POWER-TO-GAS: DEVELOPMENT OF ANALYSIS FRAMEWORK BASED ON A ROMANIAN CASE STUDY

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Renewable energy sources have recorded a massive expansion in the last decades and they now represent a considerable share of the energy mix in Europe and Romania. Consequently, the intermittent and unpredictable nature of renewable electricity has become a major issue. The Power-to-Gas concept promises to ensure the stability of energy systems in the context of an expected growth of the renewable energy sector, offering energy storage and energy transport functions, while helping avoid CO_2 emissions. The article presents a novel approach developed for analyzing Power-to-Gas projects that proves to be efficient from an investor's point of view, with focus on economic indicators.

Keywords: Power-to-Gas, renewable energy integration, energy storage, CO_2 capture

1. Introduction

The last couple of decades brought a major change in the way the scientific community and the public opinion see the future of the energy sector. While fossil fuels have been and will continue to be used at least for the foreseeable medium term future, obviously the focus has shifted on sustainable ways of producing energy, ones that don't have a finite character and a less significant impact on the environment.

At this moment, the energy sector encountered a crossroad. In numerous countries, renewable energy sources started to represent an ever-increasing percentage of the energy mix and while this certainly is good news in terms of long term sustainability of the energy sector and lowering greenhouse gas emissions, the other not so positive aspects also have to be taken in to consideration. Without doubt the one that has the biggest significance is the intermittent nature of the renewable energy sources that can be used for multi-megawatt energy production. Whether we are talking about photovoltaic panels

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and their ability to feed energy to the system during sun hours, or wind turbines that are directly dependent on wind energy, it is often extremely difficult to have a precise overview on the amount of energy they are able to produce in a given period of time. The intermittency leads to the next issue related to renewable energy sources, a very often time mismatch between the electricity they are able to supply to the grid and the demand of the market. As a consequence, renewable energy sources are not optimally used and a loss of economic value frequently occurs. In addition to all the previously mentioned issues, there are specific cases where renewable energy sources are concentrated in a certain region thanks to its energetic potential, causing a high level of saturation in the electric grid and difficulties in transporting the energy to other regions where it might be needed.
Due to the fact that traditional energy storage solutions come with certain disadvantages, the scientific community has turned its attention towards a new energy vector: hydrogen. In collaboration with the suitable energy storage and reconversion technical solutions, it has the potential to represent the answer to the issues related to the expansion of renewable energy sources, in the so-called “Power-to-Gas” projects. [1]

Power-to-Gas represents an innovative concept that offers a new and intelligent way of managing energy generation and loads, allowing a significant quantity of fluctuating electricity produced by renewable energy sources to be accommodated in the energy system. In last few years, Power-to-Gas has made a return to the spotlights of the scientific community and potentially interested industrial investors, due to the fact that the expansion of renewable energy on certain markets has caused important changes in the respective energy systems. Technologically speaking, Power-to-Gas offers two very important functions for every energy system [2]:

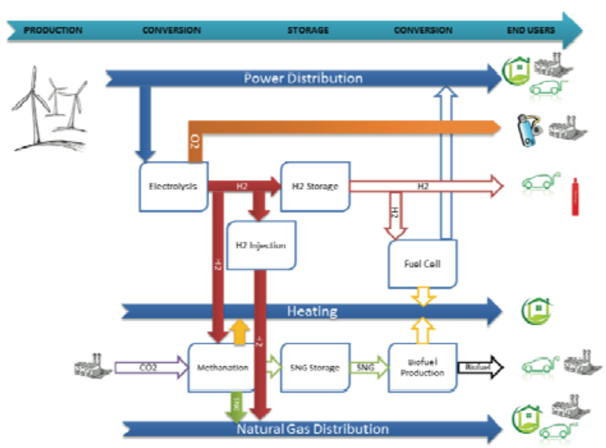

Fig. 1 Power-to-Gas concept

a. Energy storage - Power-to-Gas offers a solution for storing the otherwise unused surplus energy generated by renewable energy sources outside the electricity network, using hydrogen as an intermediate energy vector. Traditional methods for storing and reconverting the surplus energy (batteries, compressed air energy storage or hydro pumping) have been used, but the main issue is that, technologically, their storage capacity cannot scale up in order to be helpful for an energy system that relies on a high percentage of renewable energy. In terms of energy storage, Power-to-Gas is a very flexible concept, being able to offer a short term energy buffer for grid balancing services and also seasonal storage (using the existing storage capacities of the natural gas transport and distribution network), that besides a very important economic advantage, can also bring strategic value because it can contribute to the security of energy supply.
b. Energy transport - Power-to-Gas provides a solution for the taking out the energy from a certain region without the oversaturation of the electricity grid, by using the existent natural gas transport and distribution network, which in the specific cases of certain energy markets, is ready to accept and deliver the energy to the end point of the chain. Using Power-to-Gas for its transport function will help avoid extremely expensive investments for constructing new power lines, thus also bypassing the implied environmental impact.

Power-to-Gas represents a scalable complex technical solution that offers virtually unlimited storage capacity and adds an important degree of flexibility to an energy system. The goal of the article is to present a novel approach developed for analyzing Power-to-Gas projects and exemplify it using a Romanian case study. The current article takes into consideration the Power-to-Gas investor’s point of view, focusing not only on the technical and strategic advantages of the concept, but also on the economic feasibility.

2. Methodology

In the Romanian case study taken in consideration in the article the possibility of leveraging Power-to-Gas is investigated for a 50 MW wind energy park, situated in the South-Eastern part of the country, that is selling energy on the Romanian day ahead electricity market. The analysis takes into consideration two Power-to-Gas pathways: Power-to-Gas Hydrogen Injection (in which the hydrogen produced by the electrolysis units is directly injected in the natural gas grid in a safe percentage) and Power-to-Gas Methanation (the evolution of the first pathway that adds the methanation step in order to produce SNG, a gas that is fully compatible with the natural gas grid).

The first step in analyzing a Power-to-Gas project consists in defining the technical perimeter: the primary energy sources, existing transport and distribution infrastructure, secondary resources (for example water or CO_2) and identifying the possible technological pathways of the concept. In order to size the technical components of the Power-to-Gas chain in an efficient manner and establish an operational strategy, it is essential to know the available energy input from the primary energy sources. Most of the existing studies concerning the implementation of Power-to-Gas at local level and not at an energy system's level calculate the available energy input as a certain percent of the total energy production, defining this quantity as energy surplus (usually calculated based on the curtailment factor). The current article proposes a new strategy that relies on synchronizing the actual energy production of renewable sources facilities with the real energy market prices in order to establish the energy quantity that is fed to the Power-to-Gas process based on not only technical, but economic indicators as well. The next step consists in choosing several energy price threshold values under which the energy produced by the renewable energy sources is redirected to the electrolysis process involved in the Power-to-Gas technology, while the energy priced above the threshold value is sold on the energy market and injected into the grid. The amount of energy available for Power-to-Gas can be considered surplus energy or low value energy that has the potential of being better put to value by being converted, stored and transported in the Power-to-Gas chain. In order to establish the operating strategy and choose the most efficient size of the electrolyser and the further components of the technical chain, each energy price threshold scenarios is divided in several other sub scenarios defined by the installed power of the electrolysis units and for each of these scenarios a basic high level economic analysis is performed taking in to account all the technical components of the Power-to-Gas chain (electrolysis, hydrogen storage, methanation and SNG injection in the natural gas grid). NPV (Net Present Values) profits in respect to the baseline scenario in which Power-to-Gas is not used are calculated for a given project lifetime (usually 20 years for Power-to-Gas), as well as LCOE (Levelized Cost of Energy) values [3] for the energy output of the Power-to-Gas chain:

$$LCOE = \frac{CAPEX \ + \ \sum_{t=1}^{n} \frac{OPEX + Energy\ cost}{(1+i)^t}}{\sum_{t=1}^{n} \frac{Energy\ quantity}{(1+i)^t}} \ \text{[Euro/MWh]}$$

CAPEX represents the sum of all the capital costs of the Power-to-Gas installation, while *OPEX* represents the operational costs, exclusive of the costs of energy. The *Energy cost* represents the annual cost of the energy that is fed to the Power-to-Gas process, *n* is the lifetime of the project, while *i* represents the discount rate taken into consideration. The *Energy quantity* parameter represents the total amount of energy that comes out of the Power-to-Gas process, expressed in MWh and is used by multiplying the output flow of hydrogen with the energy content of hydrogen (39.4 kWh/kg).

Based on these calculated values, the financially desirable scenarios are chosen and a low level technical and economic analysis is performed in order to decide the feasibility of investing in Power-to-Gas based on a universally accepted economic indicator - IRR (Internal Return Rate) [4]. In case the IRR does not reach the values imposed by the investor, sensitivity analysis on various parameters is performed in order to set technology or cost performance targets that must be reached in order to obtain a feasible project or required policy measures (renewable methane subsidies, CO_2 certificates etc.) that will ease the way of Power-to-Gas.

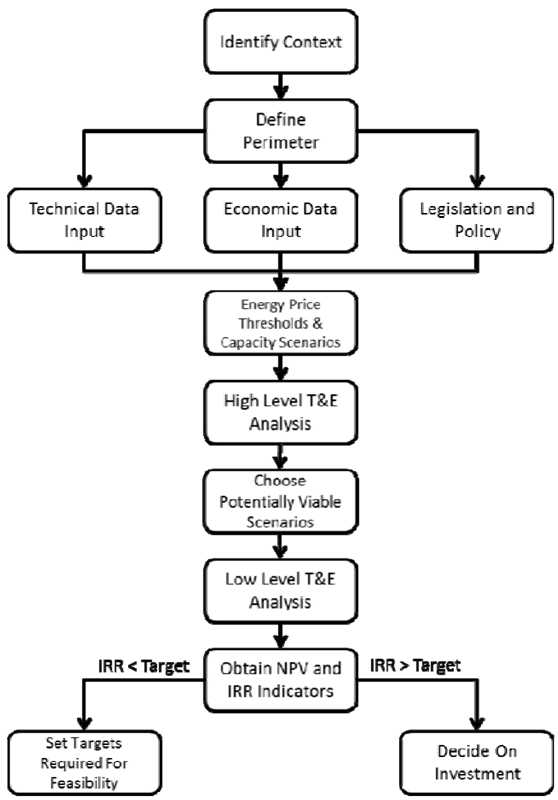

Fig. 2 Schematic representation of the novel approach used for analyzing a Power-to-Gas project presented in the current article.

In order to exemplify the novel strategy using the Romanian case the starting point is the actual yearly energy production of the 50 MW wind park correlating the production values with the real energy prices from the Romanian day ahead market (DAM prices) [5]. The next step consists in imposing energy price threshold values between 20 and 70 Euro/MWh in 10 Euro/MWh increments in order to create six different scenarios for sizing and operating the Power-to-Gas chain. All the energy (in some cases limited by the installed capacity of the electrolysis units) produced by the wind park that is priced under the chosen threshold is fed to the Power-to-Gas chain, while the energy priced above the threshold is sold on the energy market and injected into the grid. For each scenario, additional sub scenarios are created by analyzing different installed electrical capacities for the electrolysis facilities, between 10 MW and 50 MW (large installed capacity electrolysers were considered to be unrealistic from the beginning, but the analysis focused on obtaining a thorough understanding on the mutual influence of economic indicators and sizing options). In each of the sub scenarios, a high level technical sizing of the hydrogen storage capacity and the methanation reactor is made depending on the hydrogen that is produced by the electrolysis units. Technical parameters, CAPEX and OPEX costs for the different processes involved are taken from the literature [6, 7], while the methanation process was modeled and simulated using ASPEN software, starting from the hydrogen flow of the electrolysis units and a TREMP-like methanation reactor with the use of a GIBBS model, which calculates the chemical equilibrium through minimization of the Gibbs free energy of the mixture [9]. Using the calculated technical parameters, a high level economic analysis is also performed in order to calculate the NPV profit over a 20-year project lifetime compared to the baseline scenario in which no investment is made in Power-to-Gas and all the energy is sold on the market. Note that for the moment the curtailment factor for wind energy in Romania is very low due to the fact that wind energy has priority on the merit order curve [5]. However, this is expected to change in the future when renewables will have an increasing share of the energy generation mix. The analysis of the NPV profits and LCOE values obtained reveals which is the most profitable scenario. Next, a low level technical (taking into account more specific data related to the equipment and processes that are used) and economic (using an internally developed investment analysis tool) evaluation in which the most important step is calculating the profits and losses throughout the project's lifetime is performed in order to establish the feasibility of the investment based on the IRR (Internal Return Rate) indicator.

3. Results

The high level analysis of the 30 sub scenarios created by imposing the price thresholds and different electrolysis installed capacities revealed that the highest NPV profit and lowest LCOE values are obtained for a 10 MW electrolysis unit operating on a 70 Euro/MWh price threshold in the Power-to-Gas

Hydrogen Injection pathway and for a 10 MW electrolysis unit operating on a 70 Euro/MWh price threshold for the Power-to-Gas Methanation Pathway. Consequently, all the components of the two Power-to-Gas pathways are going to be sized starting from the electrolyser's installed capacity of 10 MW. In order to perform an accurate low level analysis, it is advisable to choose electrolyser models available on the market and use the specifications offered by their manufacturer. For electrolysers, a CAPEX of 900 Euro/MW and an OPEX of 2% of the initial CAPEX was considered, while for the methanation process a CAPEX of 950 Euro/MW and an OPEX of 2% of the initial CAPEX was taken into account.

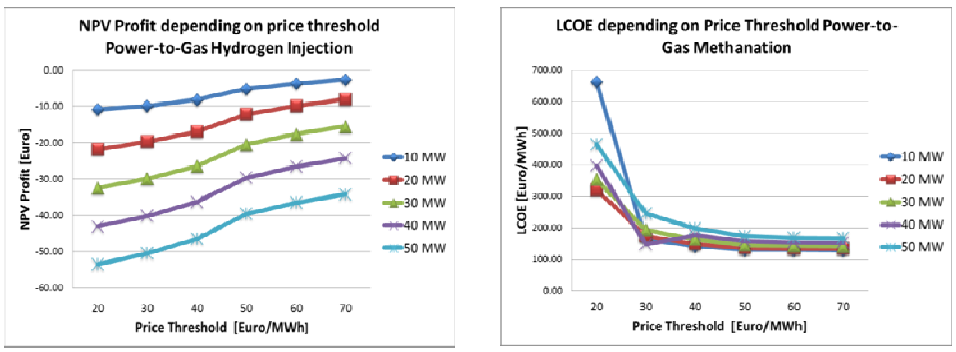

Fig. 3 High level analysis results for: a) Power-to-Gas Hydrogen Injection pathway - the most economically efficient scenario consists in choosing a 10 MW electrolyser operated with a 70 Euro/MWh energy price threshold; b) Power-to-Gas Methanation Pathway – the lowest LCOE indicates that the scenario of choice is a 10 MW electrolyser and the same energy price threshold of 70 Euro/MWh.

a. Power-to-Gas Hydrogen - the high level analysis indicated that the most profitable scenario consists in using a 10 MW electrolysis unit in conjunction with a 70 Euro/MWh price threshold, resulting in a yearly production capacity of 945310 kg H2 or 37245 MW. Modeling this scenario in the low level analysis points towards a negative NPV (for a discount rate of 14.4%) over the project's duration of 20 years in the current conditions in which there are no incentives for hydrogen enriched natural gas. In order to reach the scenario's break-even point a feed-in tariff of 72 Euro/MWh would be required for the case in which the oxygen produced by the electrolysis facilities is valued and 77 Euro/MWh if oxygen is not monetized [8]. Recovering the residual heat of the electrolysis process was not investigated in this analysis, although it has the possibility of decreasing the required subsidies at the expense of an increased initial investment and technical complexity. The overall efficiency of the Power-to-Gas Hydrogen pathway is 62% (HHV).

b. Power-to-Gas Methane - LCOE values from the high level analysis indicate the same maximum efficiency scenario consisting in using 10 MW capacity electrolysers and a 70 Euro/MWh price threshold for this pathway. In order to obtain an in-depth overview, a thorough modeling and simulation of the methanation equipment based on the TREMP process developed by Haldor-Topsoe [9] was required and it was performed using ASPEN One software. The end product of this pathway consists in substitute natural gas (SNG) with a 93.2% CH_4 concentration, a gas that is fully compatible with the natural gas grid. The yearly SNG output is 2827740 cubic meters or 28560 MWh. Integrating these figures in the low level economic analysis also leads to a negative NPV (for a discount rate of 14.4%) over the project's lifetime in the current legislative conditions in which SNG does not qualify for a feed-in tariff. The project's break-even point can be reached for a feed-in tariff for SNG of 143 Euro/MWh if the oxygen produced by the electrolysis process and methanation's residual heat are not valued and 125 Euro/MWh if both the oxygen and the residual heat are monetized. The cost of CO_2 was considered zero in the analysis. The overall efficiency of the Power-to-Gas SNG pathway is 54% (HHV), not taking into account the residual heat of the methanation process.

4. Discussion and Conclusion

In the last several years, Romania has been one of the most attractive European countries in terms of renewable energy investments. The extremely generous governmental green certificate support scheme has helped the country record a massive boost in wind power installed capacity, from nearly zero in 2007 (about 7 MW), to 1905 MW at the end of 2012, with 3990 more MW already approved. Therefore, in spite of the recently announced cuts in the renewable energy incentive scheme, Romania is and will definitely continue to be a competitive market for renewable energy investments.

However, Romania's renewable energy potential and existent investments, especially in wind energy, are concentrated in a single part of the country, Dobrogea region. This aspect raises some serious issues related to the saturation of the electricity transport and distribution network. The infrastructure is old and was not designed and sized for handling such a massive amount of fluctuating renewable energy. In addition, wind farms produce a significant quantity of energy during off-peak hours, excess energy that cannot be efficiently used, leading to a massive loss of value. The current situation added to the already approved future investments in wind farms, has led renewable energy producers, energy transport and distribution companies, authorities and policy makers to start analyzing the possibility of deploying a new technical solution that would bring balance to the energy system. Leveraging Power-to-Gas in the current Romanian context has the potential of solving all the aforementioned issues.

The novel approach presented in the article proves to be an efficient analysis tool for an investor interested in sizing, operating and determining the feasibility of Power-to-Gas in a certain context. It focuses on economic indicators and provides a clear image on whether an investment of this type can be profitable over its lifetime and if contrary, the approach allows determining the necessary targets that need to be reached in order to have a positive business case with the use of sensitivity analysis. In case the point of view is shifted to a larger level, an entire energy system, the approach needs to be upgraded in order to take into account elements that are at the moment difficult to be economically valued like security of supply, social acceptance of environmental impact and focus more on the energy storage and energy transport functions of Power-to-Gas, rather than on energy price arbitrage.

Using the approach revealed that in the current economic and legislative context, Power-to-Gas falls short of economic feasibility in the situation exemplified in the article. The situation would significantly improve with a change in current support scheme that would extend the measures applied to biogas over to renewable hydrogen and renewable methane. Legislation is already beginning to change at European level [10 – 12], therefore there are premises for a positive economic evolution of Power-to-Gas if we also take into consideration the expected reduction in capital investment costs [6] and the possible synergies with certain parts of the industrial sector that have already been identified [13].

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