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Effects of large-scale power to gas conversion on the power, gas and carbon sectors and their interactions

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ABSTRACT

The increasing share of intermittent renewable electricity production leads to operational challenges in the electric power sector. Storage will be needed, among other options, to ensure an efficient and reliable operation of the electric power system. The power to gas (PtG) concept provides a possibility to store excess renewable electric power and as such it can increase the utilisation of RES-based electricity generation. The renewable methane, produced via PtG, can be stored in the gas system and used e.g. for electricity generation. The gas system has a much larger storage capacity compared to current electricity storage technologies. However, PtG introduces extra couplings between the gas, electricity and carbon (CO_2) sector and it is not known what the effect of these new interactions could be. Therefore, an operational model has been developed that includes the gas, electricity and CO_2 sector to analyse the effects of PtG on these sectors and on the interactions between them. Based on a case study, it is found that PtG partially transfers capacity and flexibility problems, triggered by the introduction of intermittent RES-based electricity generation, from the electricity to the gas sector. Moreover, a downward pressure on the gas prices is observed. However, the effects of PtG are generally smaller than those of the large-scale introduction of intermittent renewable electricity generation. Also, complex inter-sector dependencies are introduced through the CO_2 that is required in the PtG process. If PtG is to be deployed at large scale, the study of these effects is relevant for policy makers, regulators, energy markets' participants and system operators.

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1. Introduction

The share of renewable electricity generation has increased steadily over the past years, and the current trends and energy pathways indicate a further increase [1]. However, the variability and limited predictability of electric renewable energy sources (RES) result in new operational challenges for electric power system operators in maintaining the system balance [2]. Advanced operational techniques will be needed, amongst other options, such as storage, to ensure a safe and reliable operation of the electric power system [3,4].

Several (indirect) electricity storage options exist, such as pumped hydro electricity storage (PHES), compressed air energy storage (CAES), flywheels and batteries [5–8]. These current storage technologies generally have a limited energy density (e.g. batteries) or storage potential (e.g. PHES) [9,10]. PHES may provide a large-scale storage option, but the number of countries where such large-scale PHES is possible are limited. An interesting, possible electricity storage option is the 'power to gas' (PtG) concept that converts excess electricity into hydrogen or methane that can be injected in the gas network and be used later on, e.g. for electricity production [11]. The gas system, which often includes large-scale gas storage, as such allows storing significant amounts of renewable energy, contributing to the integration of intermittent RES. Moreover, the gas system may play an important role in the future energy system due to, among other elements, its robustness, its proven reliability and the required backup of intermittent renewable electricity generation that can be provided by flexible gas-fired power plants [12–14]. Therefore, natural gas, its assets and gas-fired electricity generation are considered as available in the intermediate time horizon in the transition towards a sustainable low-carbon energy system. Furthermore, gas-fired power plants provide a potential source of CO_2, which is a required input product of the PtG process.

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Nomenclature

CAES	compressed air energy storage
CC	carbon capturing (plants)
GFPP	gas-fred (electric) power plants
LNG	liquefied natural gas
MCC	marginal carbon cost
MEC	marginal electricity cost
MGC	marginal gas cost
MILP	mixed-integer linear programming
NOH	number of operating hours
O&M	operation and maintenance
PHES	pumped hydro energy storage
PtG	power to gas
PV	photovoltaic
RES	renewable energy sources
RM	renewable methane
TSO	transmission system operator

This PtG process consists of two steps [11]. The first step is the conversion of (renewable excess) electricity and water into hydrogen and pure oxygen. The hereby produced renewable hydrogen could be directly injected in the gas network. However, the possible share of hydrogen in the natural gas network is limited [15]. The second step in the PtG process is the conversion of hydrogen and CO_2 into renewable methane (and water). Renewable methane can be injected in the natural gas network without limitations if the natural gas has a high calorific value. In this work, only the entire conversion process of electricity to renewable methane is considered. However, it must be noted that the PtG technology is currently still in development: field tests are limited to demonstration plants [16].

However, it is important to study the effects of the introduction of large-scale PtG conversion in the energy system, especially because it creates alternative linkages between the gas, electricity and CO_2 sector. The relevance of system integration studies has already been well demonstrated in the electricity sector where the introduction of intermittent RES-based generation may trigger adequacy issues due to flawed market designs [17]. Also, the gas sector can be affected by the integration of intermittent renewable electricity generation. Particularly relevant for this paper are the conclusions of [14] where the impact of wind generation on the gas system is studied. It is found there that because of wind, gas transport related costs will increase the unit price of gas due to lowered utilisation of the gas network transport capacity. Furthermore, the demand for flexible gas supplies increases due to the increased gas demand spread and limited wind predictability, and this could be mitigated to a certain degree by, e.g., a liquid spot market, increased gas storage and LNG (liquefied natural gas) terminals [14].

Therefore, the aim of this paper is to analyse the impact of the introduction of PtG on the gas, electricity and CO_2 sector. Furthermore, the operational effects of PtG on the interactions between the different sectors will be studied: The main research questions in this paper are:

- What are the operational effects of PtG on the gas sector? More specifically, what are the operational effects on the gas import profile and on the demand for gas flexibility and what could be the long-term impact of those effects on gas capacity and flexibility costs? What are the effects on the capacity requirements for the gas network and seasonal gas storage?
- What are the effects on electricity sector? More specifically, what is the impact on the marginal electricity cost?
- How much CO_2 is required to 'fuel' the PtG process? How much CO_2 storage is required?

Furthermore, we will describe the operational effects of PtG on the interactions between the different sectors. The focus of the research is on operational short-term effects. However, these effects will be looked at in a case study over a whole year, yielding indications of longer-term effects of PtG. The presented case study reflects an energy system with a high RES penetration and PtG. This case study should be seen as a possible, or rather a hypothetical, future energy scenario as PtG technology is currently not available at large scales. As there are many uncertainties regarding the technologies and the costs of a system with PtG, the main focus of the analysis is on qualitative effects, rather than claiming quantitative effects.

As will be illustrated in the results, the introduction of PtG may have a considerable impact. Most notably, PtG may increase gas system capacity and flexibility related costs. It may also have a downward pressure on the gas prices, which is in line with the findings of [14] related to the impact of wind in the energy system. Furthermore, the alternative links between the different sectors in the energy system, introduced by PtG, create complex inter-sector linkages through the CO_2 that is required in the PtG process.

The remainder of this paper is organised as follows. Firstly, the approach is discussed, giving the model layout and useful models of subsystems in the literature. Secondly, the case study is elucidated and the methodology is given to determine the installed power to gas capacity in a given energy system. Thirdly, the results are analysed. The results are discussed per sector, for both the long- and the short-term effects. Also, the effects of power to gas on the interactions between the different sectors in the energy system are analysed. At last, the main conclusions are formulated, together with suggestions for further work on this topic.

2. Approach

An operational model of the considered energy system is set up using mixed-integer linear programming (MILP), based on [18] and it is available in full detail in [19]. The energy system is comprised of the gas, the electricity and the CO_2 sector. Additionally, PtG plants are part of the model (Fig. 1). The energy system is modelled as one single system, in which the demand for each energy carrier has to be satisfied at minimal cost within the techno-economic limits of the subsystems, e.g. the operational limits of the power plants.

The presented model has been largely based on existing models available in the literature (Section 2.1). Secondly, a general description of the used model is given. More information on the model, the assumptions and the implementation is given in [19].

2.1. Available modelling frameworks in the literature

The model used in this paper did not need to be built from scratch; it has been largely based on operational models that are available in the literature for subsystems of the energy system at hand. Electric power plants are required in the model to enable the analysis of the impact of PtG on the electric power sector. Useful operational models for electric power plant dispatch

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