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

Task 2&3 – Report

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TABLE OF CONTENTS

Glossary

Dual system analysis	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.
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.
Interlinked model	Approach developed by the ENTSOs to meet the requirements of Regulation (EU) No 347/2013.
Project assessment	Process by which the ENTSOs determine the overall benefits brought by the considered project and compare them with the relevant costs
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	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.
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.

Introduction

This document is the sub-report for Tasks 2 and 3 of the focus study led by Artelys on behalf of ENTSOG and ENTSO-E on the interlinkages between gas and electricity scenarios and infrastructure projects assessment.

The report is structured as follows:

- Methodology of Tasks 2 and 3
- Interaction between projects in the presence of G2P,
- Interaction between projects in the presence of P2G,
- Interaction between projects in the presence of hybrid consumption technologies,

1 Methodology of Tasks 2 and 3

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.

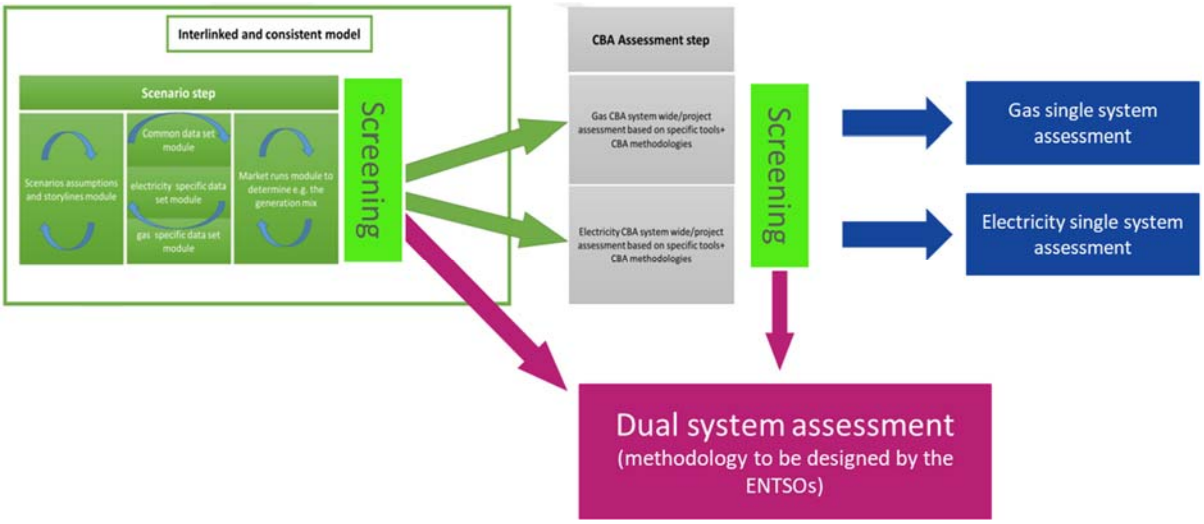

Figure 1. Illustration of the use of the screening methodology

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.

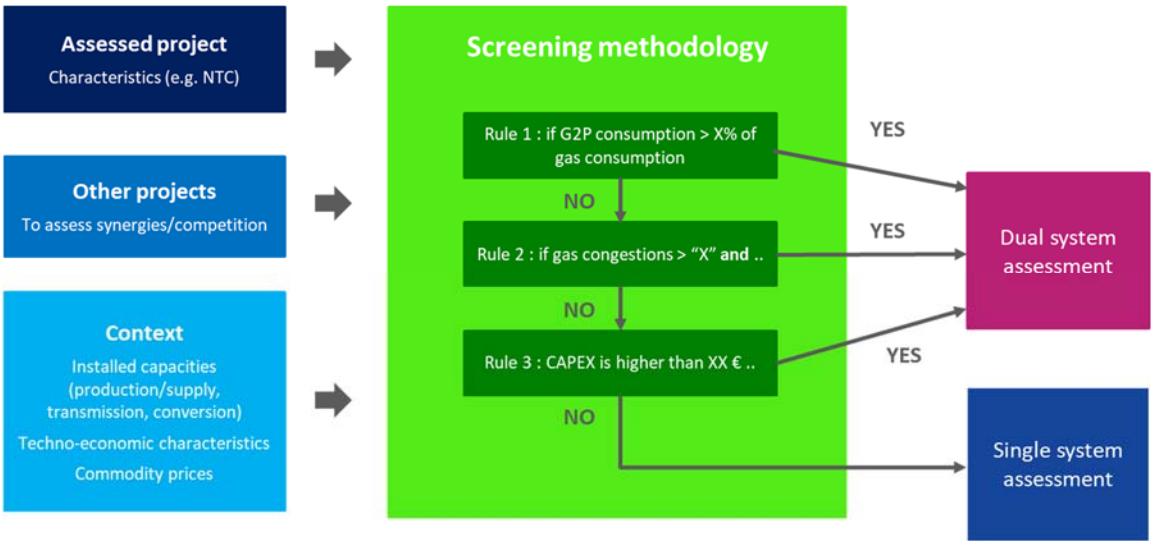

Figure 2. Proposed structure for the screening methodology

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 3. Role of Tasks 2 and 3

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).

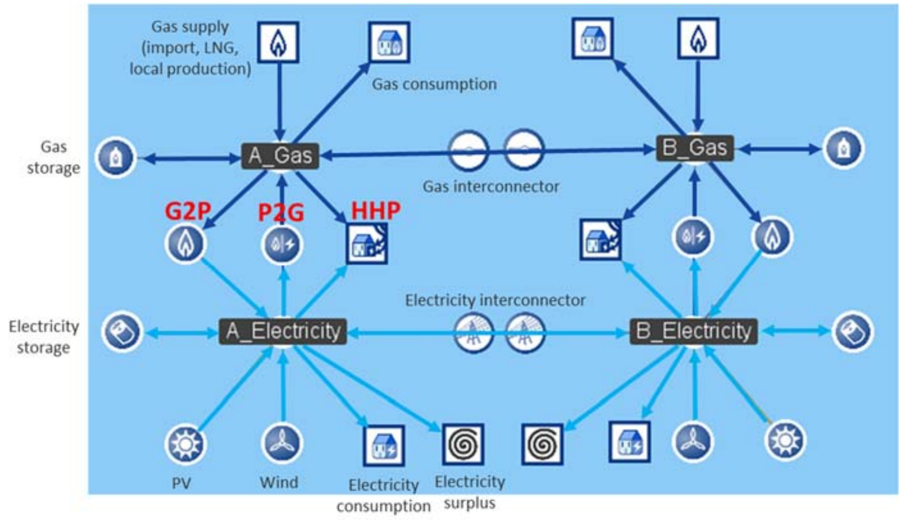

Figure 4. Illustration of the joint gas and electricity model used for Task 3

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.

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.

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.

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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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).

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.

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).

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.

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[1] 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 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

$$\begin{aligned} &\text{G2PyearlyGasConsumption} + \text{NonG2P yearlyGasConsumption} \\ &\qquad > \text{localYearlyGasProduction} + \text{maximumYearlyGasImports} \end{aligned}$$

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

Presence of a gas congestion AND priceDifference > 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.

[1] 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.

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.

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[2]:

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[3].
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 CO_2 emissions). Due to the structure of the electricity consumption and to the pattern of variable RES generation, **price-driven P2G** usually

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

[3] 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).

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[4]. 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).

3.2 Effect on the assessment of a project

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.

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).

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[4] In the recent Clean Energy Package trilogues, exploitation rules have been defined regarding the use of P2G by TSOs.

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.

3.3 Meaningful parameters of the interaction

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.

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

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 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.

4.1 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.

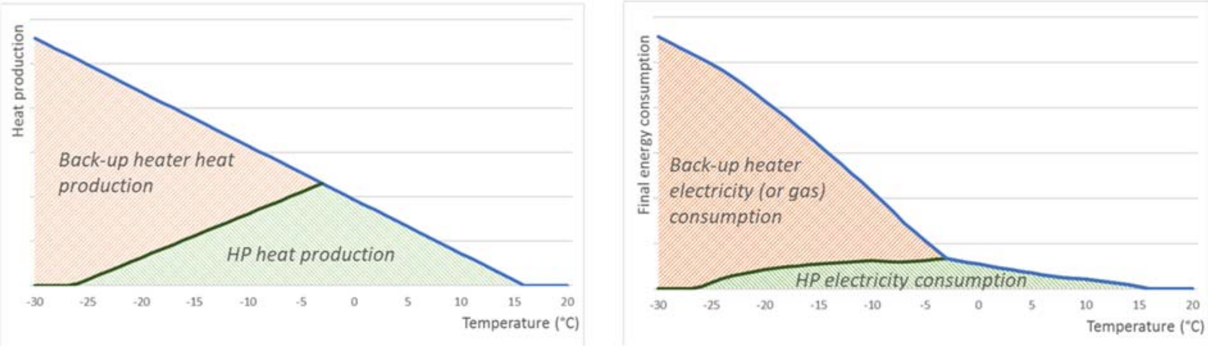

Figure 5. Operation of a hybrid heat pump depending on the temperature (heat generation – left – and final energy consumption – right - for each component of the hybrid HP)

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[5]. 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.

4.2 Effect on the assessment of a project

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.

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.

[5] 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)

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.

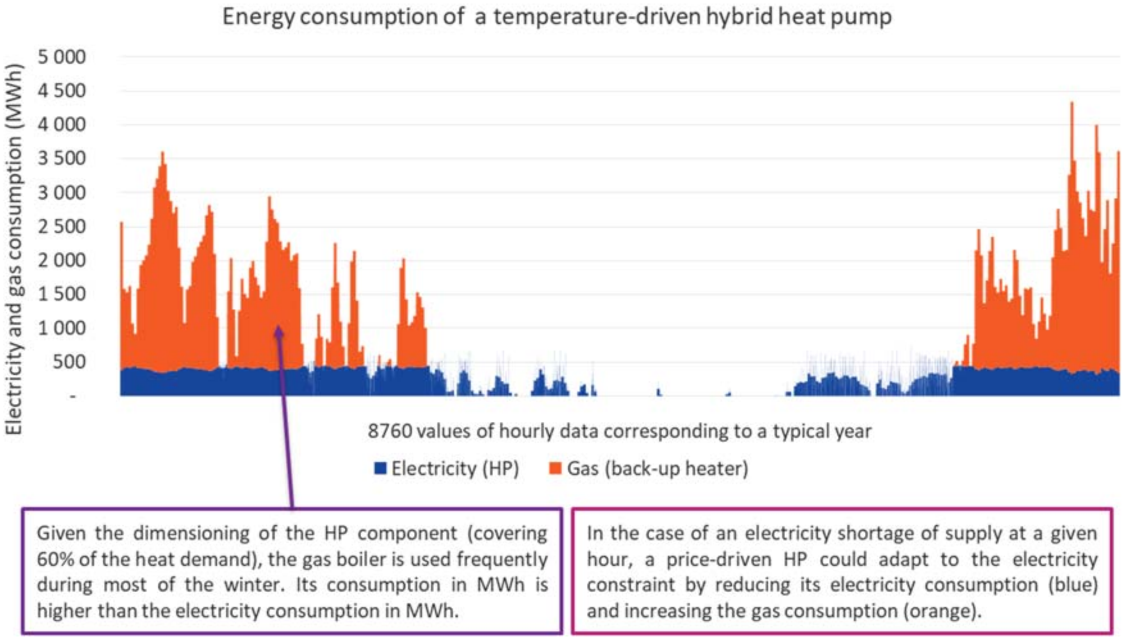

Figure 6. Illustration of the operation of a hybrid HP over a year[6].

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.
- 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).

[6] 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 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 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 Appendix: 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[7] 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

[7] 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.

5.1 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.

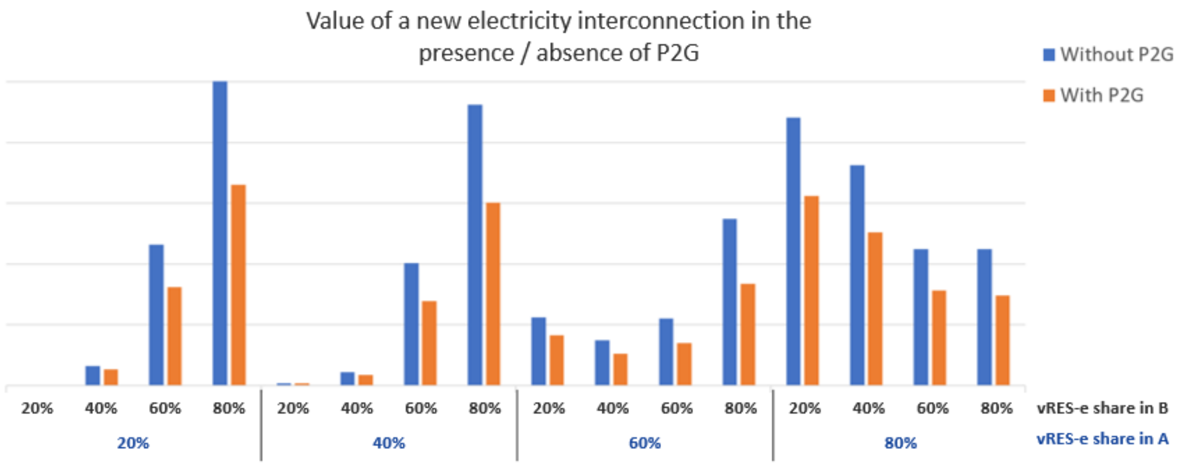

Figure 7. Value of a new power interconnector (in €/MW/year) with different vRes-e shares and with/without P2G

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.

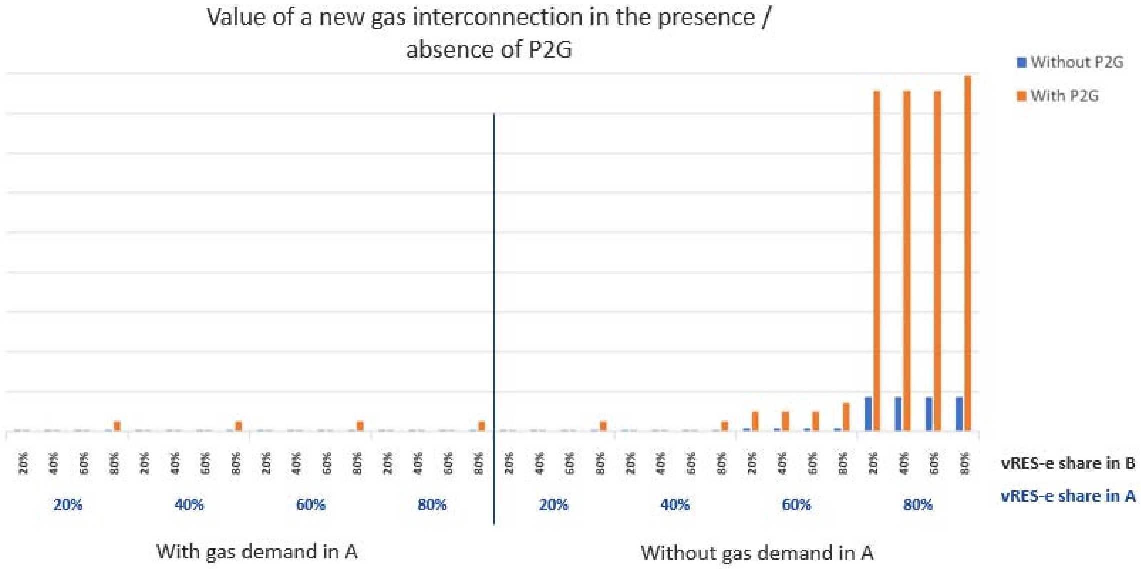

Figure 8. Value of a new gas interconnector (in €/MW/year) with different vRes-e shares, with /without P2G (orange or blue bars) and with /without gas demand in A (left and right respectively)

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[8].

5.2 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

[8] 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.

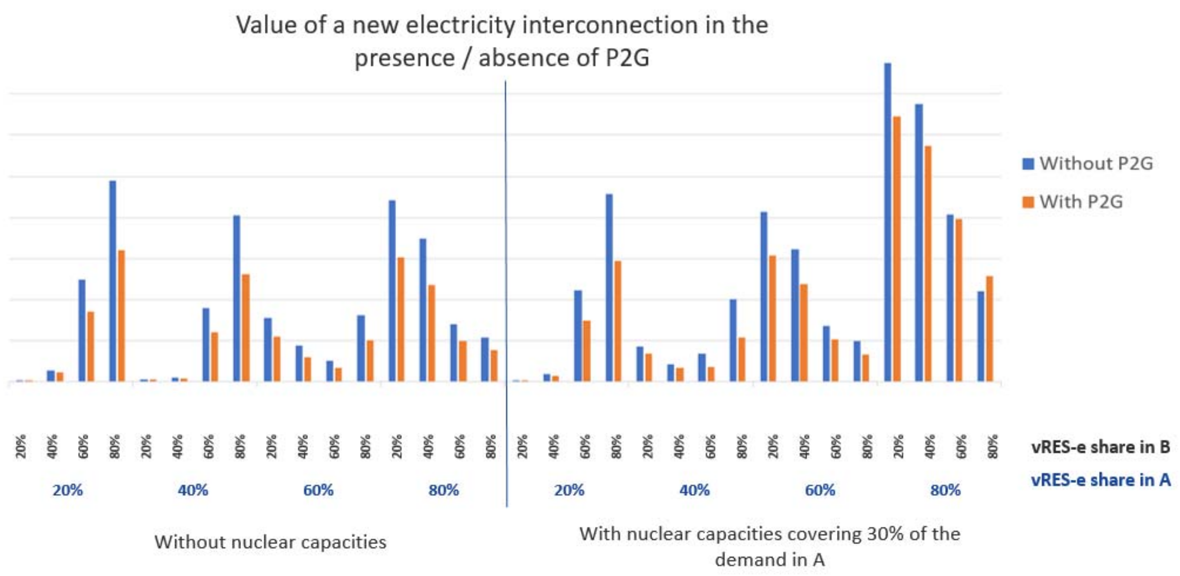

Figure 9. Value of a new power interconnector (in €/MW/year) with different vRes-e shares, with (at the left-hand side)/without nuclear capacities (at the right-hand side) and with (blue bars)/without (orange bars) P2G

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[9].

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.

[9] 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.

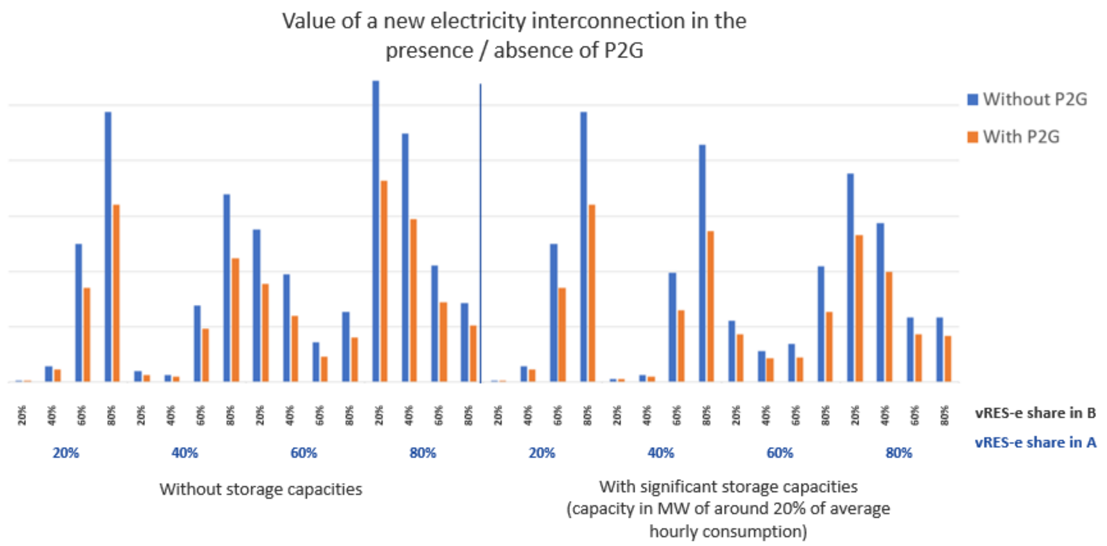

Figure 10. Value of a new power interconnector (in €/MW/year) with different vRes-e shares, with/without electricity storage (left/right) and with/without P2G (orange and blue bars respectively)

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.

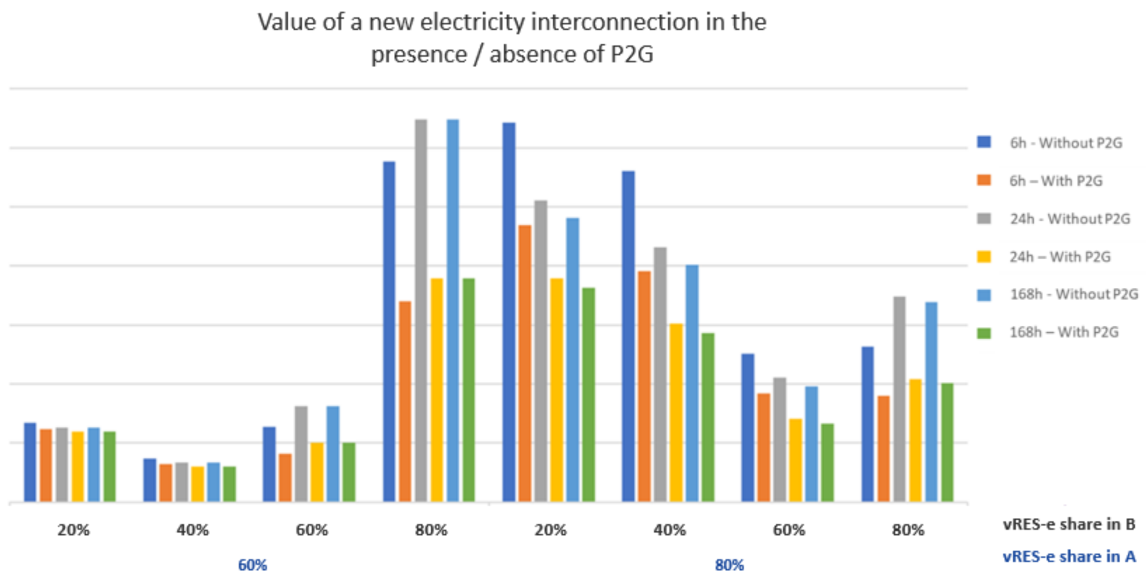

Figure 11. Value of a new power interconnector (in €/MW/year) with different vRes-e shares, with/without P2G and with different discharge time for the storage (6h, 1 day and 1 week)

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:

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

6 Tasks 2&3 Webinar – Summary of the feedback

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 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.