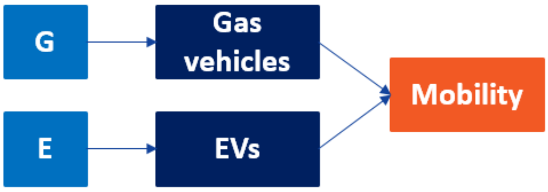
We adopt a bottom-up perspective where we aim at exhaustively listing and characterising all the interactions that directly involve both energy carriers. By interaction, we understand technologies that link both energy carriers.

We define direct and indirect interactions as follows:

- **Direct interaction** – An interaction is said to be direct if both electricity and gas are inputs or outputs of the interaction. For example, a CCGT is a direct interaction between the gas and electricity sectors as it consumes gas to generate electricity. A hybrid heat-pump (HP) is also a direct interaction as both energy carriers can be consumed to deliver heat. Direct interactions can be seen as the building blocks that dynamically link both energy sectors.



- **Indirect interaction** – An interaction is said to be indirect if gas and electricity are linked *via* a third sector. For example, the link between electric vehicles and gas vehicles is an indirect interaction since the electricity and gas are linked via mobility:



The distinction between direct and indirect interactions is particularly useful when considering the overall objective of this focus study, which is related to infrastructure project assessment. When assessing an infrastructure project, the results of simulating two situations are compared:

- **Original scenario** – The original scenario is one of the scenarios built by the ENTSOs during the Scenario Building exercise. It is defined by a set of installed capacities, demands and techno-economic characteristics. A reference grid is defined.
- **With/without the project** – The second situation is identical to the original scenario but for the presence of the project under scrutiny. If the project to be assessed is not part of the reference grid, then it is added to the scenario, while if it is part of the reference grid, it is removed from the scenario.

The value of the gas or electricity infrastructure project to be assessed can be measured through a number of different indicators that capture the influence of the infrastructure project on the operational management of the energy system.

In this context, the operational management of direct interactions are likely to be influenced by the presence of the assessed infrastructure project. For example, adding a gas or electricity interconnector would likely result in a different management of gas-fired power plants, power-to-gas units, hybrid heat-pumps, etc. due to the economic opportunities resulting from potential modifications of the gas and electricity flows.

On the other hand, indirect interactions are usually defined at scenario level, in adequacy with infrastructures. For instance, the consumption of mobility and the shares of electric vehicles and gas vehicles have to be consistent with power supply infrastructures, gas infrastructures, etc. Once defined, the annual consumption is not impacted by the addition or removal of a specific infrastructure project. Indeed, the indirect interactions cannot dynamically switch from one energy carrier to the other: for instance, the scenario-defined transport mix is not modified by the addition of one power or gas interconnection. The presence of a new project can however affect the dynamics of the consumption pattern if adequate price signals exist (e.g. the charging strategy of electric vehicles or the use of gas in district heating applications can change if a new interconnection is built).

The list of direct and indirect interactions that we identify in this sub-report can be seen as building blocks which when combined can allow for more complex interactions such as between infrastructure projects, interaction of price formation mechanisms, etc. The bottom-up methodology introduced above, primarily based on an effort to identify all potential direct interactions, is therefore very well suited to study the phenomena listed by ACER in Opinion No 07/2017.

The results presented in this sub-report have been obtained by the following means:

- **Desk-based research**: own research and literature review, based on the references cited in the terms of reference and additional references (see Section 9)
- **Stakeholder engagement**: a joint ENTSOG/ENTSO-E workshop has been organised by the ENTSOs on 17 May 2018. The purpose of this event was to present the objectives of the study

to stakeholders. The methodology proposed for this assignment has been presented by Artelys[2]. Following this workshop the ENTSOs have requested stakeholders' feedback by email on 25 May 2018. The objectives of this focus study have been presented by the ENTSOS during the 2018 Copenhagen Infrastructure Forum on 25 May 2018. Finally, the results of Task 1 have been presented by Artelys during a webinar organised by the ENTSOs on 10 October 2018.

3.3 Results of the mapping

This section lists all the direct and indirect interactions that have been identified and provides a short description of each of them together with an assessment of their impacts on the ENTSO's scenario building exercises, gas and electricity prices and infrastructure projects.

We first list all direct interactions which involve the conversion of one of the energy carriers into the other, then direct interactions where one of the energy carriers assists the other, and finally we list a number of cases where there is a competition between end-uses (indirect interactions).

Direct interactions

1. **Conversion**
    a. Gas-to-power
        i. OCGTs and CCGTs
        ii. Gas CHPs
    b. Power-to-gas
        i. Power-to-hydrogen
        ii. Power-to-gas (hydrogen or methane injection into gas network)
2. **Assistance**
    a. Electricity-driven gas compressors
    b. Hybrid heating technologies
        i. Industrial gas furnaces with electric boilers
        ii. Hybrid heating (residential & tertiary sector, district heating)
    c. Hybrid transport technologies (if any)

Indirect interactions

3. **Competition**
    a. Mobility
    b. Heating

[2] The slides are available on ENTSOG's website - https://www.entsog.eu/public/uploads/files/publications/Events/2018/20180517%20Focus%20Study%20Interlinked%20Model%20-%20Workshop%20-%20Joint%20Presentation%20final%20-%20updated%20by%20Artelys.pdf

c. Biogas

The identified interactions are presented below on the Sankey diagram used in the scenario building phase, which represents the interactions between the gas and electric systems. This diagram focuses on the perimeter covered by the gas and electricity joint scenario building, and as such it does not necessarily represent the interactions between all energies (e.g. waste heat, bio fuels, solar heat, etc.).

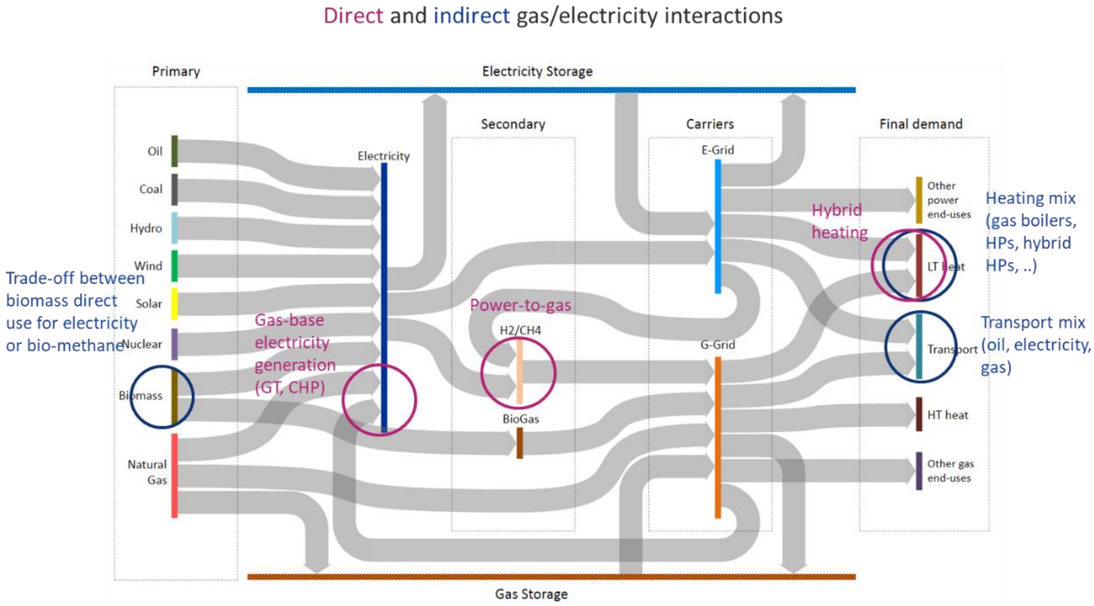


Figure 5. Direct and indirect interactions identified in task 1 on the Sankey diagram used for scenarios building phase.

Fiches describing the interactions can be found in the following sections, and are structured as follows:

- **Overview** – Short description of the considered interaction
- **Direct/indirect interaction** – Qualitative discussion of the direct or indirect nature of the considered interaction
- **Typical size/number of instances** – When available, typical size of the interlinkages (e.g. in MW) and estimation of the importance of the interlinkage at the European level in 2018
- **Relation with ENTSOs' Scenario Building Exercise** – Qualitative assessment of the characteristics (if any) of the interlinkage that are currently captured by the ENTSOs' Scenario Building Exercise.
  One should note that it is not part of the objectives of this focus study to undertake an analysis of the methodology developed by the ENTSOs to build common scenarios and to generate parameters to be used in their respective CBA analyses. However, in order to discuss the relation with the ENTSOs' Scenario Building Exercise, assumptions regarding the elaboration of the scenarios may have to be made, especially for the quantitative analyses to be carried out during Task 3. Based on [1], the ENTSOs use an iterative process where the results of simulations with sector-specific models are compared. Assumptions related to prices and

generation volumes may then be updated to ensure an overall consistency between gas-to-power consumption (gas-specific model) and gas-fired electricity generation (electricity-specific model) at the annual level.

- **Impact on gas and electricity prices** – Qualitative assessment of the potential structural impacts on prices[3] of the considered interaction. For both direct and indirect interactions, we aim at qualitatively assessing whether the considered interlinkage can impact the gas and electricity prices in two ways:
  - First, via the deployment of the considered technology (ceteris paribus). What would happen should we change the assumptions made at the scenario-level?
  - Second, we aim at providing an analysis of the way the operational management of the technologies involved in the interaction can change when an infrastructure project is added to the system.
- **Impact on infrastructure projects** – Qualitative assessment of the potential impacts of the considered interaction on the valuation of infrastructure projects.

3.4 Direct interlinkages

3.4.1 OCGTs and CCGTs

Interaction #1 – *Gas-to-power – OCGTs and CCGTs*	
Overview	**OCGTs** are mature gas-to-power technologies. Due to their efficiency (around 40%, see e.g. [20]), producing electricity with OCGTs is costlier than with most of the other currently available technologies. OCGTs are therefore primarily used to cover peak periods, thanks to its short start-up time. **CCGTs** are mature gas-to-power technologies that combine a gas turbine with a steam turbine, allowing for efficiencies of the order of 60% (see e.g. [20]). OCGTs and CCGTs can indifferently run on methane or bio-methane (upgraded biogas).
Direct/Indirect nature of the interlinkage	OCGTs and CCGTs are direct interactions since these technologies take gas as input and generate electricity.

[3] The qualitative assessment of the interaction sources focuses on gas and electricity commodity prices. The effect on these prices can translate into evolution of other prices, e.g. capacity prices. Gas price refers to the price of gas in the gas network, which can come from different sources: natural gas, SNG, H2, bio-methane, etc.

Typical size and number of instances in 2018	Typically, OCGT capacities ranges from 30 to 600 MW_e and while CCGT capacities range from 100 to 1500 MW_e. The overall gas-fired installed capacity over ENTSO-E's area is around 240 GW [5].
Relation with ENTSOs' Scenario Building Exercise	The installed capacity of OCGTs and CCGTs (together with their techno-economic characteristics) are part of the assumptions that are made during the Scenario Building Exercise.
Impact on gas and electricity prices	The installed capacity of OCGTs and CCGTs has a high impact on electricity and gas prices. Indeed, if the installed capacities were to be less important (ceteris paribus), more expensive electricity generation technologies would have to be used, leading to higher electricity prices. On the other hand, the demand for gas from gas-fired power plants would decrease, which can lead to lower gas prices in scenarios with a significant penetration of electricity for heating (in which gas demand for electricity is an important part of the total consumption). In case one were to increase the OCGT and CCGT installed capacities, the electricity price may decrease if these additional capacities can displace more expensive ones. If this is the case, gas prices would increase as a result of the higher demand for gas. The operational management of gas-fired generation capacities is primarily driven by fuel and CO_2 prices and by the installed capacities of other technologies, including infrastructure elements. Indeed, adding an interconnector or a storage unit can modify the arbitrage opportunities and impact the management of OCGTs and CCGTs, and thereby the gas and electricity prices. The precise impact on gas and electricity prices is however strongly dependent on the commodity prices and other installed technologies. For example, adding an electricity storage element will lead to lower average electricity prices, but the impact on gas prices depends on the merit order between gas-fired generation and the other technologies. If coal is cheaper than gas, the introduction of an electricity storage element would result in a higher exploitation of coal technologies, leading to a lower demand for gas from the power sector, which could lead to lower gas prices (in scenarios where gas consumption for power is a high part of the consumption).
Impact on infrastructure projects	The presence of OCGTs and CCGTs can have a significant impact on the assessment of infrastructure projects: on one hand, gas needs to be routed to the power generation units which can affect the imports of gas in the country (in volume and capacity), while on the other electricity has to flow from OCGTs and CCGTs to load centres (which can affect the exports of electricity, in volume and capacity.

3.4.2 Gas CHPs

Interaction #2 – *Gas-to-power – Gas CHPs*	
Overview	Gas-fired CHPs use gas to generate electricity and useful heat. Most small-scale CHPs are based on reciprocating engines. CHPs can be used in a number of different settings: - District heating - Industrial applications - Micro-cogeneration (domestic or tertiary) The operational management of CHPs might be subject to constraints from one or both of its outputs: for example, the heat demand profile might induce constraints on the management of the CHP. Such constraints have to be properly accounted for when assessing the flexibility that can be brought by CHPs to the electricity sector.
Direct/Indirect nature of the interlinkage	CHPs are direct interactions since these technologies take gas as input, and generate electricity and heat.
Typical size and number of instances in 2018	Typical size: 50 kW_e to several MW_e Approximate installed capacity in Europe: 120 GW_e/300GW_{th} [21]
Relation with ENTSOs' Scenario Building Exercise	The installed capacity of gas-fired CHPs (together with their techno-economic characteristics and constraints) are part of the assumptions that are made during the Scenario Building Exercise.
Impact on gas and electricity prices	The presence of gas CHPs in an energy system can have a structural impact on gas and electricity prices similar to that of OCGTs and CCGTs (see Section 3.4.1). However, because of the constraints imposed by the supply of heat, CHPs operational planning is more regular than OCGTs' and CCGTs'. The deployment of CHPs can thus affect electricity prices mostly during the winter, and can also affect gas prices, gas needs increasing with the CHP capacity.
Impact on infrastructure projects	The constraints on the operational management of CHPs imposed by the supply of heat reduced the flexibility of CHPs, and hence their impact on the assessment of infrastructure projects.

3.4.3 Hydrogen production

Interaction #3 – *Power-to-gas – Power-to-H2 for direct use*	
Overview	The first power-to-gas technology to be investigated is the production of hydrogen for industrial or mobility use. The injection into the gas network will be discussed in the next fiche. Different electrolysis technologies are available, among which the most commonly used being alkaline and proton exchange membrane (PEM). Solid oxide electrolyte cells have not yet fully reached market maturity (see e.g. [22]). The hydrogen produced by such technologies when coupled to a steady source of electricity (e.g. nuclear or RES with batteries) can be a competitor to typical hydrogen production technologies such as steam methane reforming (SMR), potentially coupled to carbon capture and storage (CCS).
Direct/Indirect nature of the interlinkage	Power-to-gas technologies are direct interactions since these technologies take electricity as input, and generate gas.
Typical size and number of instances in 2018	Electrolysis is a mature technology, used in various industrial environments. Recent projects that exploit cheap RES generation include HyBalance in Denmark (hydrogen to be used in the industry and for mobility) and H2Future in Austria where the electrolyser will also provide ancillary services.
Relation with ENTSOs' Scenario Building Exercise	Assumptions related to power-to-hydrogen, where hydrogen is used in the industrial or mobility sector, should be part of the assumptions that are made during the Scenario Building Exercise. Indeed, the scenarios have to reflect assumptions on the amount of hydrogen being produced by taking it into account when setting the assumptions related to electricity generation technologies' installed capacities (to ensure enough electricity is available to produce hydrogen) and to gas supply mix (since power-to-hydrogen is competing with alternative sources of hydrogen production that use methane).
Impact on gas and electricity prices	The impact on prices of different assumptions of installed capacities of power-to-hydrogen depend on the role of hydrogen in the scenario. Indeed, the deployment of this technology is capped to the capacity allowing it to cover the demand for hydrogen from different end-uses (e.g. mobility, industry).

	In a scenario strongly relying on hydrogen, the deployment of power-to-hydrogen solutions can have a high impact on gas and electricity prices, while for other scenarios the impact can be lower. Structurally, the presence of power-to-hydrogen technologies can trigger an increase of electricity prices, especially during low and negative price episodes in poorly connected areas. Indeed, the electricity consumption of power-to-hydrogen technologies increases the demand for electricity and thereby power prices. Finally, when adding an infrastructure project, the power-to-hydrogen technologies will adapt their operational management according to the new conditions. As for other technologies, the precise impact depends on the location of the power-to-hydrogen technology relative to the infrastructure project. For example, a new electricity interconnector could result in fewer episodes of low electricity prices in poorly connected areas and hence limit the hydrogen production by electrolysis. On the contrary, if an area has high variable e-RES surpluses, and there is high power-to-hydrogen capacities in a neighbour area, a new electric interconnector can increase the use of power-to-hydrogen.
Impact on infrastructure projects	The development of power-to-hydrogen can have an important impact on the assessment of infrastructure projects, especially if decarbonisation strongly relies on hydrogen. Indeed, local hydrogen production could decrease the need for gas imports (for SMR) and reduce electricity exports.

3.4.4 Hydrogen or methane injection in the gas network

Interaction #4 – *Power-to-gas – Injection in the gas network*	
Overview	This interaction between the gas and electricity systems takes place when injecting hydrogen generated via electrolysis or methane produced by combining hydrogen with CO_2 into the gas network for storage and subsequent use (e.g. power generation, heating, mobility). The overall power-to-CH4 is CO_2-neutral, since the CO_2 emissions released by the gas use (e.g. in a gas turbine, gas mobility, etc.) had previously been captured (e.g. from industrial CO_2 intensive processes or direct air capture) and used in the methanation process. Power-to-gas is a natural candidate to provide flexibility to the energy system, in particular for seasonal storage in gas storage facilities.
Direct/Indirect nature of the interlinkage	Power-to-gas technologies are direct interactions since these technologies take electricity as input, and generate gas.
Typical size and number of instances in 2018	At the moment, hydrogen injection lighthouse projects and large-scale demonstration projects have been launched (e.g. HyDeploy in the UK, GRHYD and JUPITER1000 in France, Eoly in Belgium). While electrolysis and catalytic reactors are well-established technologies, their combination to produce and inject methane into the gas network is still at an early stage of its development. A number of demonstration projects are ongoing (see e.g. JUPITER1000, CO2-SNG, STORE&GO, Méthycentre, HELMETH, etc.). As for hydrogen blending, the deployment of power-to-C H4 depends both on regulatory and techno-economic factors.
Relation with ENTSOs' Scenario Building Exercise	Assumptions related to power-to-gas with injection in the gas network, are part of the assumptions that are made during the Scenario Building Exercise. Indeed, the scenarios ensure consistency between assumptions on the installed capacities of power-to-gas technologies that are consistent with the electricity demand, the power generation installed capacities, and the gas supply. A process similar to the one ensuring consistency checks between gas-to-power and gas-fired electricity generation could be applied to power-to-gas (i.e. a consistency check between the amount of electricity going into power-to-gas solutions in the electricity-specific tool and the amount of gas produced by these technologies in the gas-specific tool).

	Additionally, hydrogen injection can have a significant impact on infrastructure needs in the gas network
Impact on gas and electricity prices	As for hydrogen production, the presence of power-to-gas technologies can trigger an increase of electricity prices, especially during low and negative price episodes in poorly connected areas. Indeed, the electricity consumption of power-to-gas technologies increases the demand for electricity and thereby power prices. In turn, the gas prices may also be impacted since the supply from other sources would decrease since part of the supply is taken care of by power-to-gas solutions. Finally, when adding an infrastructure project, the power-to-gas technologies will adapt their operational behaviour according to the new conditions. As for other technologies, the precise impact depends on the location of the power-to-gas technology relative to the infrastructure project.
Impact on infrastructure projects	The development of power-to-gas can have an important impact on the assessment of infrastructure projects, especially if decarbonisation strongly relies on green gases. For example, a zone might end up exporting gas instead of electricity, which will considerably impact the assessment of interconnection projects. The development of power-to-gas is also related to variable e-RES development and more generally power supply which have to be consistent as defined by the scenario.

3.4.5 Electricity-driven gas compressors

Interaction #5 – *Electricity-driven gas compressors*	
Overview	Gas compressors are mechanical devices allowing to increase the pressure of gas, and thereby trigger gas flows in pipelines for delivery to markets, and flows in and out of gas storage units. Gas compressors may be driven by gas-fired reciprocating engines, gas turbines, or electric motors. The presence of electricity-driven gas compressors can have a significant impact on security of supply in extreme events (e.g. in case of electricity black-out, gas could not be taken out of storage to supply OCGTs, CCGTs or gas-fired CHPs).
Direct/Indirect nature of the interlinkage	Electricity-driven gas compressors are direct interactions since these technologies can be seen as taking electricity and gas as inputs, and generate gas.
Typical size and number of instances in 2018	Typical size: 20 to 75 BHP, i.e. 15 to 55 MW
Relation with ENTSOs' Scenario Building Exercise	The deployment of gas compressors should be coherent with the evolution of the gas demand in the ENTSOs' assessment (gas compressors are a type of project collected as part of the TYNDP project collection process). The electricity consumption of electricity-driven gas compressors should be accounted for in the electricity demand but will remain limited.
Impact on gas and electricity prices	Electricity-driven gas compressors are likely to have a low structural impact on electricity prices, except in during peak electricity demand periods where a high demand for electricity triggers a demand for extracting gas from storage, which would then impact the electricity prices by increasing the

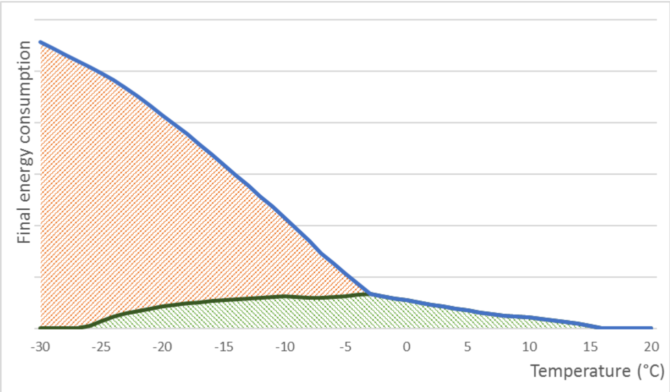
	electricity demand from electricity-driven gas compressors.
Impact on infrastructure projects	The presence of electricity-driven gas compressor in a system creates a security of supply interaction between gas and electricity. Indeed, a blackout can make inoperable gas facilities like gas storage that are relying on electric compressors, which could trigger gas and power curtailments..

3.4.6 Hybrid generation of industrial heat

Interaction #6 – *Hybrid heating technologies* – hybrid generation of industrial heat	
Overview	Industrial heat can be generated by a number of different technologies, among which gas furnaces (the gas combustion heats air that is distributed via a blower motor) and electric boilers (water is heated to generate steam, which is then distributed through a series of pipes). High-temperature heat is mainly supplied by gas solutions. Coupling both gas-based and electricity-based technologies allows for a greater flexibility and adaptability (e.g. to adapt the consumption to the gas and electricity prices). For example, one could imagine electric resistances immerged in fossil-fuelled boilers (see e.g. [23] and [24]). In [23], the authors estimate that electricity-driven equipment could replace up to several dozen Mtoe of natural gas in the industry if the cost of electricity and of the technologies themselves continue to decrease. However, the economic potential for hybrid equipment is not discussed.
Direct/Indirect nature of the interlinkage	Hybrid heating technologies are direct interlinkages since the can consume both gas and electricity to supply heat.
Typical size and number of instances in 2018	Currently the hybrid heating technologies are not very developed in Europe.
InRelation with ENTSOs' Scenario Building Exercise	In their scenarios, the ENTSOs publish the number of hybrid heat pumps. Further details related to the hybrid equipment in the industry could be a useful addition. The assumptions should be consistent with the amount of energy that is needed for low- to high- temperature applications, and with the electricity generation and transmission capacities. If relying on variable e-RES, gas generation capacities might also be considered to provide flexibility.
Impact on gas and electricity prices	The presence of hybrid equipment can significantly impact gas and electricity prices by dynamically adapting to electricity and gas prices, although the inertia of the various hybrid solutions may reduce the ability to react to price signals.
Impact on infrastructure projects	The deployment of hybrid industrial equipment may impact the need for network reinforcements, depending on what the alternative technologies are. Unless very large industrial complexes begin using hybrid technologies or high-temperature applications use electricity instead of gas, the

	deployment of hybrid technologies will not be one of the key drivers of the value of potential infrastructure projects. .

3.4.7 Hybrid heating equipment for domestic or district heating use

Interaction #7 – *Hybrid heating technologies – Hybrid equipment*	
Overview	Hybrid individual heat pumps can be deployed in residential and tertiary environments. These devices primarily use electricity to produce heat. However, as the temperature decreases, the efficiency of the heat pump drops. One of the solutions to avoid over-dimensioning heat pumps (and the accompanying infrastructure such as electricity generation and storage capacities) is to use a backup heater, which can be gas-fired.  **Figure 6 - Back-up (red) and heat-pump (green) consumption Source: Artelys** Hybrid heat-pumps can therefore provide flexibility to the electricity systems by progressively switching to a gas boiler mode as temperature decreases and/or when the electricity prices are high. In district heating applications, where centrally generated heat is distributed for domestic or tertiary use, hybrid heat-pumps can also participate in the provision of heat next to CHPs, geothermal/solar heat, waste heat, etc. As in a domestic application, heat pumps on district heating networks can be combined with gas boilers.
Direct/Indirect nature of the interlinkage	Hybrid heating technologies are direct interlinkages since they can consume both gas and electricity to supply heat.
Typical size and number of instances	The typical size of a residential/tertiary heat pump is around 2-20 kW_{th}, while those active on district heating applications can reach over 20 MW_{th}. Several commercially available heat-pumps for domestic applications have the ability to dynamically switch from one fuel to the other depending on the respective prices of gas and electricity.

Relation with ENTSOs' Scenario Building Exercise	In their scenarios, the ENTSOs publish the number of heat -pumps, including the number of hybrid heat-pumps. Adding details related to the capacity and efficiencies of these technologies could be a useful step forward. The assumptions should be consistent with the amount of energy that is needed to supply heat-pumps, with the electricity generation capacity, with gas supply and the electricity and gas transport infrastructure. If heat-pumps are primarily linked with a strong variable e-RES deployment, gas generation capacities might also be considered to provide flexibility.
Impact on gas and electricity prices	Hybrid heat pumps can significantly impact power prices during very low temperature episodes by shaving electricity consumption peaks, compared to a situation where heating is only relying on heat-pumps. If hybrid heat pumps are temperature driven, switching to a gas consumption when the temperature becomes lower than a threshold, additional infrastructure projects will not impact their operational management. However, if the hybrid heat pumps share in the heating mix becomes very important and their operation is price-driven, the switch in consumption from electricity to gas (or the opposite) could lead to change in gas and electricity prices.
Impact on infrastructure projects	The deployment of hybrid heat pumps may impact the need for network reinforcements, depending on what the alternative technologies are and may impact the assessment of infrastructure projects.

3.5 Indirect interlinkages

3.5.1 Mobility

Interaction #8 – *Mobility: electric mobility and gas mobility*	
Overview	In the mobility sector, electricity and gas-powered vehicles (hydrogen/liquefied or compressed methane) will likely see their share increase in the coming years and decades, and progressively replace conventional vehicles using high-carbon fuels. The role of electricity, gas and synthetic fuels in mobility depends on a number of factors: costs of producing the vehicle, cost of producing the fuel, constraints associated to each technology, sector (passenger cars, delivery vans, trucks, vessels, planes, etc.). Some sectors might not allow for a straightforward electrification (e.g. heavy duty, shipping, aviation). One should also note that there is a certain degree of inertia when it comes to choosing between various potential mobility technologies.
Direct/Indirect nature of the interlinkage	Mobility is an indirect interlinkage since electricity and gas interact via a third sector, and do not directly interact via electric or gas vehicles.
Typical size and number of instances	In 2016, there were around 200 000 electric vehicles (see e.g. [25]) and around 1 300 000 gas vehicles in Europe (see e.g. [26]).
Relation with ENTSOs' Scenario Building Exercise	The deployment of electric and gas vehicles is a choice that has to be made during the scenario development phase, in a coherent and consistent way with the installed capacity for power generation, gas supply, electricity and gas transport infrastructure, etc.
Impact on gas and electricity prices	Choosing a portfolio of vehicles rather than another one will have a very important impact on gas and electricity prices, especially as conventional high-carbon fuels are phased-out. The impact of electric mobility on prices is complex to apprehend since electric cars might also be a source of flexibility (power-to-grid mode) for the power system.
Impact on infrastructure projects	The assessment of a given infrastructure project is highly likely to be considerably impacted by the assumptions related to mobility. However, as noted above, the choice of mobility solutions made at the Scenario Building stage should be coherent with other assumptions, and in particular with the gas and electricity infrastructure (e.g. more power supply infrastructures are needed in a scenario with a high share of electric mobility). Therefore, one should be careful when performing sensitivity analyses of the assessment of

	an infrastructure project to the composition of the mobility fleet. Indeed, changing the composition of the mobility fleet ceteris paribus might lead to unrealistic valuations of the considered infrastructure project. For instance, considering a scenario with a higher electric mobility without adapting the electric supply infrastructures will increase the electricity prices and increase the potential benefits from interconnection with other countries.

3.5.2 Heating

Interaction #10 – *Heating – Gas heating and electric heating*	
Overview	A wide range of technologies can supply heat, some are using electricity, others are using gas, and then some can use either gas or electricity. Hybrid technologies have been addressed in previous sections, this fiche only concerns gas heating and electric heating.
Direct/Indirect nature of the interlinkage	Heat is an indirect interlinkage since electricity and gas interact via a third sector, and do not directly interact via electric or gas heating technologies (only caveat being hybrid technologies treated in previous sections).
Typical size and number of instances	The typical size of heating systems depends on their application (residential/commercial/industry/district heating/etc.)
Relation with ENTSOs' Scenario Building Exercise	The deployment of electric and gas heating technologies is a choice that has to be made during the scenario development phase, in a coherent and consistent way with the installed capacity for power generation, gas supply, electricity and gas transport infrastructure, etc.
Impact on gas and electricity prices	Choosing a portfolio of heating technologies rather than another one will have a very important impact on gas and electricity prices. Indeed, a high share of electric heating will increase the seasonality of electric prices.
Impact on infrastructure projects	The assessment of a given infrastructure project can be impacted by the assumptions related to heating. However, as noted above, the choice of heating solutions made at the Scenario Building stage should be coherent with other assumptions, and in particular with the gas and electricity infrastructure. Therefore, one should be careful when performing sensitivity analyses of the assessment of an infrastructure project to the heating technologies portfolio (changing the composition of the heating sector ceteris paribus might lead to unrealistic valuations of the considered infrastructure project). Indeed, increasing the share of electric heating without increasing peak generation will increase prices at peak hours.

3.5.3 Biogas

Interaction #10 – *Biogas*	
Overview	Biogas is produced by breaking down organic matter (animal by-products, vegetable by-products, waste, dedicated crops). Biogas is primarily composed of methane and carbon dioxide. Biogas can be used in a wide range of applications: it can serve as a fuel after having been compressed, can be used by CHPs to produce electricity and heat, etc. A number of additional applications require biogas to undergo a cleaning and upgrading process so as to be turned into biomethane (CH_4) by removing water, CO2, hydrogen sulphide, etc. Biomethane can be injected into the gas network and be employed for applications ranging from electricity production to domestic heating or mobility.
Direct/Indirect nature of the interlinkage	Biogas is an indirect interlinkage between the electricity and gas sectors as biogas can either be turned into electricity (e.g. in CHPs) or be injected into the gas grid (when installations can dynamically switch between a gas-injecting mode and CHP mode according to electricity and gas prices, this interaction could be considered as being a direct interaction)
Typical size and number of instances in 2018	Biogas can be produced in installations requiring from circa 10 000 tonnes of biomass per year (e.g. individual farms, small waste processing units) to up to 100 000 tonnes per year (e.g. animal by-products processing plants, large waste processing plants).
Relation with ENTSOs' Scenario Building Exercise	Assumptions related to the way biogas is being used (mainly share being injected into the gas network and share being dedicated to electricity production) should be part of the assumptions that are made during the Scenario Building Exercise. These assumptions have to be consistent with the electricity demand (since CHPs burning biogas can reduce the needs for electricity supply) and gas supply (since biomethane can be injected into the gas grid). Furthermore, the infrastructure should also be dimensioned so as to be able to cope with the way the scenarios assume biogas is being used.
Impact on gas and electricity prices	Choosing a portfolio of biogas applications rather than another one will have a very important impact on gas and electricity prices, especially in scenarios with important biogas deployment, as it will either reduce the needs for electricity supply (if biogas is directly burnt) or reduce the gas import needs (if biogas is mostly converted to biomethane)

Impact on infrastructure projects	The assessment of a given infrastructure project can be impacted by the assumptions related to biogas. However, as noted above, the assumptions related to the way biogas is used that are made at the Scenario Building stage should be coherent with other assumptions, and in particular with the gas and electricity infrastructure. Therefore, one should be careful when performing sensitivity analyses of the assessment of an infrastructure project to the biogas exploitation portfolio (changing the way biogas is being used ceteris paribus might lead to unrealistic valuations of the considered infrastructure project). Indeed, reducing the share of bio-gas direct use for electricity and increasing the bio-methane generation without adapting the electricity mix will increase electricity prices and increase the potential value of electric interconnectors.

4 Task 2 and 3 – Qualitative and quantitative analysis of the effect of interlinkages on the analysis of gas and electricity infrastructure projects

4.1 Methodology of Tasks 2 and 3

4.1.1 Context and objective of Tasks 2 and 3

The objective of this focus study is to provide recommendations to the ENTSOs on the design of a screening methodology which will allow the ENTSOs to determine, in a given scenario (corresponding to a given context for the energy system), for which gas and electricity infrastructure projects a more thorough investigation of the impacts of the interlinkages between gas and electricity systems should be performed. The screening methodology should therefore aim at identifying the relevant projects for which the interactions between the gas and electricity systems have a sizable impact on their assessment.

The objective of Tasks 2 and 3 is to understand in what conditions the interactions between gas and electricity systems are such that they need to be taken into account via a dual system assessment. The design of the dual system assessment is outside the scope of this study.

The screening would be used in the TYNDP process and could take place directly after the scenario building phase or after the single system CBA assessment step, as presented in the next figure. The benefits of both options will be discussed in Task 4.

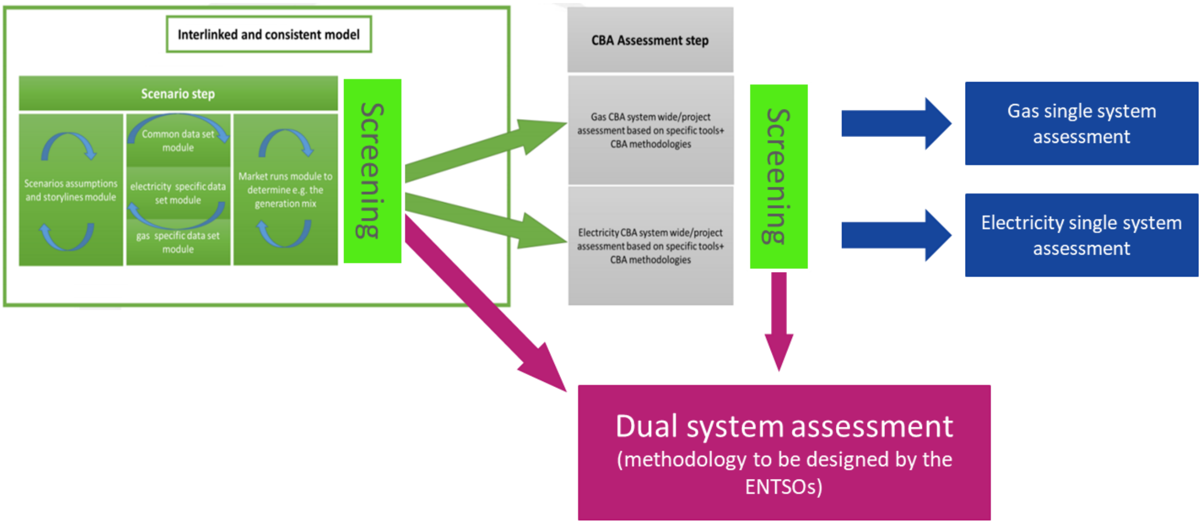


Figure 7. Illustration of the use of the screening methodology

The recommendations regarding the screening methodology involve using as inputs: the characteristics of the project being assessed and of other projects, and the energy context (scenario).

In case the screening takes place after the single system assessment, the results of this assessment could be one of the inputs of the screening methodology.

An example of structure for the screening methodology is given below.

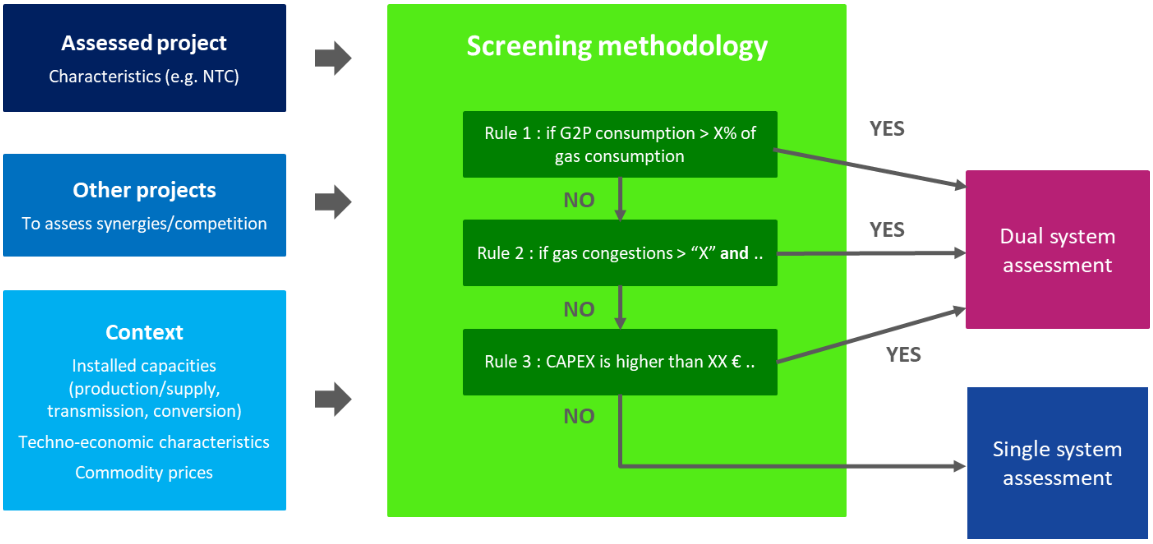


Figure 8. Proposed structure for the screening methodology

The main objective of Tasks 2 and 3 is to identify what parameters should be involved in the screening methodology and what thresholds on these parameters trigger the need to use a dual system analysis in the assessment step of an infrastructure project.

Figure 9. Role of Tasks 2 and 3

4.1.2 Methodology

In order to identify the situations in which assessing a given infrastructure project would require to use a dual system analysis, we have sought to answer the following questions:

- **First**, what are the interlinkages between gas and electricity systems? This was the objective of Task 1, which identified three main sources of interlinkages between gas and electricity systems, namely gas-to-power (G2P), power-to-gas (G2P) and hybrid consumption technologies.
- **Second**, what form do these interactions take? How do these interactions affect the assessment of projects?
- **Third**, what are the meaningful parameters impacting these interactions and are there thresholds above which the interaction becomes important?

In order to answer these questions, for each source of interlinkage identified in Task 1 (i.e. gas-to-power, power-to-gas, and hybrid heating), the process has been to first look into more details on how these assets are operated, and the types of interaction between gas and electricity infrastructures they create. For these interactions, we have qualitatively assessed the meaningful parameters that affect their intensity.

When relevant, we have confirmed the presence of these interactions with state-of-the-art simulations of the gas and electricity systems, using Artelys Crystal Super Grid. In this step, we have modelled generic gas and electricity networks for two fictional areas, taking into account their connection to each other with gas and electricity interconnectors, and the connection between gas and electricity networks with G2P, P2G and hybrid heating consumptions (here hybrid heat pumps).

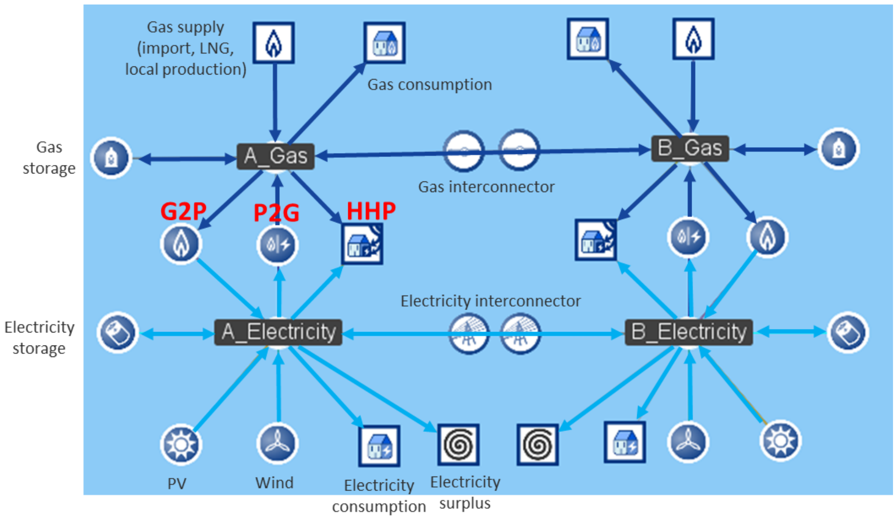


Figure 10. Illustration of the joint gas and electricity model used for Task 3

The values of the thresholds have then been estimated by combining the results of the qualitative assessment with the results of a large number of simulations of generic gas and electricity systems, taking into account different values of key parameters such as:

- The level of G2P, P2G and hybrid consumptions in the mix,
- The share of vRES-e or nuclear capacities in electricity generation,
- The capacity and volume of electricity storage in the system,
- The quantity of seasonal gas storage,
- The level of interconnection between areas,
- The difference of prices of gas between sources, etc.

4.1.3 Including project costs in the screening methodology

The costs of an infrastructure project, while not directly impacting the gas and electricity systems' operations, are an important factor in the cost-benefit analysis and could be included in some way in the screening methodology as its goal is to detect the **relevant cases** for application of a dual system assessment.

Indeed, the project costs can directly affect the relevance of a project for a dual system assessment:

- When the costs of a project are very low (or respectively high), its profitability (or the losses it will generate) might be clear without requiring a dual system assessment,
- For very large projects, in terms of capacity and/or CAPEX, it might be relevant to systematically run a dual system assessment.

Several options can be considered to take the CAPEX into account during the screening methodology:

- The costs of a project could be taken into account with a rule of thumb on its value, based on the results of previous TYNDP exercises,
- Project costs could be taken into account as an additional layer in the screening process based on an estimation of the potential benefits of the project. For example:
    - For an electricity interconnector between two areas, the CAPEX (per MW) could be compared to the yearly sum of the absolute difference of price between these areas (i.e. the marginal revenues of the interconnector). If the CAPEX is such that the project cannot be beneficial under the considered circumstances, we might recommend in Task 4 that the project should not be selected for dual system assessment.
- Project costs could be taken into account in a pre-screening process based on the result of the single system cost benefit analysis. In this case the single system CBA would have to be carried out *before* the screening, and a potential dual system assessment would be carried out after the screening.

These options will be refined in Task 4, where we will provide our recommendations on the screening methodology.

4.2 Interaction between projects in the presence of G2P

In this section we focus on the interaction between infrastructure projects, such as gas and electricity interconnections whose value are to be assessed by the ENTSOs, in the presence of **gas-to-power** assets (CCGTs, OCGTs, and CHPs). Indeed, as an electricity-generating and as a gas-consuming technology, gas-to-power creates a link between the gas and electricity systems that can affect the assessment of infrastructure projects.

4.2.1 Interactions between gas and electricity systems in the presence of G2P

As described in Task 1, gas-to-power regroups different types of gas-based electricity generation technologies, mostly combined cycle gas turbines, open cycle gas turbines, and gas combined heat and power generation. The operation of these electricity generators are either driven by electricity needs (OCGT, CCGT and some CHPs) or by heat needs (CHPs). The gas consumption of these assets can create constraints on the gas system on different timescales.

In particular, the gas-to-power creates mostly constraints at an **annual** level:

- The consumption of G2P can in some areas represent a significant share of the gas demand and can lead to congestions in the gas import capacities, triggering either an increase of the gas price or security of supply issues;
- The consumption of G2P is usually following a seasonal pattern, given that the heat and electricity generation of these assets is mostly needed in the winter. This phenomenon can increase the seasonality of the gas demand which is usually handled by gas storages and LNG imports.

At a **monthly or weekly scale**, the variability of the gas consumption for G2P can be significant, in particular in an area where the electricity system has a large share of wind power. Indeed, in the case of weeks with low wind, generation by gas-fired power plants may be required to meet the demand. However, the flexibility of the gas system that is required to meet the demand in this case is of a lower magnitude than the one required to cover the seasonal variations of the gas demand. Therefore, as long as the constraints at an annual level are handled, one may safely assume that monthly and weekly constraints are handled too.

At the **daily level**, the gas consumption for G2P can be very 'peaky' due to behaviour of the power system (e.g. CCGTs may generate 0 MW during off-peak hours, and be at maximum capacity a couple of hours later). This variability of the gas consumption is not in itself problematic for the gas supply/demand equilibrium at national or European level, as it can be absorbed to a large extent by linepack storage.

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4.2.2 Effect on the assessment of a project

The effect gas-to-power has on the gas and electricity systems may affect the assessment of infrastructure projects. In this section, we assess qualitatively what are these effects for gas and electricity interconnection projects. In particular, the objective is to assess if taking into account the constraints of the gas system (resp. electricity system) can affect the assessment of electricity infrastructure projects (resp. gas infrastructure projects).

Since the most impacting constraints on the gas system brought by G2P are annual, we consider the following two cases:

- A case where the gas-to-power consumption triggers issues of gas security of supply in the area
- A case where the gas consumption for G2P triggers a congestion on the gas import capacities in an area and creates a price differential with its neighbours (beyond the tariffs/fees).

4.2.2.1 Effect on electricity projects assessment

We first consider a case where the gas consumption for G2P may trigger gas security of supply issues. In other words, the overall gas consumption is higher than the import capacities of the area, taking into account the potential LNG imports, storage volume and injection/withdrawal capacities or local gas production.

In this case, adding a power interconnection can allow to use electricity imports (provided the neighbouring area has available generation technologies), instead of using the local G2P for electricity generation. The interconnection can thus reduce the G2P use and avoid some gas loss of load. This phenomenon can affect the assessment of the electricity interconnection project since the value brought by an electricity interconnection project by solving some of the gas constraints is usually not taken into account in a single system analysis.

Similarly, if the gas consumption for G2P creates congestions between areas leading to the appearance of price differentials, adding an electricity interconnection can reduce the gas consumption in the area and reduce the congestions. When considering the electricity system on its own, with no representation of the gas congestion or of the price difference, this value for the electricity interconnection is not taken into account.

In both these cases, the value of the electricity interconnection related to the potential reduction of gas constraints would diminish if the gas constraints are less important, e.g. in the case of a higher gas interconnection with neighbouring areas.

4.2.2.2 Effect on gas projects assessment

In a case where the gas consumption for G2P creates gas security of supply issues, adding a gas interconnection can not only improve the gas security of supply, but also the electricity generation costs. In this case, the gas interconnection allows G2P to be used more often.

When the gas consumption for G2P creates gas congestions between areas leading to a difference of prices, adding a gas interconnection can allow the system to gain access to cheaper gas sources. It allows to reduce the costs of electricity generation by G2P and thus the overall costs for the electricity system.

In both these cases, the addition of flexibility on the electricity side can reduce the value of the gas infrastructure since the electricity network would be used to transfer G2P generation from one area to the other (instead of transferring gas from one area to the other).

4.2.3 Meaningful parameters of the interactions

The intensity of the interactions between G2P and infrastructure projects discussed above depends on several parameters of the gas and electricity systems. The key family of parameters are:

- The **share of G2P gas consumption** compared to the overall gas demand: if G2P only plays a minor role in the gas system, the impact of the interaction between G2P and infrastructure projects will not significantly impact the assessment of gas and electricity infrastructure project.

- The **flexibility of the gas system**, which depends on the import capacity (the higher the import capacity, the higher the flexibility), the gas storage capacity and the difference of gas price/congestions with neighbouring areas.
- The **flexibility of the power system**, linked to the structure of the generation mix and consumption in the area. In particular, the presence of electricity interconnections, electricity storages or generation sources more expensive than G2P (e.g. some biomass units, reciprocating engines) helps avoiding the use of G2P in the constrained area.

4.2.4 Identification of situations triggering a dual assessment

As described in the previous sections, the G2P interactions between gas and electricity systems that affect gas and electricity infrastructure projects assessment start occurring when the G2P consumption creates congestions on the gas network, leading to either security of supply issues or price differences beyond the transmission tariffs.

This will only be the case when the yearly G2P gas consumption represents an important share of the total yearly gas consumption. In order to focus on relevant cases, we recommend to set a minimum level on this share. In particular, we identified qualitatively that as long as the share of G2P in the gas consumption is below 5 % of the total gas consumption, the interactions created by G2P remain limited and do not trigger the need for a dual system assessment.

Size of G2P in the gas system

$$\text{G2PyearlyGasConsumption} \geq 5\% \text{ of yearlyGasConsumption}$$

In addition, the interaction between the gas and electricity systems investigated in this section only occurs when there is some flexibility on the electricity system side that allows for a reduction of the electricity generation from gas-to-power assets. These flexibilities include available capacities of electricity interconnections, electricity storage or generation assets that are more expensive than G2P in a situation where the gas system is not constrained. If there is some available capacity[4] then there can be some interactions.

Electricity flexibilities

Presence of electricity capacity margin

Finally, a dual system assessment is recommended either when there are some gas security of supply issues or when a congestion leads to a difference of gas prices between neighbouring areas. These

[4] The presence of these margins could be for instance assessed with the results of the scenario building phase. More details on this will be added in the Task 4 report.

situations can be identified by the ENTSOs during the scenario building phase. We propose below three conditions to help identify them.

Gas security of supply issue due to yearly supply

$$\mathrm{G2PyearlyGasConsumption} + \mathrm{NonG2P\ yearlyGasConsumption} > \mathrm{localYearlyGasProduction} + \mathrm{maximumYearlyGasImports}$$

OR

Gas security of supply issue due to the seasonality of consumption

$$StorageCapacity < \sum_t (gas\ consumption_t - import\ capacity)^+$$

OR

Gas price difference between areas due to a congestion

$$\text{Presence of a gas congestion AND priceDifference} > \text{transmission tariff}$$

If the conditions on the three blocks are satisfied (i.e. gas consumption for G2P is sizable, there is an electricity capacity margin, and one of the three conditions in the last block is met), then there is an interaction between gas and electricity systems due to the presence of G2P and a dual assessment should be conducted when considering a future gas or electricity infrastructure project.

The conditions proposed in this sections may be detailed or improved in task 4.

4.3 Interaction between projects in the presence of P2G

In this section we focus on the interaction between infrastructure projects, such as gas and electricity interconnections whose value are to be assessed by the ENTSOs, in the presence of **power-to-gas** assets. Indeed, as an electricity-consuming and gas-producing technology, power-to-gas creates a link between the gas and electricity systems that can affect the assessment of infrastructure projects. We consider a generic power-to-gas capacity, that could correspond for instance to an electrolyser or methanation installation.

4.3.1 Interaction between gas and electricity systems in the presence of P2G

As described in Task 1, the presence of power-to-gas in the system can create an interlinkage between the gas and electricity systems. The characteristics of the interlinkage differ depending on the way power-to-gas assets are operated. Several exploitation mode can be imagined, we describe four main options below[5]:

[5] Note that the operation of a specific power-to-gas installation could be a combination of the three options.

1. P2G can be operated with a dedicated electricity generation capacity (e.g. in North Sea, directly below wind projects). In this case, gas is generated only when the electricity generation capacity is active. This project can thus be considered as a **pure gas production project**. As such, it is independent from the electricity wholesale market and does not constitute a relevant gas/electricity interlinkage since it can be taken into account directly in the scenario building phase as a gas source.
2. P2G can be operated to satisfy a given need of gas (e.g. a given hydrogen consumption in a specific industrial complex). In this case, the P2G activation is driven by the needs of gas and the installation can be considered as a **pure electricity consumer** (with specific characteristics depending on the gas use). As such it does not create a relevant interlinkage between gas and electricity systems since it can be taken into account directly in the scenario building step[6].
3. P2G can be operated based on the **electricity wholesale market price**. In this case its capacities are activated only when the electricity price is lower than the price of the alternative gas source (e.g. SMR for hydrogen production), taking into account the efficiency of the P2G technology (and including the potential savings in CO2 emissions). Due to the structure of the electricity consumption and to the pattern of variable RES generation, **price-driven P2G** usually functions during summer when there are potential surpluses of electricity. This creates a direct interlinkage between the gas and electricity systems which can lead to several constraints or issues on volume, gas exchanges between countries or storage that can lead to the need for a dual system assessment when assessing gas and electricity projects.
4. P2G can be operated based on the system's point of view. In this case, the P2G capacities are used as fully integrated network components as defined in the Clean energy for all Europeans package[7]. Similarly to price-driven P2G, they would be used to solve more local constraints on the network, e.g. for integrating the local vRESe surpluses. This creates a direct interlinkage between the gas and electricity systems which can lead to several constraints or issues on volume, gas exchanges between countries or storage that can lead to the need for a dual system assessment when assessing gas and electricity projects.

In the rest of this section will only be considered **price-driven P2G assets or P2G assets operated based on the system's point of view**, as the other types of operation can be captured at the scenario building stage (either as a gas source or an electricity consumer).

[6] Power-to-gas can also be used as a complement of another hydrogen generation source, such as steam methane reforming. In this case, the power-to-hydrogen capacity is used only when the cost of generation of hydrogen by P2G is lower than the costs of the concurrent producer. Its operation depends in this case of the price of electricity and fits in the third category (price-driven P2G).
[7] In the recent Clean Energy Package trilogues, exploitation rules have been defined regarding the use of P2G by TSOs.

4.3.2 Effect on the assessment of a project

4.3.2.1 Effect on electricity projects assessment

Price-driven power-to-gas capacities are **competing** with exports and/or storage for the use of cheap electricity. Indeed, P2G consumption can reduce the volume of electricity that is available for exports and increase the local price of electricity thus reducing the depth and value of exports. This is especially true in areas with high P2G and vRES-e or nuclear capacities (that either function in must-run or want to maximize their use). Hence, the benefits brought by electricity interconnections which export electricity from an area with P2G is generally reduced by the presence of price-driven P2G.

In some cases, there can however be **synergies** between P2G and interconnectors (or storage assets). Indeed, if the P2G capacities are in an area next to another area with high RES surpluses, a new electricity interconnection could allow to export the cheap electricity to the area with P2G capacities. In some configurations, for instance when both areas have access to cheap electricity generation technologies, both phenomena can appear simultaneously.

4.3.2.2 Effect on gas projects assessment

As a gas source, power-to-gas can reduce the needs for additional import capacities in the area and needs to be taken into account when assessing gas infrastructure projects (this requires P2G projects of several hundred MW to materialise).

If the gas production from P2G is higher than the local gas consumption, and that the existing gas export and storage capacity are saturated, it can increase the value brought by gas interconnection projects. We expect this case to be quite exceptional, for example in the case of large wind farms coupled with electrolysers. However, the operation of such projects are not expected to be price-driven but rather to convert most its electricity into gas, the remainder being either curtailed or injected in the electricity network. These projects can thus be viewed as an independent gas and electricity source, as discussed above.

4.3.3 Meaningful parameters of the interaction

4.3.3.1 For electricity projects

Many variables affect the synergy or competition between electricity exports and P2G. They can be summarised as follows:

- The **volume of cheap electricity available in the area** with P2G, depending e.g. on the share of vRES-e in the system and on the flexibilities in the electricity system (storages, interconnections with other countries). On one hand, since RES technologies are a source of electricity with low variable costs, their presence increases the opportunities for P2G and for exports. On the other hand, existing flexibilities can help integrating the cheap electricity. The higher the existing flexibilities, the lower the room for P2G and additional electricity interconnectors

- The **value and limitations of electricity interconnection capacities** (if any), depending on the vRES-e share in the neighbouring areas and the electricity price in the neighbouring areas. The value of exports (based on arbitrage) depends on the neighbouring electricity system. If electricity spreads are high, the value of the additional interconnection capacity will be higher. If there is already high RES generation in neighbour areas, export opportunities can be lower.
- The **value and limitations of gas system in the area** (if any), in particular the presence of non-G2P gas demand (i.e. demand for mobility, heating, industrial processes, etc.), and the price of gas in the network (conventional or renewable gas). Indeed, the way P2G assets are operated can depend on price of alternative gas sources (e.g. SMR for hydrogen production). Therefore, the competition between P2G and electricity infrastructure projects also depends on the characteristics of the local gas system.

4.3.3.2 For gas projects

Similarly, the interaction between P2G and gas interconnection projects depends on many variables:

- The **gas demand** in the area: If there is no gas demand that can be fulfilled by P2G, the P2G production has to be exported. The presence of P2G therefore impacts the assessment of gas infrastructure projects.
- The **existing gas interconnection capacities**, as if there are already enough gas capacities to export/store the P2G generation, P2G will not significantly impact the assessment of new gas infrastructure projects
- The **P2G gas production profile**, which depends on many parameters, and especially the share of vRES-e and nuclear power (sources of cheap energy) in the local electricity mix, the flexibilities of the local electricity system (storage, export capacities), the share of vRES-e in neighbouring areas and the gas price, which affects the competition between P2G and electricity exports

4.3.4 Identification of situations triggering a dual assessment

In order to identify more precisely the situations where a dual system assessment is recommended, we have simulated the operation of gas and electricity systems in two generic areas and assessed the value of gas and interconnection projects in the presence different capacities of price-driven power-to-gas assets. For that purpose, we performed several thousand simulations with different values of the meaningful parameters for this interaction to estimate the impact they have on the assessment of gas and electricity projects. In particular, for these simulations, we considered different values for:

- P2G capacities,
- Gas & electricity interconnections capacities,

- Capacity and volume of electricity storages,
- vRES-e share and nuclear share in the electricity mix of both areas,
- Presence of a local gas demand.

These simulations have helped identify thresholds on several parameters of the energy system – in particular on the P2G capacities and on the amount of low variable-cost generation – which we present below. The main results of these analysis are presented in Appendix.

The following thresholds are found to be relevant to identify the electricity projects for the assessment of which the interactions between the electricity and gas systems are important:

- The **price-driven or system-driven P2G** has a significant impact only if it represents a non-negligible part of the electricity system. We have found that below the following threshold, it is not useful to perform a dual system assessment of electricity and gas infrastructure projects:

Capacity of price-driven or system-driven P2G

$$\text{P2G capacity} \geq 5\ \%\ \text{of}\ (\text{nuclear} + \text{vRes}_e)\ \text{capacity}$$

- There is a significant interaction between gas and electricity systems in the presence of power-to-gas as soon as the share of RES and nuclear in the electricity consumption is high and leads to large surpluses of cheap electricity during a significant number of hours. The presence of pumped hydro storage (or other storage assets), as a competitor of the use of this cheap electricity, increases the share of RES or nuclear admissible in the system before witnessing this interaction. The simulations performed helped identifying the threshold of 60% on the share of low variable costs electricity generation:

Structure of the electricity mix

$$\frac{\text{vRESe yearly Generation} + \text{Nuclear yearly Generation}}{\text{Electricity yearly consumption (incl. pumping)}} \geq 60\%$$

If these two conditions are met then there is an interaction between gas and electricity that can necessitate a dual assessment for electricity projects.

In addition to the conditions above, another condition is necessary to trigger the need for a dual system assessment for gas projects. Indeed, power-to-gas can create a need for additional gas interconnections when the local gas system is such that it cannot make good use of the gas volume produced by P2G. This last condition can be written as:

Structure of the gas system

$$\text{P2GGasProduction} \geq \text{LocalGasDemand} + \text{StorableVolume} + \text{ExportableVolume}$$

The conditions proposed in this sections may be detailed or improved in task 4.

4.4 Interaction between projects in the presence of hybrid consumption

In this section we focus on the interaction between infrastructure projects, such as gas and electricity interconnections whose value are to be assessed by the ENTSOs, in the presence of hybrid gas and electricity consumption technologies. Indeed, as a gas and electricity consuming technologies, hybrid gas/electricity consumers create a link between the gas and electricity systems that can affect the assessment of infrastructure projects.

We focus on the case of the hybrid gas/electricity heat pumps which is a typical case of a hybrid consumer that exist already. We then extend the conclusions of the analysis to a more generic hybrid consumer, in order to be able to take into account the potential hybridation of end-uses.

4.4.1 Interactions between gas and electricity systems in the presence of hybrid heat pumps

Hybrid heat pumps systems are used to produce heat and are composed of a classic electric heat pump component combined with a gas boiler functioning as back-up. In general, at temperatures above minus 5°C, the electric heat pump can cover most or all of the heat consumption. At lower temperatures, the electrical heat pump efficiency and capacity decrease and the gas back-up covers the remaining heat demand. We present below the typical operation of hybrid heat pumps depending on the temperature. The bivalent temperature is there -5°C.

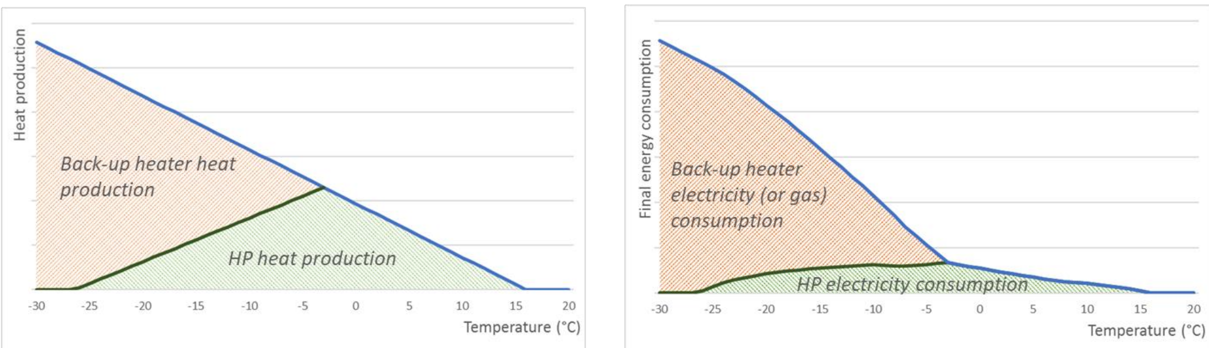


Figure 11. Operation of a hybrid heat pump depending on the temperature (heat generation – left – and final energy consumption – right - for each component of the hybrid HP)

Hybrid heat pumps can create interactions between the gas and electricity systems. The interaction is however different depending on the way hybrid heat pumps are operated. If the hybrid heat pump is "**temperature-driven**" like described above, the electric heat pump always functions in priority, and the gas will act as a pure back-up. In this case, the interlinkage between gas and electricity systems is low as both consumptions can be taken into account independently and are independent from the status of the gas and electricity infrastructure. Their effect on both systems can be estimated separately at the scenario-building phase (the number of temperature-driven heat pumps generates a known amount of gas and electricity demand).

On the other hand, if the hybrid heat pump is "**price-driven**" (or "market-driven"), the gas back-up is activated in replacement of the heat pump as soon as the heat generation cost of the boiler is lower than the heat generation cost of the heat pump, i.e. when:

$$\frac{\text{Gas price}}{\text{Gas boiler efficiency}} \leq \frac{\text{Electricity price}}{\text{Heat pump coefficient of performance}}$$

This only happens at peak hours, when the electricity price is very high[8]. In this case, switching to the gas back-up to avoid the additional electricity consumption of the heat pump can be beneficial to the electricity system, by reducing the stress at peak hours and thus reducing the needs for additional capacity (typically CCGTs, OCGTs or interconnections). This however requires having enough gas being available to switch to the gas-consuming mode.

4.4.2 Effect on the assessment of a project

4.4.2.1 Effect on the assessment of electricity projects

If the hybrid heat pump (HHP) is **temperature-driven**, the power consumption cannot be dynamically adapted to the system. Hence, the HHP has the same impact as any other gas and electricity demand, and its influence on the interconnection value can be captured through a single electricity system assessment, assuming the importance and dynamics of this demand are carefully and consistently calibrated in both the gas and electricity sectors.

If the HHP is **price-driven**, and if there is no constraint on the electric system (the electricity prices are low), the HP is used at its maximal capacity (when there is a heat demand). Adding electricity interconnection will not affect the electricity consumption nor the gas consumption. However, if there is limited electric supply and the HHP is sometimes used as a gas boiler in its entirety (i.e. the HP component is too expensive due to electricity prices and HP efficiency), an electricity interconnection project can enable the use of the electrical HP part by reducing the constraints on the electrical system.

[8] With typical efficiencies of 90%, 300% and 40% for respectively, the gas boiler, the heat pump and a gas turbine, it is usually less costly to produce electricity with the gas turbine to use it in the heat pump, rather than use the boiler directly (excluding investment costs). The gas back-up is used preferably when the HP is at full capacity, or when the price is high or when the efficiency of the HP decreases (at very low temperatures)

4.4.2.2 Effect on the assessment of gas projects

If the HHP is **temperature-driven**, the gas consumption from the HHP can add constraints to the gas system. If it does then it can have an impact on the potential need for new gas infrastructure projects. Again, this impact can be captured in a single system analysis, assuming the dimensioning of this demand is done consistently with the calibration of the electricity demand.

If the HHP is **price-driven,** the overall gas consumption of the HHP will be similar to the one of temperature-driven HHP, as the difference in consumption due to the dynamic operation of the price-driven HHP (punctual switch from electricity to gas consumption) will remain low. As such it does not usually trigger the need for a dual assessment. However, if the volume of energy switchable between carriers is such that it triggers a gas supply constraint or a gas price difference, then the interaction affects the assessment of the gas project.

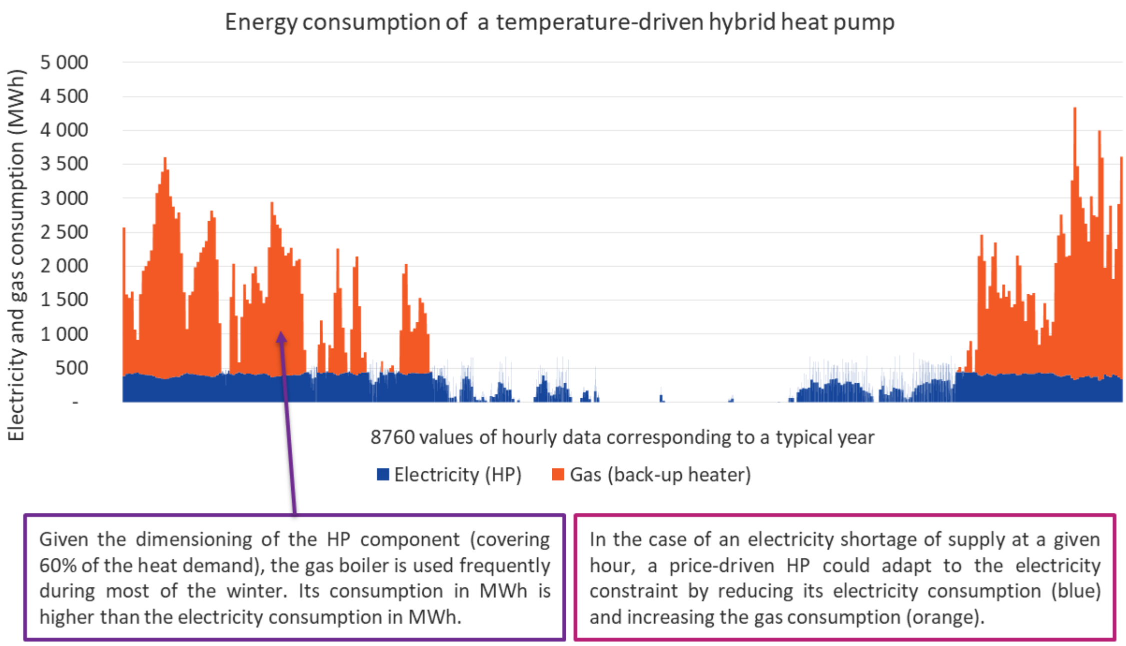


Figure 12. Illustration of the operation of a hybrid HP over a year[9].

4.4.3 Meaningful parameters

The meaningful parameters in the described interactions are the following:

- The number of **price-driven HHP** compared to the overall gas demand. If the share of price-driven HHP is important, the flexibility (dynamic switch from power to gas) can bring some value to the electric system or create constraints in the gas system. Temperature-driven HHPs can be considered as any other consumption in a single gas system analysis.

[9] Illustrative data based on METIS Study S6 on behalf of the European Commission. More information on https://ec.europa.eu/energy/en/data-analysis/energy-modelling/metis.

- The presence of **constraints on the electricity system:** if there are no electricity SoS issues/scarcity prices, electricity consumption will be preferred in the HHP, and there will not be a switch to a gas consumption. These constraints depend of the **structure of the electricity mix** (production, consumption and transmission).
- The presence of **constraints in the gas system** if the switch is made from electricity to gas. For HHP, the additional consumption of gas in the case of a switch is relatively low so it is expected that there won't be active very frequently.

4.4.4 Identification of situations triggering a dual assessment

Interactions between gas and electricity systems linked to the presence of hybrid consumption technologies that creates a need for a dual assessment occur when:

- The share of hybrid consumption is significant in both electricity and gas demand.
- The hybrid consumption technology is price-driven,
- There are constraints on the electricity and gas systems due to the hybrid consumption technologies

While the need for a dual system assessment depends on a lot of parameters as described above, based on our qualitative assessment, we recommend to limit the investigation to the cases where the price-driven consumption of hybrid technologies is superior to 5% of the gas and electricity demand.

Quantity of price-driven hybrid consumption

$$\text{Gas consumption of price} - \text{driven hybrid technologies} \geq 5\% \text{ of yearly gas consumption}$$

$$\text{Electricity consumption of price} - \text{driven hybrid technologies} \geq 5\% \text{ of yearly electricity consumption}$$

If this condition is respected, the interactions between gas and electricity systems requiring a need for a dual assessment start when there are issues on the gas or electricity systems (or both).

Constraints on the gas and electricity systems

Electricity security of supply issues when the hybrid technologies function as electricity consumers

OR

Gas security of supply issues or congestion when the hybrid technologies function as gas consumers

OR

Issues in both systems

The conditions proposed in this sections may be detailed or improved in task 4.

5 Task 4 – Summary and recommendations for the design of a screening methodology

5.1 Main findings of the previous tasks

In Task 1, we have identified the main sources of interlinkages between gas and electricity systems by doing a generic mapping of all the potential interlinkages today and in the future. Three main sources of interlinkages were identified:

- **Gas-to-power** (G2P), corresponding to the gas-based production of electricity, e.g. in OCGTs, CCGTs and CHP.
- **Power-to-gas** (P2G), i.e. the use of electricity to generate either H_2 by electrolysis or CH_4 by methanation,
- **Hybrid consumption technologies** (HCT), i.e. technologies allowing to consume either electricity or gas at each time to satisfy the consumption of an end-use (e.g. hybrid heat pumps, equipped with both a HP component and a gas back-up).

These three sources of interlinkage can create interactions between the electricity and gas systems that can affect the assessments of gas and electricity infrastructure projects. In the following sub-sections, we describe shortly the main findings of tasks 2 and 3 where we studied these potential interactions, identified the situations in which they may occur and when it could affect the assessment of new infrastructure projects.

5.1.1 Interactions in the presence of G2P

As gas consumption and electricity generation technologies, gas-to-power assets can add constraints to the gas system that directly depends on the electricity system. These constraints can take different forms: a congestion between areas leading to a gas price difference beyond the transmission tariffs, a constraint on the gas storage level due to the seasonality of the gas demand, an augmentation of the dependence of the area to a given gas supply sources.

The presence of gas-to-power can trigger the need for a dual system assessment when evaluating the interest of gas or electricity infrastructure projects:

- Taking into account the flexibility of the electricity system (brought e.g. by interconnections, storages, demand response and peak generation sources beyond gas) can reduce the constraints on the gas system by adapting the local gas consumption for electricity and affect the assessment of gas interconnectors
- Taking into account potential constraints on the gas system due to G2P can affect the assessment of electricity interconnectors.

In particular, if the use of the existing or planned flexibilities of the electricity system can affect the amplitude of these constraints, it requires a dual system assessment for new infrastructure projects.

5.1.2 Interactions in the presence of P2G

As electricity consumption and gas production technologies, power-to-gas assets can affect the assessment of gas and electricity infrastructure projects. While some of the power-to-gas assets are well taken into account at scenario level without requiring to perform a dual assessment (e.g. P2G in must-run or connected to a dedicated electricity generation capacity), we identified in Tasks 2 and 3 that dynamically operated power-to-gas assets (i.e. price-driven P2G or P2G operated based on the system's point of view) can require a dual system assessment when looking at **electricity** infrastructure projects. It is especially the case in the presence of a large quantity of low variable costs energy sources such as vRES-e or nuclear power which generate potential electricity surpluses, for the use of which a competition between electricity interconnections and P2G assets can occur.

This dynamic interaction can require a dual assessment for **gas** infrastructure projects if (in addition to the previous requirement) the potential volume of gas generated via P2G is superior to the absorption capacity in the local gas system. This condition is unlikely to be met in most cases in the next decades as the P2G generation would require to be very significant.

5.1.3 Interactions in the presence of HCT

As technologies consuming both electricity and gas, hybrid gas/electricity consumption assets add constraints to both gas and electricity systems and can affect the assessment of gas and electricity infrastructure projects. It is only the case when the switch between electricity and gas is dynamic, i.e. the gas and electricity consumption changes depending on the prices of both energies (the hybrid consumption technology preferring to use the cheapest solution at each time).

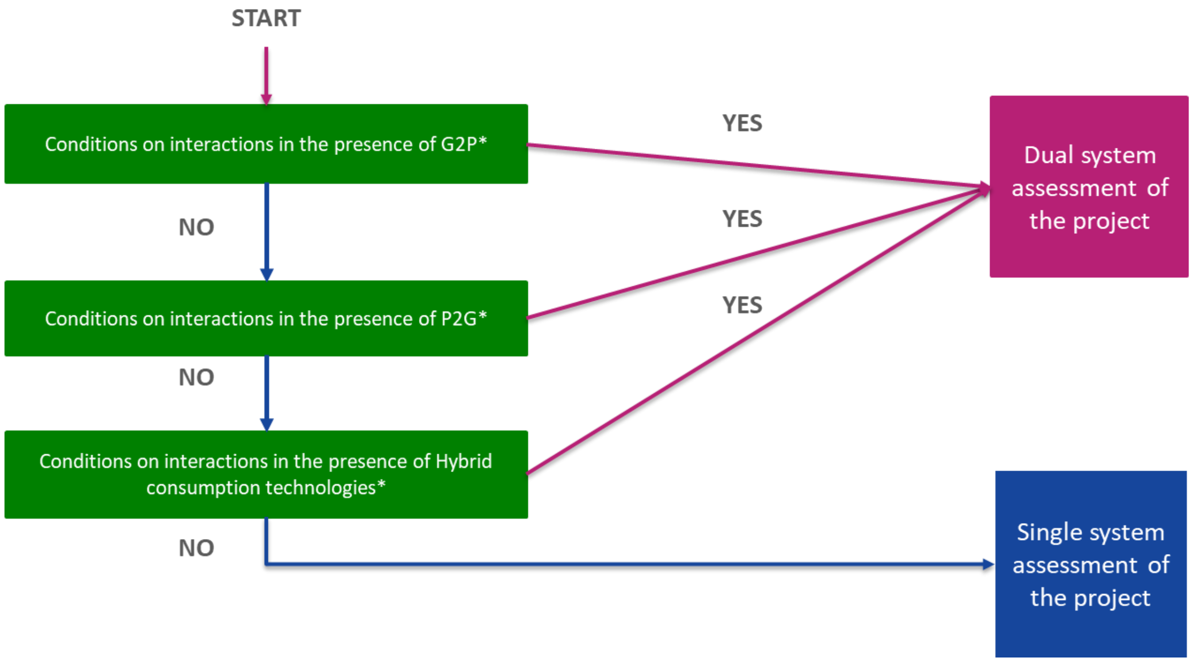
If there is a significant quantity of these dynamically operated HCT, there is a competition between gas and electricity for the supply of this consumption and a dual assessment is required for new gas and electricity infrastructure projects.

We however do not anticipate currently a high development of hybrid consumption technologies except for hybrid heat pumps which are in most cases not operated based on energy prices but rather are driven by the temperature difference, which do not create a need for a dual system assessment since this can be taken into account at the scenario building level.

5.2 Recommendations for the screening methodology

5.2.1 Structure of the screening methodology

Given the results that have been obtained in Tasks 1, 2 and 3, and the dependence of the screening on scenario-based elements, the screening should take place after the scenario building phase, and could be divided in three steps, each step screening the need for a dual assessment in the presence of each of the three sources of interlinkages discussed above (G2P, P2G, HCT). Each step would require checking several conditions in relation to its specific interlinkage.



In the following subsections we describe in more details the conditions for each of the three green boxes shown on the figure above. These conditions are to be checked in both areas when assessing the need for a dual assessment of an interconnection project. In this case, if the conditions are valid for one area, there is a need for dual assessment, as the interaction between the electricity and gas systems of one area starts being significant.

5.2.2 Conditions relative to gas-to-power

To assess if there is a need for a dual system assessment when looking at a gas or electricity infrastructure project in the presence of G2P, three conditions need to be checked (independently in both areas for interconnections):

- Existence of a significant amount of G2P in the gas system
- Presence of gas constraints related to the use of G2P
- Presence of electricity flexibilities to avoid gas consumption from G2P

We detail below these conditions.

Condition 1.1: Quantity of gas-to-power in the system

A prerequisite for G2P creating interaction in the system is the presence of a significant share of gas consumption for G2P in the gas system. This can be assessed directly with the results from the scenario building step by comparing the gas consumption from G2P with the total gas consumption. If the ratio is above 5% then the following conditions need to be checked.

Condition 1.2: Presence of gas constraints related to the use of G2P

An interaction occurs between gas and electricity only if there are constraints on the gas system due to the presence of G2P. These constraints can be of different types:

- *Constraint on the annual gas import capacities*: it occurs when the yearly gas demand (including G2P) is higher than the sum of the gas volume producible locally and the maximum volume of gas importable (including LNG).
- *Constraints on the gas storage level:* it occurs when the storage capacities is too low (in volume or in capacity) to handle the seasonal variability of the consumption (including the variability of G2P)
- *High supply source dependence:* it occurs when the gas supply of an area depends very highly on the provision of gas by a given supply source.

These constraints can be assessed right after the TYNDP scenario building step with the inputs of the gas scenarios (i.e. before a single assessment).

If these constraints are due to the presence of G2P (i.e. if they are present with G2P and absent when disregarding G2P) then a dual system assessment is required for assessing gas or electricity infrastructure projects.

Condition 1.3: Presence of electricity flexibilities to avoid gas consumption from G2P

There is an interaction between gas and electricity systems that requires a dual system assessment for a new asset only if the flexibility of the electricity system can avoid to use G2P in the constrained area. This flexibility can take different forms:

- Presence of electricity storages (hydro or batteries), interconnections or demand response capacities that could be operated differently when taking into account the gas constraints,
- Presence of additional generation (potentially more expensive than gas-based generation) that could be used in replacement of the lack of availability of CCGT, OCGT or CHP capacities due to constraints on the gas system.

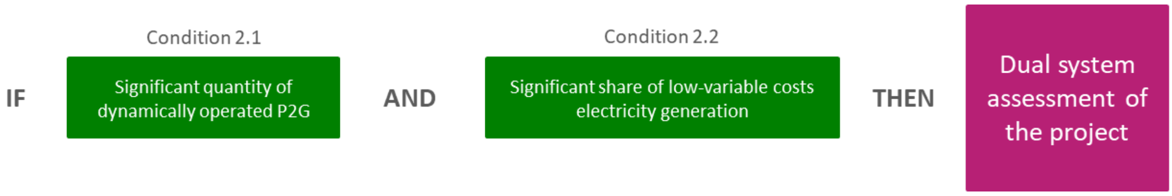
One possibility to assess this flexibility could be to use simulation results of the electricity model in the TYNDP scenario building step and the indicators provided in this exercise. For instance, if LOLE is already high when using G2P, it means there is no available flexibility. Capacity margin could be also a good indicator.

5.2.3 Conditions relative to power-to-gas

5.2.3.1 For electricity projects

To assess if there is a need for a dual system assessment when looking at an **electricity** infrastructure project in the presence of P2G, two conditions need to be checked (independently in both areas for interconnections):

- Presence of a significant amount of dynamically operated P2G in the electricity system
- Presence of a substantial generation of low-variable costs technologies (nuclear, vRES-e)



We detail below these conditions.

Condition 2.1: Quantity of dynamically operated power-to-gas in the system

P2G can create interactions requiring a dual system assessment when studying an electricity infrastructure project when there is a significant share of dynamically operated power-to-gas in the system. We identified in Task 3 that the interaction starts requiring a dual assessment when the capacity of the dynamically operated P2G is above 5% of the low variable costs technologies (nuclear + vRES-e) capacity.

$$dynamicallyOperated\ P2G\ capacity \geq 5\%\ of\ (Nuclear\ +\ vRESe)\ capacity$$

Condition 2.2: Presence of a substantial generation of low-variable costs technologies (nuclear, vRES-e)

The interaction created by the power-to-gas becomes important when the generation of low-variable cost technologies become substantial. In particular, we identified in Task 3 that the effect of P2G required a dual system assessment when studying electricity infrastructure projects when:

$$\frac{\text{vRESe yearly Generation} + \text{Nuclear yearly Generation}}{\text{Electricity yearly consumption (incl. pumping)}} \geq 60\%$$

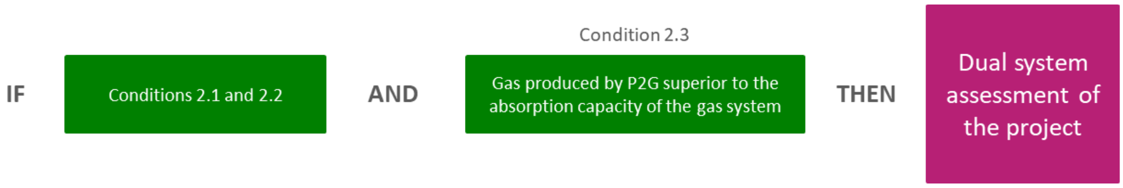
Note that the yearly consumption on the denominator has to take into account the consumption from pumped storages, highlighting the fact that pumped storage competes with P2G to exploit the potential surpluses created by the variability of vRES-e generation.

Both these conditions can be checked after the electricity simulations performed in the TYNDP scenario building step.

5.2.3.2 Additional condition for gas projects

To assess if there is a need for a dual system assessment when looking at a **gas** infrastructure project in the presence of P2G, in addition to the two conditions 2.1 and 2.2, another condition has to be checked:

- Quantity of P2G superior to the absorption capacity of the gas system



Condition 2.3: Quantity of P2G superior to the absorption capacity of the gas system

There is a need for a dual system assessment in the presence of P2G for gas interconnections only when the gas produced is too important to be absorbed by the gas system, i.e. in the case of gas injected in the gas network, when:

$$\begin{aligned} &\text{P2GGasProduction} + \text{local gas production} + \text{gas imports} \\ &\qquad \geq \text{yearlyGasDemand} + \text{StorableVolume} + \text{ExportableVolume} \end{aligned}$$

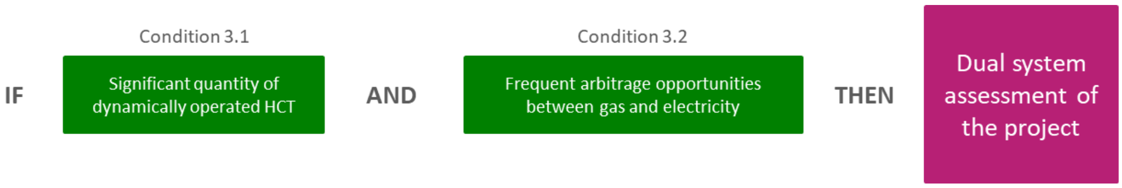
Indeed in this case, new export capacities would be required to make use of this gas, so there is a trade-off between producing this excess P2G and building the infrastructure **or** not producing this extra gas and using the electricity surplus for other purposes.

This condition can be checked using the results of the gas model after the scenario building step. They will be very unfrequently met as it would require a very substantial capacity and volume of P2G.

5.2.4 Conditions relative to hybrid consumption technologies

To assess if there is a need for a dual system assessment when looking at an electricity or gas infrastructure project in the presence of hybrid consumption technologies (HCT), two conditions need to be checked (independently in both areas for interconnections):

- Presence of a significant amount of dynamically operated HCT in the electricity and gas systems
- Frequent arbitrage between gas and electricity consumption in the HCT



We detail below these conditions.

Condition 3.1: Quantity of dynamically operated HCT in the system

HCT can create interactions requiring a dual system assessment when studying an electricity or gas infrastructure project when there is a significant share of dynamically operated HCT in the system. We identified in Task 3 that the interaction starts requiring a dual assessment when the capacity of the dynamically operated HCT is above 5% of either the gas or electricity yearly consumption.

$$\text{dynamicallyOperated HCT gas consumption } \geq 5\% \text{ of total gas consumption}$$

$$\text{OR}$$

$$\text{dynamicallyOperated HCT electricity consumption } \geq 5\% \text{ of total electricity consumption}$$

These constraints should be verifiable at scenario level with the results of the simulations performed. Given the current and forecasted deployment of hybrid technologies (especially for dynamically operated technologies) we anticipate that these constraints will not be met very frequently.

Condition 2.2: Frequent arbitrage opportunities between gas and electricity

The interaction created by HCT occur only if the trade-off between using gas or electricity is a close call. In most cases, this is unlikely to happen. Indeed, in the case of hybrid heat pumps, the coefficient of performance of the heat pump component is such that even if it were dynamically optimized versus gas and electricity prices, the heat pump component will be used at its maximum capacity at each hour, the gas boiler being used only as a back-up when the heat pump component is not sufficient to cover the heat consumption[10].

The interaction thus occurs when, for a given hybrid consumption technology:

$$\frac{GasPrice}{GasEfficiency} \sim \frac{ElectricityPrice}{ElectricityEfficiency}$$

This condition could be verifiable by looking at the efficiencies of the gas and electricity components of hybrid technologies. In order to assess the potential electricity and gas prices, as a proxy one could use coal, CCGT and OCGT variable generation costs (given their efficiencies) and gas prices of different gas sources as a proxy.

[10] Indeed, using the HP component (COP of 3) with electricity generated by an OCGT (efficiency of 40%) consumes less gas than using a gas boiler (efficiency of up to 90%) and is thus cheaper – obviously excluding investment costs.

5.2.5 Focusing on relevant infrastructure projects

The costs of an infrastructure project, while not directly impacting the gas and electricity systems' operations, are an important factor in the cost-benefit analysis and could be included in some way in the screening methodology as its goal is to detect the **relevant cases** for application of a dual system assessment.

In particular, project costs could help assessing which are the relevant projects to be considered in a dual system assessment since they allow to:

- Evaluate if a project is more or less profitable using either rules of thumbs or the results of a single system assessment to compute its potential benefits,
- Identify the projects with high financial stakes

This step could be performed either before or after checking the conditions for gas/electricity interactions in the presence of G2P, P2G or HCT.

5.3 Examples of application of the screening methodology

We present below two examples of application of the screening methodology as described in the previous paragraphs. Both these examples feature fictional areas and projects whose parameters are described. We then apply the proposed screening methodology to see if these projects would require a dual system analysis.

Note that the application of the methodology to real situations may require adaptations or adjustments from the ENTSOs.

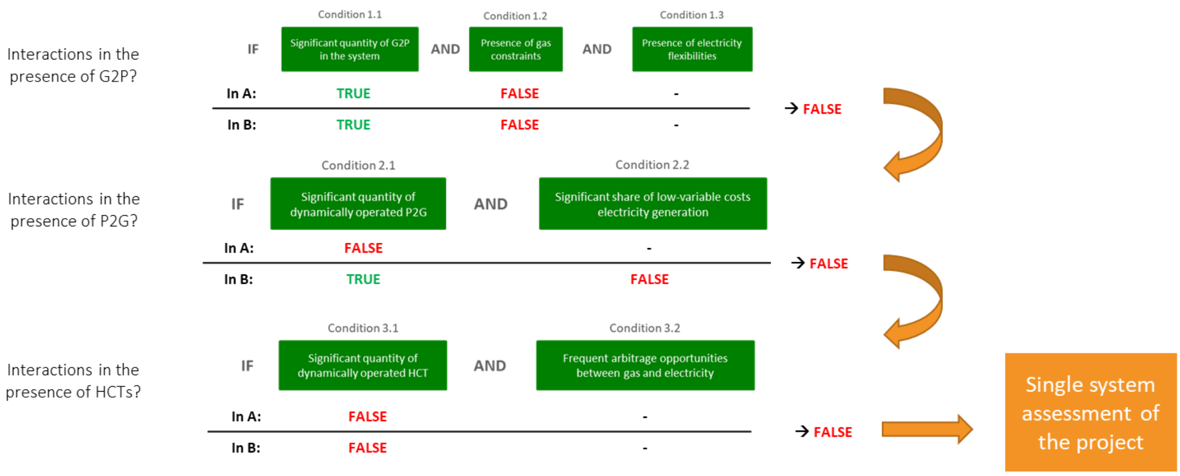
5.3.1 Example 1: Electricity interconnection in the presence of P2G

We consider here two areas A and B that are considering a possible investment in an electricity interconnection. Both areas have G2P and P2G capacities which may trigger a need for a dual system assessments. The relevant characteristics of their system are presented in the table below.

Areas	Total gas demand [TWh]	G2P demand [TWh]	Presence of gas constraints	Presence of electrical flexibilities	P2G capacities [GW]
A	480	55	No (from simulations)	Yes (from simulation)	5
B	45	8	No (from simulations)	Yes (from simulation)	1

Areas	Nuke + vRes capacities [GW]	Nuke + vRes production [TWh]	Electrical demand [TWh]	HCTs (Heat pumps) [GW]	Arbitrage gas – electricity opportunities
A	140	420	460	Negligible	-
B	11	14	60	Negligible	-

To assess the needs for dual system assessment we go through the different conditions as presented in the chart below:



Even if there are some G2P capacities in both area, conditions 1.2 are false for both areas, so there are no significant interactions in presence of G2P. Similarly, even though there are some significant P2G capacities in B, the generation from vRES or nuclear capacities is under the threshold (60%) of condition 2.2 (which is thus false) meaning that there are no significant interactions between gas and electricity systems in the presence of P2G. Finally, there are no significant HCTs in both areas.

The application of the proposed screening methodology would thus recommend to assess the interest of the project in a single system (electricity) assessment.

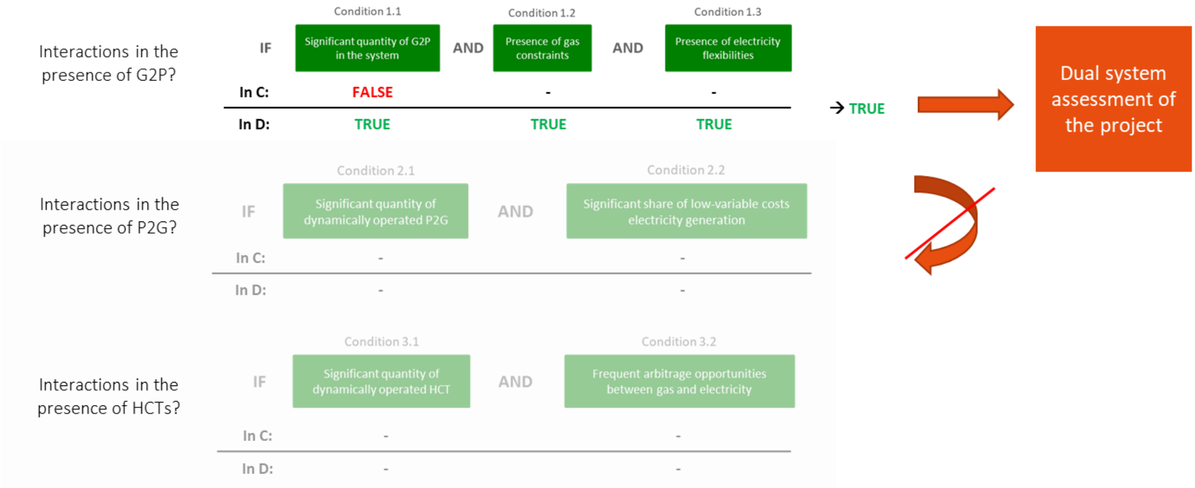
5.3.2 Example 2: Gas interconnection near areas with significant G2P

We consider here two areas C and D that are considering a possible investment in a gas interconnection. There are no P2G or HCT capacities in both areas, but the volume of G2P in each area is significant. The relevant characteristics of their system are presented in the table below.

Areas	Total gas demand [TWh]	G2P demand [TWh]	Presence of gas constraints	Presence of electrical flexibilities	P2G capacities [GW]
C	95	3	Yes (from simulations)	Yes (from simulation)	0
D	11	1	Yes (from simulations)	Yes (from simulation)	0

Areas	Nuke + vRes capacities [GW]	Nuke + vRes production [TWh]	Electrical demand [TWh]	HCTs (Heat pumps) [GW]	Arbitrage gas – electricity opportunities
C	4	15	48	Negligible	-
D	1	5	16	Negligible	-

To assess the needs for dual system assessment for the project, we go through the different conditions as presented in the chart below:



In area D, the three conditions of interaction in the presence of G2P are true:

- The volume of gas consumption of G2P is high in comparison to the total gas consumption of the area.
- There are gas constraints in the area.
- There are some electricity flexibilities in the system.

The application of the screening methodology would thus recommend to perform a dual system analysis to take into account the gas/electricity interactions.

Note that in this case, there is no need to look at the conditions 2.X and 3.X.

6 Appendix 1 - Assessment of the thresholds on vRES-e in the presence of P2G

In the qualitative analysis of interactions between P2G and infrastructure projects, we have identified that one of the prominent factors on the occurrence of an interaction between gas and electricity systems was the presence of a large quantity of electricity produced by technologies with low variable-costs such as vRES-e. Indeed, P2G and infrastructure projects generally compete to access cheap electricity resources (either to turn them into gas, or to export them to other areas).

In order to be able to evaluate a threshold above which the amount of vRES-e in the electricity mix is such that a dual system assessment is recommended, we have simulated the behaviour of generic gas and electricity systems corresponding to two typical areas, one of which hosting P2G capacity.

We have then performed several thousand simulations with different values for vRES-e capacity and other key parameters, to identify situations where the power-to-gas creates a significant interaction between gas and electricity systems and would necessitate to perform a dual system assessment when evaluating a new gas or electricity infrastructure project.

For each set of parameters, we have evaluated the economic value of new gas and electricity interconnection projects, which corresponds to the social welfare they bring to the system (or equivalently, to the reduction of total costs they allow for). The simulations we have performed are structured as sensitivity analyses of the value of new projects to different parameters, around a reference situation of the system. While not aiming at being completely exhaustive, the simulated cases cover a large range of situations, which we have used to derive our results.

The simulations are performed with the energy system modelling and optimisation tool Artelys Crystal Super Grid over a whole year (8760 consecutive time-steps), using an hourly time resolution.

The reference situation is the following:

- Two fictional[11] areas A and B with electricity and gas consumptions of a relatively similar size (in terms of TWh/year).
- Electricity systems with a variable share of vRES-e, G2P capacities completing the electricity supply. Some electricity storage assets are also considered to integrate part of the potential RES surplus. In a variant we also consider the case of an additional nuclear capacity.
- Gas systems with a generic supply of gas at a given cost (equal in both areas) and with a given maximum capacity, corresponding to all the potential gas supplies of the area (imports, LNG, local generation). We also consider gas storage assets, either seasonal (to cover the

[11] In order to guarantee the consistency of the dataset, simulations performed are based on real data for Spain and France. This data covers gas and electricity consumption and vRES-e normalized generation profiles, which allows to keep the natural correlation of wind, solar irradiation and temperature across the simulations.

winter/summer variation of the consumption) or daily (corresponding to linepack storage, whose flexibility can handle most daily variation)
- A given level of gas and electricity interconnection between gas and electricity system in A and B.
- A capacity of P2G varying from 0 MW to an excess capacity of P2G.

We present below some of the most illustrative results derived from this analysis.

6.1 Influence of vRES-e on the assessment of gas and electricity assets in the presence of P2G

The first parameter studied is the share of **vRES-e in both areas**, as a % of the total electricity consumption in each area. The following figure presents the value of a new electricity interconnection project (typically measured in €/MW/y) depending on the vRes-e share in both areas and with/without P2G in both areas. We considered 4 different values (namely 20%, 40%, 60% or 80%) for the vRES-e share in each area.

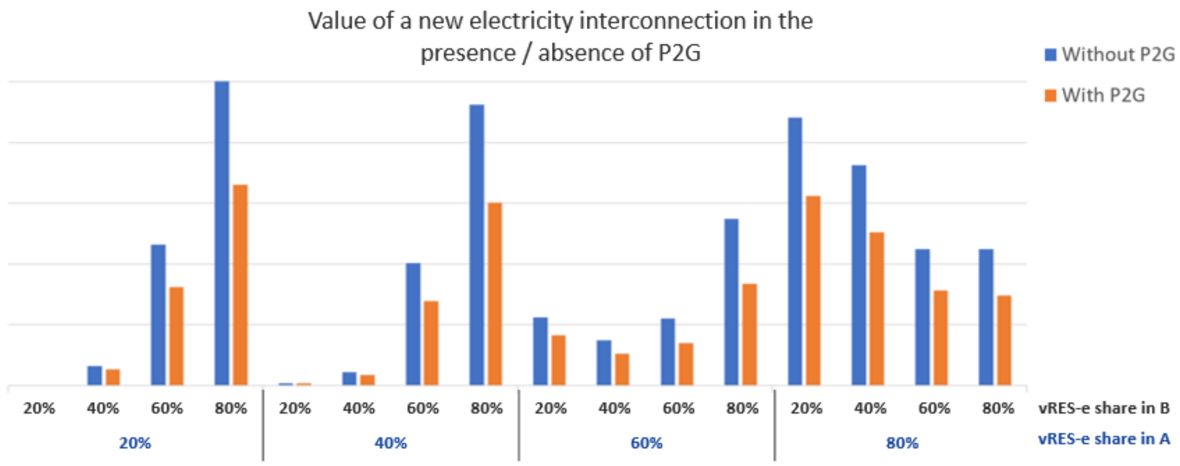


Figure 13. Value of a new power interconnector (in €/MW/year) with different vRes-e shares and with/without P2G

In the absence of P2G (in both areas), due to the structure of the electricity mix considered in both areas (vRES-e and G2P in both systems), the value of the interconnection increases overall with the vRES-e share in both area since the value benefits from the exports of RES-e surpluses of one area to the other area. At very high vRES-e shares in both areas, we note that the value decreases since there are often simultaneous surpluses in both areas.

In the presence of P2G (in both areas), we note the same trends, but P2G lowers the value of the electricity project in each of the configurations we have explored. This is due to the fact that P2G reduces the surplus available for exports and increases the price in the exporting area, reducing the benefits brought by a new electricity interconnection project. This reduction of value is the most prominent in situation with a vRES-e share of 60% or higher in either A or B, the effect of P2G being very reduced when the share is lower than 60%.

We also note **the effect of the vRES-e share** on the value of **gas interconnectors**. In the following figure, we present the value of a new gas interconnector depending on the vRES-e share, the presence of P2G in both areas and the presence of a gas demand in the area.

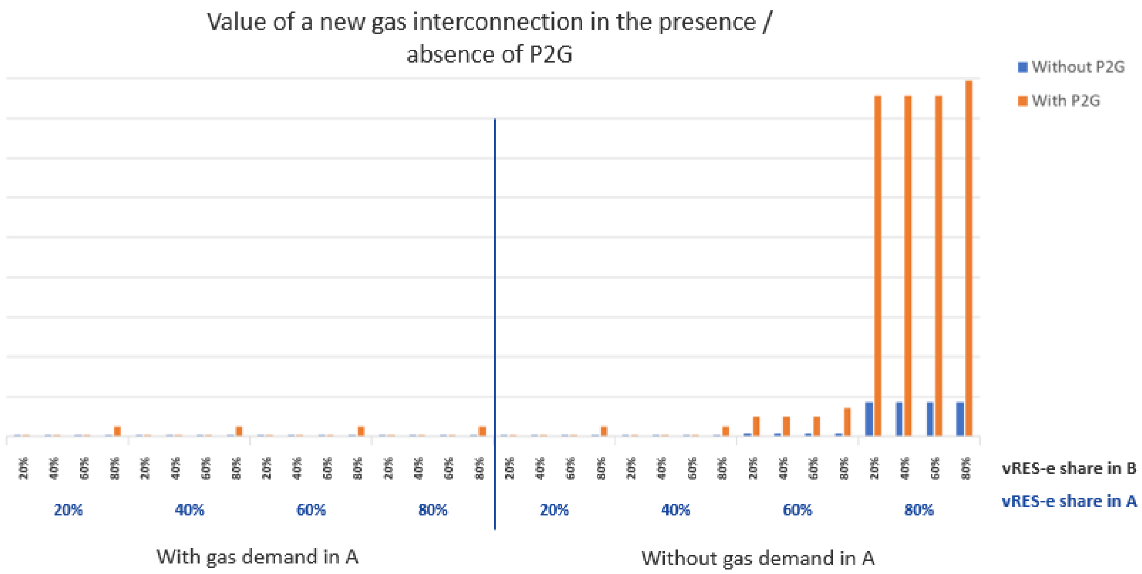


Figure 14. Value of a new gas interconnector (in €/MW/year) with different vRes-e shares, with /without P2G (orange or blue bars) and with /without gas demand in A (left and right respectively)

We confirm with these results that the presence of P2G does not give a value for new gas interconnectors if there is a local gas demand that can absorb the production of gas by P2G. Indeed, since the price of gas is similar in both areas by construction, there is value for a new gas interconnection only if there is surplus gas production (by P2G) that needs to be exported in the neighbor area. This value increases with the share of vRES-e, and is significant only when the vRES-e share is around 60 or 80%.

Overall, there is an effect on the value of the gas interconnection only when the share of vRES-e is very high and when the local gas market is smaller than the generation of gas by P2G. This situation will be very rare since one can expect that P2G will not be built alone (i.e. without specific gas interconnections) in areas without gas consumptions[12].

6.2 Influence of nuclear and storage capacities on the assessment of electricity assets in the presence of P2G

The **share of nuclear generation** in the electricity mix, as source of cheap electricity that can be used for P2G, has also been studied. We present in the following figure a sensitivity on the value of the

[12] While projects of P2G near offshore wind farms in the North Sea correspond to these criterion, the P2G project will be built with a corresponding gas pipeline to export the gas produced. The project Wind + P2G + gas pipeline can in this case be considered as a full gas producer in the connected area.

electricity interconnection to the nuclear capacity, all things equal otherwise, in the presence or absence of P2G.

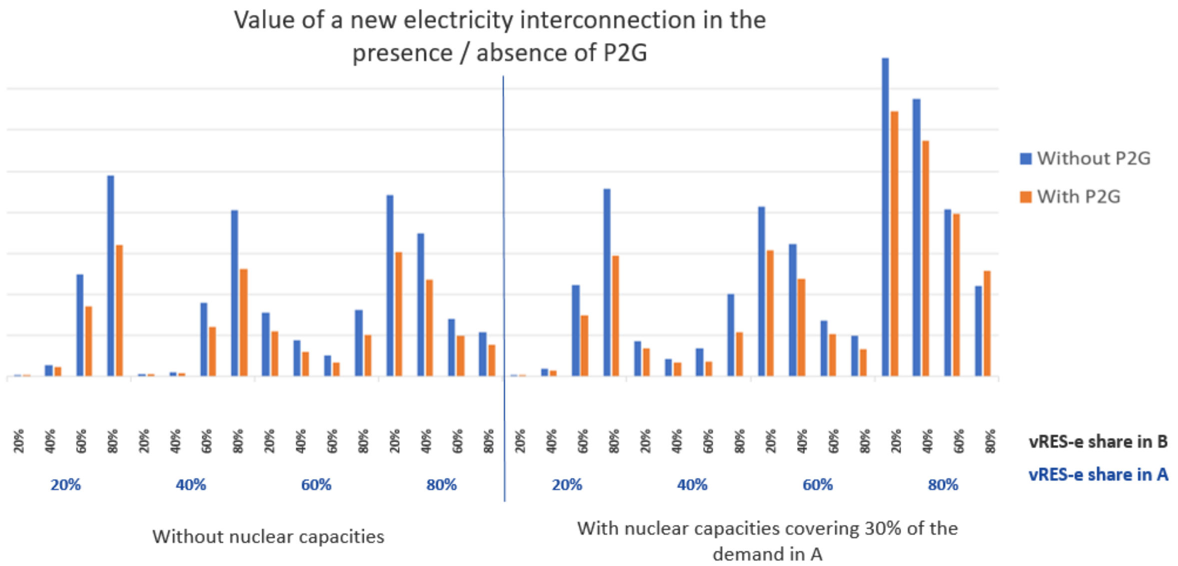


Figure 15. Value of a new power interconnector (in €/MW/year) with different vRes-e shares, with (at the left-hand side)/without nuclear capacities (at the right-hand side) and with (blue bars)/without (orange bars) P2G

In the absence of P2G, the figure show that nuclear capacities bring value to power interconnectors. Indeed, nuclear capacities increase the amount of cheap electricity available for exports which increases the value of the interconnection. In the presence of P2G, the value of the interconnection is reduced similarly to the case without nuclear capacities.

We however note that this phenomenon starts to be significant at 40% of vRES-e share. The threshold on vRES-e is thus lower when there is additional nuclear capacity[13].

The influence of storage on the interaction is also important as is presented in the figure below, for a storage of a high capacity (20% of the average hourly consumption) and a 6-hour discharge time.

[13] At very high shares of renewables, the value of the electricity interconnector can increase in the presence of P2G. Indeed in such situations, when one zone saturates its P2G use (either due to its capacity or ability to use/export gas), electricity surpluses can be exported to a neighbouring area where it will be used to produce gas via the neighbour's P2G capacity.

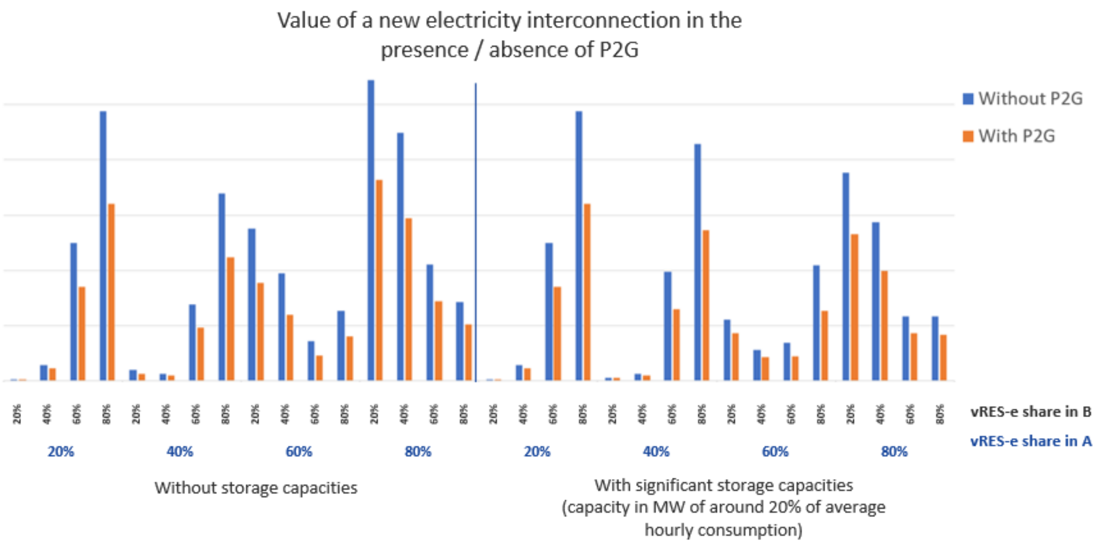


Figure 16. Value of a new power interconnector (in €/MW/year) with different vRes-e shares, with/without electricity storage (left/right) and with/without P2G (orange and blue bars respectively)

Indeed, as a way to integrate the surplus of cheap electricity in the system, storage reduce the value of interconnection for exports and thus the effect of P2G on this value. The size of the storage also plays a role: a higher storage capacity tends to reduce the effect of P2G on the value of the interconnection, as presented in the figure below.

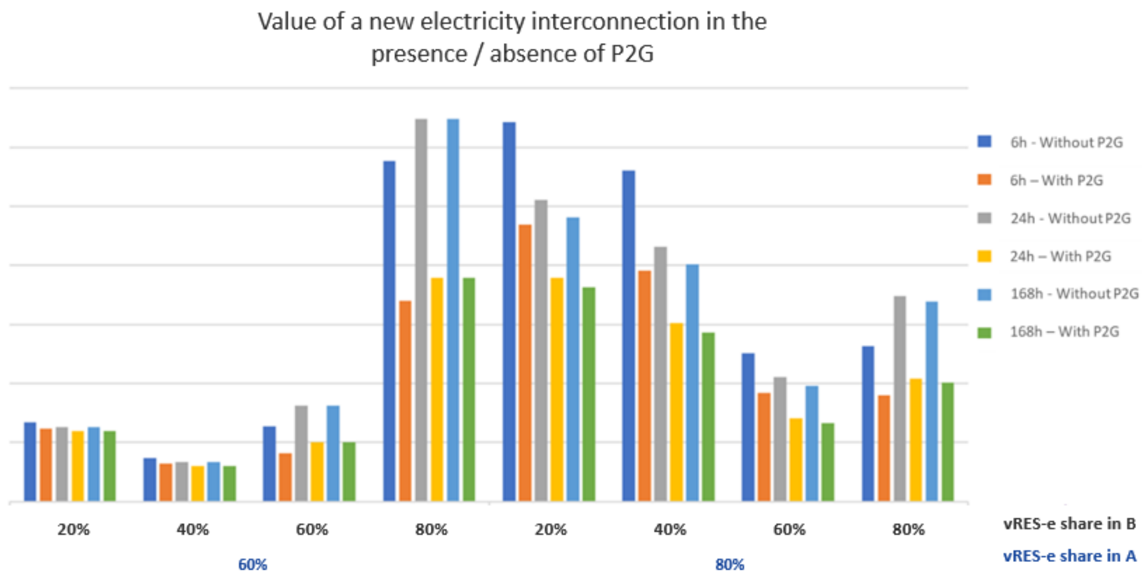


Figure 17. Value of a new power interconnector (in €/MW/year) with different vRes-e shares, with/without P2G and with different discharge time for the storage (6h, 1 day and 1 week)

Given these results the final condition to assess if there is an interaction between gas and electricity system in the presence of P2G takes into account vRES-e and nuclear share in electricity generation and the additional consumption from pumped hydro:

$$\frac{\text{vRESe yearly Generation } + \text{ nuclear yearly Generation}}{\text{Electricity yearly consumption (incl. pumping)}} \geq 60\%$$

7 Appendix 2 – Summary of the feedbacks obtained during the webinars

7.1 Summary of the feedback on webinar 1 about Task 1

On 10 October 2018, during a webinar organised by the ENTSOs, Artelys has presented the results of Task 1. The attendees, representing gas and electricity TSOs, NGOs, European institutions, etc., have had the occasion to share suggestions and to ask questions.

We provide a summary of the main themes of interest below:

Exhaustivity of the Sankey diagram

Some comments have been made on the Sankey diagram use for the scenario building exercise. In particular, participants mentioned that some elements are missing:

- Alternative sources for heat
- The role of interconnectors and of energy efficiency
- The electricity consumption of some CO_2 capture processes

Answer: While they are not displayed for simplification of the diagram, these elements are captured by the Scenario Building exercise. Details have been added in Section 4.3.

Power-to-gas operation

One participant mentioned that the use of power-to-gas is not limited to RES-e surplus periods, but that in some scenarios power-to-gas installations will have to run even in periods of relatively high electricity prices.

Answer: The paragraph on power-to-gas has been updated and now accounts for situations in which the gas production via power-to-gas is not limited to periods of RES-e surplus.

Power-to-gas development

Participants asked if the injection of both hydrogen and SNG into the gas grid was taken into account. Another participant mentioned that power-to-hydrogen will likely be deployed before power-to-gas.

Answer: The report mentions both H2 and SNG injection and both are considered in the study. On the second point, studies show indeed that the economic viability threshold of P2H is likely to be reached before that of P2G.

Gas prices

Participant asked some precisions about the denomination 'prices' in the report.

Answer: In the report, prices refer to commodity prices for both gas and electricity, i.e. the prices of gas and electricity in the network or equivalently the marginal gas and electricity prices. It has been clarified in Section 4.3.

7.2 Summary of the feedback on webinar 2 about Tasks 2&3

On February 7th 2019, during a webinar organised by the ENTSOs, Artelys has presented the preliminary results of Tasks 2 and 3. The attendees, representing gas and electricity TSOs, NGOs, European institutions, etc., have had the occasion to share suggestions and to ask questions.

We provide a summary of the main themes of interest below:

Operation of P2G

Participants raised that some of the operation modes of P2G are not directly taken into account in the 3 main categories described (for instance, power-to-Hydrogen coupled to a steam methane reforming installation).

Answer: While we have summarized the operation types in 3 main categories, real projects can combine these operation types. We have added some elements on this in section 4.3.1.

Infrastructural substitution between gas and electricity

One participant asked how infrastructural substitution was taken into account in the approach.

Answer: The substitution between gas and electricity is partly taken into account directly in the scenario building phase. Indeed, the evolution of the yearly consumption of gas and electricity takes into account the changes in supply mix (for instance, switch from electric heater to heat pumps or gas boiler).

The dynamic substitution is taken into account in the modelling used in the study. For instance, we model hybrid heat pumps that are price-driven, meaning that they switch to a gas consumption if the electricity is expensive.

7.3 Task 4 Webinar – Summary of the feedback

On April 11th 2019, during a webinar organised by the ENTSOs, Artelys has presented the outcomes of tasks 2 and 3 on hybrid consumption technologies, and of task 4 on the proposed screening methodology. The attendees, representing gas and electricity TSOs, NGOs, European institutions, etc., have had the occasion to share suggestions and to ask questions.

We provide a summary of the main themes of interest below:

Condition 2.3 on P2G

The condition 2.3 on the interaction in the presence of P2G has been clarified following participants remarks. Some interactions can occur as long as P2G creates some surplus gas in the area, i.e. if the volume of gas produced by P2G and other sources or imported exceeds the sum of the gas consumption in the area plus the gas that could be exported or stored.

Impact of indirect interactions

As participants noted, indirect interactions, i.e. possible choices between gas and power appliances for heating and mobility, will define the evolution of gas and power systems in the medium and long term. While they are the focus on the scenario building in which they are carefully looked at, they are not in the scope of the study.

Taking into account hybrid consumptions

As noted by participants, the dynamic operation of “market-driven” hybrid consumption technologies is considered in a simple schematic way. In reality the dynamic choice between gas and electricity that has to be made at each time when operating a market-driven hybrid heat pump will have to take into account the gas and electricity tariffs for the consumer. Additionally, it will have to take into account the current value of the COP which will vary depending on the temperature.

For that purpose, condition 3.2 on HCT specifies that an interaction in the presence of HCT can occur if there are “frequent arbitrage opportunities” between gas and electricity uses for the HCT. The presence of such opportunities will depend on a lot of parameters, including the previously mentioned parameters. The occurrence of such opportunities will have to be investigated during the use of the screening methodology.

8 Glossary

ACER	Agency for the Cooperation of Energy Regulators
CBA	Cost benefit analysis
CCGT	Combined cycle gas turbine
CCS	Carbon capture and storage

CHP	Combined heat and power
Dual system analysis (DSA)	Methodology used for project assessment that captures the operational interlinkages between the gas and electricity systems. The methodology for dual system analysis is to be developed by the ENTSOs.
ENTSO-E	European Network of Transmission system operators of electricity
ENTSOG	European Network of transmission system operators of gas
Flexibility of the electricity system	According to the ENTSO-E, the flexibility of the electricity system is its capability to accommodate fast and deep changes in the net demand (load minus intermittent RES) in the context of high penetration levels of non-dispatchable electricity generation.
Gas-to-power (G2P)	Gas-based production of electricity, e.g. in Open Cycle Gas Turbines (OCGTs), Combined Cycle Gas Turbines (CCGTs) and Combined Heat Plants (CHP)
HP	Heat pumps
Hybrid consumption technologies (HCT)	Technologies allowing to consume either electricity or gas at each time to satisfy an end-use (e.g. hybrid heat pumps, equipped with both a HP component and a gas back-up).
Interlinked model	Approach developed by the ENTSOs to meet the requirements of Regulation (EU) No 347/2013.
OCGT	Open cycle gas turbine
Power-to-gas (P2G)	The use of electricity to generate either H2 by electrolysis or CH4 by methanation
Price-driven	A technology is price-driven if its operation depends on the prices of electricity and gas. (e.g. power-to-gas or HCT can be price-driven in some cases).
Project assessment	Process by which the ENTSOs determine the overall benefits brought by the considered project and compare them with the relevant costs
RES	Renewable energy sources

Screening methodology	Methodology used to determine whether a project assessment should be conducted using a single system analysis or a dual system analysis.
Scenario	Set of assumptions describing the gas and electricity sectors (demand, infrastructure, commodity prices, etc.). Since TYNDP 2018, the TYNDP scenarios are jointly developed by ENTSOG and ENTSO-E.
Single system analysis (SSA)	Methodology used for project assessment that only partially captures the operational interlinkages between the gas and electricity systems. ENTSOG and ENTSO-E CBA methodologies are examples of single system analyses.
TYNDP	Ten-year network development plan
vRES-e	Variable Renewable Energy Sources of electricity. It corresponds mostly to solar PV, wind turbines and hydro run-of-river whose generation is considered as must-run and depends on the weather.

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