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Repurposing Existing Combined Cycle Power Plants with Methane Production for Renewable Energy Storage

Diego Santamaría*, Antonio Sánchez, Mariano Martín

Department of Chemical Engineering, University of Salamanca, Plz Caidos 1-5, 37008, Salamanca, Spain.
* Corresponding Author: diegosg@usal.es.

ABSTRACT

Energy storage is essential for transitioning to a renewable system based on renewable sources. To meet this challenge, Power-to-X technologies are attracting more attention. This work explores converting the excess of electric energy obtained from wind or solar sources into hydrogen and then into methane leveraging existing natural gas infrastructure for easier storage and transport. The process involves two stages: Firstly, the methane production step using Power-to-X technologies during excess renewable energy periods and, secondly, the electricity generation step during high demand with CO_2 capture for reuse in methane synthesis, forming a closed carbon loop. In this way the Power-to-X process is integrated with repurposed combined cycle power plants (CCPPs) creating a Power-to-methane-to-power system. Two approaches are evaluated: oxy-combustion, which simplifies process CO_2 purification and air combustion, which needs a more complex CO_2 purification, such as amine absorption or PSA systems. The results show that ordinary combustion capturing CO_2 by amines is the most profitable process, especially when it is assumed that the oxygen produced by the electrolyzer is sold. For a CCPP with a nominal capacity of 400MW, the cost of electricity production ranges from 450 $/MWh to 490 $/MWh when the income from oxygen sales is neglected. If the oxygen produced can be fully absorbed by the market, the electricity production cost decreases to 250 $/MWh and 300 $/MWh.

Keywords: Process Design, Carbon Capture, Energy Storage, Hydrogen, Methane.

INTRODUCTION

Renewable energy sources (RES) are transforming power systems and will be predominant in the years to come. For example, by 2030, an increase of more than 90% in the electricity generation from RES is expected with solar PV and wind being the leading technologies. However, these generation alternatives fluctuate according to the weather conditions, causing a paradigm shift from the current steady-state systems. Therefore, energy storage technologies will be required to ensure a stable power grid and the balance between electricity production and demand at every time. Different alternatives have been proposed, which can be classified as follows: mechanical, chemical, electrochemical, and electrical.

Among them, hydrogen is emerging as a highly attractive option. According to the current predictions, by 2050, the global demand for hydrogen could increase up to 585 Mtpa under a Net Zero scenario. However, some significant challenges are associated with hydrogen utilization highlighting the low volumetric energy density and the difficult storage conditions. Thus, for medium/long-term storage horizon, the use of hydrogen as such is not considered the most suitable option. Other chemicals produced from hydrogen have been proposed to overcome its issues. These options offer beneficial conditions in terms of volumetric energy density, storage and transport conditions, etc. allowing an effective deployment as grid-scale energy storage system. Among these chemicals, methane, methanol, and ammonia emerge as the most promising options. Although methane is a gas, with the difficulties associated with this phase, this component is attracting attention due to the possibility of using the existing natural gas infrastructure to handle this hydrogen carrier. This allows storage and transport of significant amounts of green methane to address the challenges associated with an energy system with a high penetration of renewables. The use of methane as energy storage system involves two main steps. The first one is related to the production of methane using Power-to-X processes in time periods with high energy production. Subsequently, a second step is the back transformation into electricity with the possibility of capturing CO_2 to synthesize again methane as required.

In this field, Xiang et al. [1] evaluated the implementation of the carbon capture technology in a natural gas combined cycle power plant coupled with oxy-combustion. A simple condensation step is selected as CO_2 separation alternative due to the oxy-combustion conditions. An extended work including two CO_2 capture retrofits in natural gas power plants in presented by Strojny et al. [2]. In particular, amine absorption and calcium looping have been investigated. Other works have assessed the production of methane through CO_2 methanation. For instance, Blanco et al. [3] evaluated the potential implementation of Power-to-methane processes in the European Union using a life cycle assessment approach. However, a comprehensive analysis of the two stages to introduce green methane as energy storage has not yet been performed.

Therefore, in this work, a holistic process design analysis of the Power-to-methane-to-power is developed to be integrated as grid-scale energy storage system. Specifically, the integration of this technology with existing combined cycle power plants is proposed to repurpose current infrastructure, thereby reducing the capital costs associated with the energy transition. In the first stage, devoted to methane production, CO_2 (from carbon capture) is combined with green hydrogen produced from water electrolysis using renewable energy (wind and PV solar). This stage will take place in periods with high renewable generation (exceeding demand). The second stage is related to the production of electricity from the previously produced methane. This will take place during periods when renewable generation is not sufficient to meet demand. In this case, the existing combined cycles are evaluated by coupling carbon capture technologies. Two different approaches have been evaluated. Firstly, the use of oxy-combustion together with a simple carbon capture unit (condensation). A second option is to maintain the existing air combustion but with a more complex carbon capture technology (amines or pressure swing adsorption in this case). The captured CO_2 is stored to be used in the methanation section as required. Therefore, this comprehensive approach demonstrates the potential of green methane as an efficient solution for grid-scale energy storage, enabling the repurposing of natural gas-based infrastructure to support the transition to a sustainable energy system.

PROCESS ANALYSIS

This work compares three methane combustion processes. The first two utilize conventional combustion (air-based combustion), which requires a carbon capture system due to the high nitrogen content in the exhaust gases. These processes differ in their carbon capture technology: one employs amine absorption technology, while the other uses PSA systems. The third process replaces air with pure oxygen (oxy-combustion), resulting in exhaust gases mainly composed of CO_2 and water.

The diagram of each process can be seen in Figure 1, Figure 2 and Figure 3.

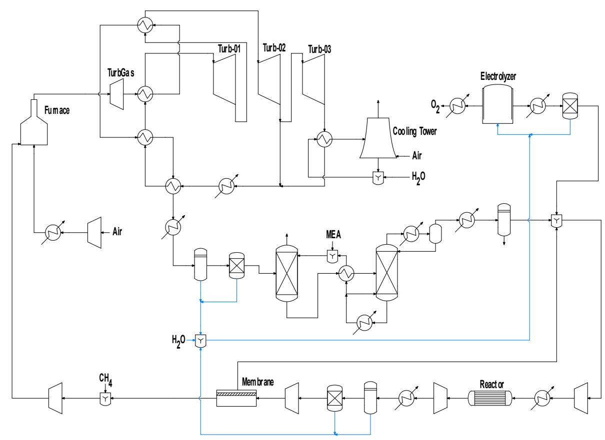

Figure 1. Process flow diagram of process using ordinary combustion and absorption as carbon capture system.

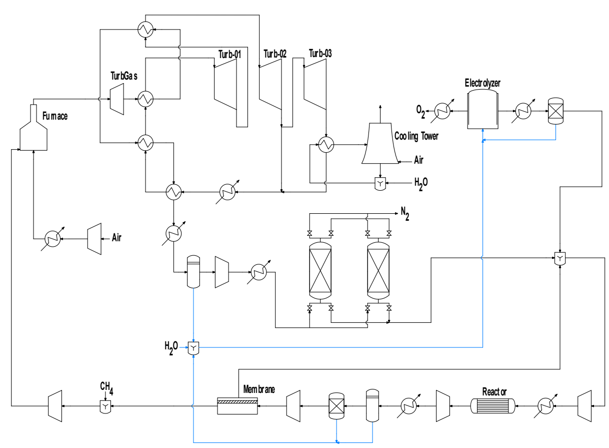

Figure 2. Process flow diagram of process using ordinary combustion and adsorption with PSA as carbon capture system.

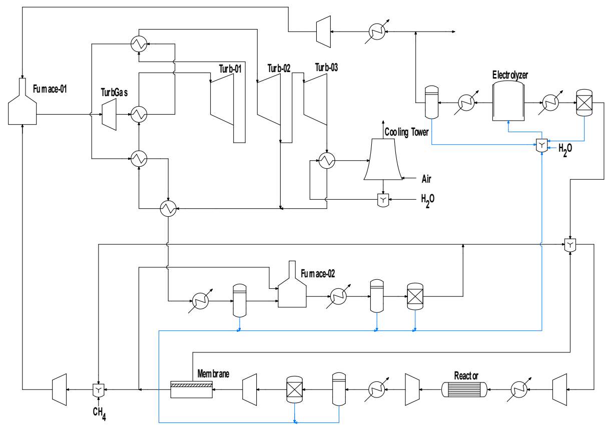

Figure 3. Process flow diagram of process using oxy-combustion.

Process Description

The processes can be divided into four sections. 1) the combined cycle power plant where electricity is produced by burning methane. 2) The second one consists of capturing or purifying CO2. 3) The third one corresponds to renewable hydrogen production by an electrolyzer. 4) Finally, the reaction of H2 and CO2 to produce methane. The methane generated in this section is used as feed of the first. Thereby, the cycle can be closed. The different sections are described as follows.

Combined Cycle Power Plant

The Combined Cycle Power Plant is composed of two thermodynamic cycles to maximize efficiency. The first one is the Brayton cycle, which takes place in a gas turbine and the second one is the regenerative Rankine cycle, which involves a system of steam turbines (high-pressure, medium-pressure, and low-pressure turbines). Although the reuse of existing CCPPs is proposed, they are also modeled to create a complete model.

The operation of a CCPP begins by introducing the feed, which has been previously conditioned, into the combustion chamber. The composition of the feed varies depending on the modeled processes, but the treatment is the same for all the cases: the feed stream must be compressed and its temperature adjusted to the required level. The combustion chamber is modeled as adiabatic where complete combustion is ensured by adding an excess of comburent. Moreover, an inert substance must be introduced with the comburent to prevent the furnace temperature from exceeding the critical limit of 1600 ºC and avoid material problems. For ordinary combustion the oxygen is already mixed with nitrogen from the air. However, in the case of oxy-combustion, pure oxygen is mixed with CO_2 from combustion exhaust gases to achieve the conditions required.

The gas turbine is modeled as a polytropic expansion process with an efficiency of 85%. After passing through the gas turbine, the exhausted gases, which still contain significant thermal energy, are utilized as a heat source for reheater and preheater in the regenerative Rankine cycle with reheating.

In the Rankine cycle, the steam exiting the low-pressure turbine is condensed using a water refrigeration cycle with a cooling tower. The performance of the tower is modeled using Mickey's method [4]. The increment of temperature is limited to 8-10 ºC following rules of thumb to ensure a proper operation. In the cooling tower, the water temperature is reduced by evaporating a fraction of the water so to compensate this lost make-up water is required. To calculate it, the air humidity and water temperature in the cooling tower must be considered.

In general, the equipment of CCPP is the same for all alternative processes, but the following subsections are different for each one.

CO_2 Separation

The CO_2 separation section is designed to be integrated with existing CCPPs, creating a closed carbon loop to prevent emission into the atmosphere. Various treatments methods for the exhaust gases are proposed, including the following. When the methane is burned using air as the comburent the exhaust gases are composed mainly of CO_2, H_2O, a small amount of O_2 (as previously it was introduced in excess) and a large amount of N_2. Nitrogen acts as an inert component and must be separated from the CO_2 to enable a proper operation of methanation. To reach the CO_2 purification two technologies are evaluated: adsorption with PSA system and amine absorption system.

Adsorption with PSA system. The process flow diagram can be seen at Figure 1. The PSA columns use as adsorbent material zeolite 13 X [5]. This process is modeled using a Langmuir solid-gas adsorption isotherm. Mainly, the nitrogen can cross the bed while the CO_2 is captured. It can be assumed the small amount of oxygen in inlet gases is not trapped, since the adsorption capacity of zeolite 13 X for oxygen is minimal [6]. Then, the CO_2 is sent to the methane production section and the not captured gases (N_2, H_2O, O_2) are released into the atmosphere.

Amine absorption system. The process flow diagram is shown at Figure 2. This system consists of two columns. The first one is the absorption column where the exhaust gases from the gas turbine brought into contact with amine solution of 20 % monoethanolamine (MEA). The non-absorbed gases are released into the atmosphere. The amine solution rich in CO_2 is heated and sent to the second column or stripping column. Here the CO_2 is desorbed from the amine solution and a pure steam of CO_2 is reached. Then, the amine solution is mixed with fresh amine solution to make up for losses and refeed to the first column. The model of this section is based on first principles and industrial data.

In contrast, the exhaust flue gases of oxy-combustion are only composed of CO_2, H_2O and O_2. The flow diagram of this process can be seen at Figure 3. In this case the CO_2 must be also purified. The water is easily removed by condensation and the elimination of the oxygen is done by sending the gases to a second combustion chamber where extra methane is added to ensure the complete remotion of oxygen. The chamber combustion temperature is limited thanks to the large amount of CO_2 there is in the inlet steam. After this step, the humidity steam is reduced by condensation to reach a better operation of methane production.

Renewable hydrogen production

The hydrogen is produced through water electrolysis and is the same for all alternative processes. Since it is proposed that the electricity used for electrolysis came from renewable energy sources such as wind or solar, the hydrogen produced can be considered green hydrogen. The water required for this operation is provided by the various drying operations throughout the system, minimizing the need for external water. Nowadays, several types of electrolyzers are available: Proton Exchange Membrane (PEM), Anion Exchange Membrane (AEM), Alkaline and Solid Oxide Ceramic (SOEC). Among them, PEM technology is selected due to the high purity of gases produced, its advanced commercial maturity and its short start-up time [7].

The electrolyzer generates two streams, one contains mainly hydrogen and the other contains oxygen. Both streams are subjected to a drying process to remove the residual water. The hydrogen stream is mixed with the CO_2 previously purified while the intended use of the oxygen depends on the analyzed process. The oxygen obtained under ordinary combustion process can be sold. However, the oxygen obtained under oxy-combustion process is used as a comburent in this process. In this way, the oxygen is completely integrated in the process.

Methane production

The CO_2 stream, the hydrogen stream and the recirculation steam are mixed and compressed to reach the methanation reactor conditions. The methanation reactor is a fixed bed reactor with thermal control. A nickel-based catalysis is used. The reactions for methane production are shown below, eqs 2, 3, 4. The reactor behavior is modeled using equilibrium conditions. The typical temperature range is between 250 ºC and 400 ºC and the pressure is up to 20 bar [8].

$$CO + 3H_2 \rightleftarrows CH_4 + H_2O \qquad (2)$$

$$CO_2 + H_2 \rightleftarrows CO + H_2O \qquad (3)$$

$$CO_2 + 4H_2 \rightleftarrows CH_4 + 2H_2O \qquad (4)$$

The outlet reactor stream is expanded into a gas turbine and cooled to remove water by condensation. As there is hydrogen in this stream, it is recovered and recirculated to the methane production by a membrane separation. Finally, the purified methane is sent to the CCPP combustion chambre, closing the cycle.

Optimization procedure and Techno-economic analysis

The processes are modeled using mass and energy balances, thermodynamic equilibria, experimental data and rules of thumb and they are optimized to maximize the electricity production and minimize the energy consumption derived of the process. For this purpose, a NLP is solved for each of the suggested cases. The objective function is the same for all cases, see eq (1), and the objective is to maximize the electrical efficiency of the cycle. The problem is formulated as a MINLP, which is decomposed into three NLP. The first one modeled the process using ordinary combustion with absorption as the carbon capture technology. This model contains 1491 variables and 1279 equations. The second one also employs ordinary combustion but using adsorption with a PSA system for carbon capture, in this case 1045 variables and 1202 equations. Finally, the third one models the oxy combustion process, which contains 1379 variables and 1229 equations.

$$OBJ = Max\ (W_{generated} - W_{consumed}) \qquad (1)$$

The capital cost of every piece of equipment is calculated with a function of a characteristic variable such as power for turbines or area for heat exchanges. This characteristic variable also indicates which option of equipment is the most suitable and if it is necessary to add a new unit because the capacity of the previous one is excesses. The investment cost is estimated from the unit costs using the factorial method [9]. To perform the scale-up analysis, the different Spanish CCPP capacities have been used. The Spanish CCPPs can be categorized into three distinct capacity ranges: 400 MW, 800 MW, and 1200 MW with small deviation. Each group of a CCPP typically has a capacity of 400 MW, which means that the different types of power plants usually comprise 1, 2, or 3 groups, respectively, although there are also groups with a capacity of 800 MW.

RESULTS

The methodology has been applied to the Spanish CCPPs which are located in the peninsular territory, in total there are 30 plants. Figure 4 illustrates the evolution of electricity production cost for various groups of power plants when the oxygen generated as a byproduct during the electrolysis process is sold. Among the analyzed processes, the most profitable is the ordinary combustion with absorption for carbon capture, followed by ordinary combustion process with PSA systems for carbon capture and finally oxy-combustion process.

A remarkable point of this figure is the significant impact of economies of scale on electricity production costs. Specifically, as the size of the groups of power plant increases, the production cost per unit of electricity decreases. Another important aspect is the important difference in electricity production costs between the ordinary combustion processes and the oxy-combustion process. For ordinary combustion processes, the electricity production cost ranges between 250 $/MWh and 300 $/MWh for CCPP groups with a nominal capacity of approximately 400 MW and between 90 $/MWh and 120 $/MWh for CCPP groups with a nominal capacity of around 800 MW. In contrast, the electricity production cost for oxy-combustion process is higher, approximately 470 $/MWh for 400 MW CCPP groups and 270 $/MWh for 800 MW CCPP groups.

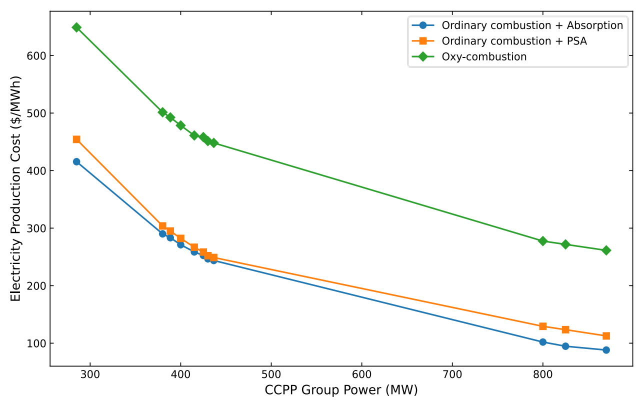

Figure 4. Comparation of electricity cost obtained with the different alternatives processes when the oxygen produced in the electrolyzer as subproduct is sold.

The reason for that big difference is due to the utilization of oxygen. In the oxy-combustion process, the oxygen produced during electrolysis is consumed completely for methane combustion, eliminating the option of selling it. In the ordinary combustion processes, it is assumed that all the oxygen generated as a byproduct is sold, which provides an additional revenue line that offsets the electricity production cost. This difference in oxygen utilization has a profound impact on the economic results of the processes, making the ordinary combustion configurations more cost-effective under these assumptions.

To take into account the effects of oxygen sales on electricity production costs, Figure 5 presents the costs under the assumption that the oxygen generated during the electrolysis process is not sold. In this scenario, the electricity production costs for the oxy-combustion process remain unchanged, as the oxygen produced in this process is already consumed entirely for methane combustion. However, the electricity costs for the processes based on ordinary combustion increase significantly, bringing them much closer to the costs of the oxy-combustion process. Without the additional revenue from selling oxygen, the cost advantage of these processes diminishes substantially. Figure 5 also shows an interesting trend for larger groups of power plants. Specifically, for groups with a nominal capacity exceeding 800 MW, the cost dynamics begin to change, and the oxy-combustion process emerges as the most profitable option. This suggests that, at larger scales, the oxy-combustion process offers significant economic advantages. However, only 7% of CCPP groups in Spain have a capacity higher than 800 MW, limiting the scope of this benefit.

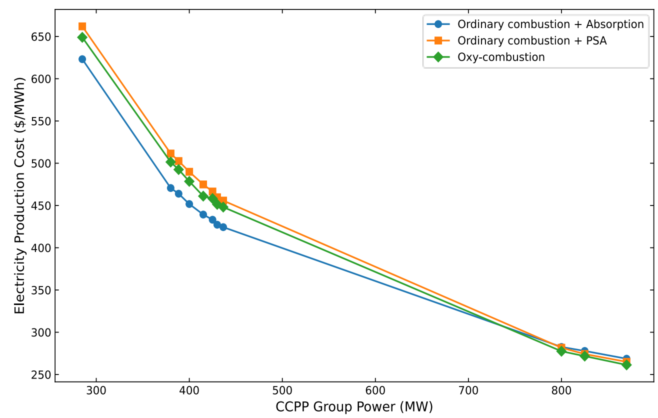

Figure 5. Comparation of electricity cost obtained with the different alternatives processes when any subproduct is sold.

The yields of this process have been calculated according to the following equations (5, 6, 7) and the results can be seen in Table 1.

$$\eta_{CCPP} = \frac{Power\ generated\ tubines\ CCPP}{LHV_{CH_4} \cdot F_{CH_4}} \tag{5}$$

$$\eta_{PtG} = \frac{LHV_{CH_4} \cdot F_{CH_4}}{W_{aux.met.} + W_{electrolyzer} + W_{carbon\ capture}} \tag{6}$$

$$\eta_{process} = \frac{Power\ generated}{Power\ consumed} \tag{7}$$

A typical CCPP usually achieves an efficiency ranging between 55% and 62% [10]. Processes based on ordinary combustion fall within this range, while the efficiency of the oxy-combustion process is lower. However, this trend is inverted when Power-to-Gas efficiency is analyzed. Although the oxy-combustion process requires the same hydrogen production as ordinary combustion processes, it eliminates the need for a carbon capture system, which improves the performance process. As a result, the best PtG efficiency results are achieved with oxy-combustion process (39.78%). The global efficiency of the processes analyzed is relatively similar, ranging between 17.56% and 14.98%.

Table 1: Efficiencies of the processes.

	Ordinary C. + Absorption	Ordinary C. + PSA	Oxy-combustion
η_{CCPP} (%)	65.39	65.65	43.28
η_{PtG} (%)	32.56	34.06	29.68
$\eta_{process}$ (%)	18.14	20.88	11.65

CONCLUSIONS

Different processes to integrate renewable energy with CCPP as energy storage systems are optimized and evaluated. The current CCPP could be part of this type of system by coupling the new sections of hydrogen production, carbon capture and methane production. Renewable energy (wind or solar) is employed to produce hydrogen by a PEM electrolyzer when there is an excess in the electric grid. Then it is mixed with CO2 purified to generate methane, which is again burned at the combustion chamber in the CCPP. The three processes are optimized and modeled using the first principles, thermodynamics equilibria, rules of thumb. Next, the cost estimation studies are performed and, finally, a scaling study using as base the capacity of the Spanish CCPP.

A large difference exists between the electricity production cost in ordinary combustion processes and oxy-combustion process. For a CCPP group with nominal power of 400 MW ordinary combustion processes reach a production cost of 250 -300 $/MWh and around 470 $/MWh for oxy-combustion processes. However, the difference is reduced when it is considered that oxygen cannot be sold, and the production cost is approaching the oxy-combustion ones.

The process global efficiencies are not particularly high (14.98% - 17.56%), but they demonstrate the potential of these technologies as a viable alternative for energy storage. This highlights the importance of future development and optimization of these processes to expand the number of options available for integrating renewable energy into the storage energy system.

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