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# POWER-TO-GAS-TO-POWER: MANAGEMENT OF RENEWABLE ENERGY SURPLUS. HYBRIDIZATION AND INTEGRATION WITH CLASSIC ELECTRICAL GENERATION TECHNOLOGIES

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There was a very significant increase in installed wind power between 2009 and 2019. The forecast for 2020-2030 is also very high. A scenario with a lot of installed wind power will generate surplus energy and it will be necessary to use energy vectors and storage technologies. An energy vector with great potential is renewable gas. Energy storage in gases is known as Power to Gas. Highlights hydrogen and synthetic natural gas. The hybridization of new and existing technologies can generate new energy models. An important factor will be the investments to be made by stakeholders (companies and public administration). In addition, many current plants (combined cycle plants) may continue in the future energy mix with the installation of CO2 capture systems. How to use captured CO2 can be the key. Finally, the state of the art of various technologies must be taken into account. A disruptive change can radically modify the approaches and forecasts. This paper shows the state of the art of renewable gases. The feasibility to manage the surplus of energy with renewable gas, and its use in the power plants and current energy infrastructures.

*Keywords: power surplus; power to gas; hydrogen; synthetic natural gas; carbon capture*

# GASIFICACIÓN DE LA ELECTRICIDAD: GESTIÓN DE EXCEDENTES DE ENERGÍA RENOVABLE. HIBRIDACIÓN E INTEGRACIÓN CON TECNOLOGÍAS CLÁSICAS DE GENERACIÓN ELÉCTRICA

Hubo un aumento muy importante de la potencia éolica instalada entre 2009 y 2019. La previsión para 2020-2030 es también muy elevada. Un escenario con mucha potencia eólica instalada generará excedentes de energía y será necesario emplear vectores energéticos y tecnologías de almacenamiento. Un vector energético con gran potencial es el gas de origen renovable. El almacenamiento de energía en gases es conocido por Power to Gas. Destacan el hidrógeno y el gas natural sintético. La hibridación de nuevas tecnologías y las existentes pueden generar nuevos modelos energéticos. Un factor importante serán las inversiones a realizar por los involucrados (empresas y administración pública). Además, muchas centrales actuales (centrales de ciclo combinado) es posible que sigan en el mix energético futuro con la instalación de sistemas de captura de CO2. Cómo emplear el CO2 capturado puede ser la clave. Por último, el estado del arte de diversas tecnologías debe tenerse en cuenta. Un cambio disruptivo puede cambiar el planteamiento. En este trabajo se expone el estado del arte de los gases renovables. La viabilidad para gestionar el excedente de energía con gas renovable, y su uso en las centrales de generación y las infraestructuras energéticas actuales.

*Palabras clave: excedentes de energía; gas renovable; hidrógeno; gas natural sintético; captura de carbono*

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## 1. Introduction.

The future wind energy surpluses and the development potential of energy vector technologies such as $H_2$ and synthetic $CH_4$ allow us to propose hybrid models with different renewable and non-renewable generation technologies. These new hybrid models can manage surplus energy from renewable sources for use at other times with greater demand.

The massive installation of renewable energy begins to produce large surplus energy in certain periods of time, even with negative energy prices. This trend is already common in Europe and the United Kingdom, and will become stronger as more installed power becomes available and the repowering of existing wind farms begins

Negative energy prices are generated when the Electric System operators need to maintain consumption to avoid network stability problems or unscheduled shutdowns of installations with high start-up and shutdown costs. This oversupply situation forces producers to pay consumers to keep up with demand.

Negative prices are an opportunity to manage surplus energy using energy vectors (gases) such as $H_2$ and synthetic $CH_4$. Generation plants for the production of these gases ($H_2$ and synthetic $CH_4$) have high production costs in a classic environment of positive energy prices, and are not even competitive in costs compared to other energy generation technologies.
Research on surplus energy and energy vectors through the use of gases has had a significant development since the beginning of the 21st century.

Professor Sterner (2009) in his book “Bioenergy and Renewable Power Methane in Integrated 100 per 100 Renewable Energy Systems” conducted extensive research on PV-WIND-RPM hybridization.

The PV-Wind-RPM system had limitations in the RPM processes. The synthetic methane generation process was not sufficiently developed to be raised on an industrial scale (year 2009). On the other hand, it provided improvement alternatives to generate synthetic methane:

- Use of residual heat. The generation of $CH_4$ from $CO_2$ is a very exothermic process.
- The $O_2$ that is generated in the electrolysis to obtain $H_2$ can be used in oxy-fuel combustion power plants. The combustion process with high $O_2$ content instead of air (oxy-fuel) has better efficiency and improves $CO_2$ capture.

At the 26th European Photovoltaic Solar Energy Conference in Hamburg (Germany), Sterner and others (2001) presented a global analysis for different PV-WIND-RPM-CCGT hybridizations. Analyzed the capture of $CO_2$ with CCS or direct air capture (DAC) systems).

- The costs of PV-WIND-RPM-CCGT hybridizations have to be lower than natural gas plants equipped with CCS, and coal plants equipped with CCS. It is necessary to reduce as much as possible the costs of the source energy (PV and WIND).
- Levelized costs of energy (LCOE) had large variations depending on the area. The range of the area with very abundant wind and / or solar resources was around 80 - 90 € / MWh (68 - 76.5 £ / MWh). The area with moderate wind and / or solar resources in between was around 140 - 170 € / MWh (119 - 144.5 £ / MWh).

- A potential selection of each preferred technology was made according to the geographical area:
    - **PV-WIND-RPM-CCGT hybridization with CCS:** Northern Europe, United Kingdom, Iceland, Central South America (Brazil-Argentina border), Southern Chile and Argentina.
    - **Hybridization PV-WIND-RPM-CCGT with DAC:** Australia, central US, SAHEL area, North China and India and South Russia.

Maroufmashat and Michael Fowler (2017) present an updated study of the different pathways of power to gas (P2G). The efficiencies of each alternative provide information to develop plans and strategies for the transition to an economy with low CO2 emissions. The results obtained of average efficiency for the following alternatives:

- The use of P2G as hydrogen for heat purposes has an average efficiency of 63%.
- The efficiency of hydrogen for transport is approximately 64%.
- The renewable power to fuels has an average efficiency of 68% (current) and 72% (future).
- A large steam methane (SMR) reform unit has an efficiency in a range of 70%.

Maroufmashat and Michael Fowler (2017) indicate that in future years P2G can be competitive with SMR. Improvements in technologies can increase the overall efficiency of P2G routes in future years by 2 to 5%, which makes them more feasible for implementation.

Becker and others (2019) provide detailed, more realistic and reliable information on a synthetic natural gas generation plant on an industrial scale. Until then (2019) most of the analyses performed on the RPM generation were based on laboratory “demo plants”.

The main characteristics of the synthetic natural gas plant developed by Becker and others (2019) are:

- Use of Sabatier reactors with three stages of methanization.
- The SNG plant includes an Organic Rankine cycle for energy recovery from the exothermic process of $CO_2$ methanization.
- The generation of $H_2$ is carried out using PEM electrolysis technology.
- The plant has been simulated with industrial software (ASPEN) for a full-scale plant
- The plant processes 40 t / day of $H_2$ and 218.2 t / day of $CO_2$, to generate 81.1 t / day or 51.3 MW of SNG (92.7% $CH_4$).
- The efficiency is 78%, greater than that indicated by Maroufmashat and Michael Fowler in (2017).

Most other studies on PTG (Power to Gas) and synthetic natural gas are focused on the use of biogas. This is the case of the works of Götz and others (2016), and Simonis and others (2017).

Other analyses such as Safari and Dincer (2018) of hybrid systems have not only been carried out, but focused on the optimization of synthetic natural gas production and wind speed.

## 2. Model Features.

The analysis carried out in this work starts from a hybrid model (Figure 1) of Wind - Power-to-Gas - CCGT. The UK market is taken as a reference, due to the great potential for generating surplus renewable energy from wind power. The model consists of several power plants that exchange flows of mass, energy and money between themselves and the external agents that surround them. The studio model consists of:

- One green hydrogen generation plant using proton exchange technology (PEM)
- One synthetic $CH_4$ generation plant based on a Sabatier reactor
- One combined cycle plant (CCGT) with one $CO_2$ capture and utilization plant (CCU) installed.

The inputs and outputs in the model are:

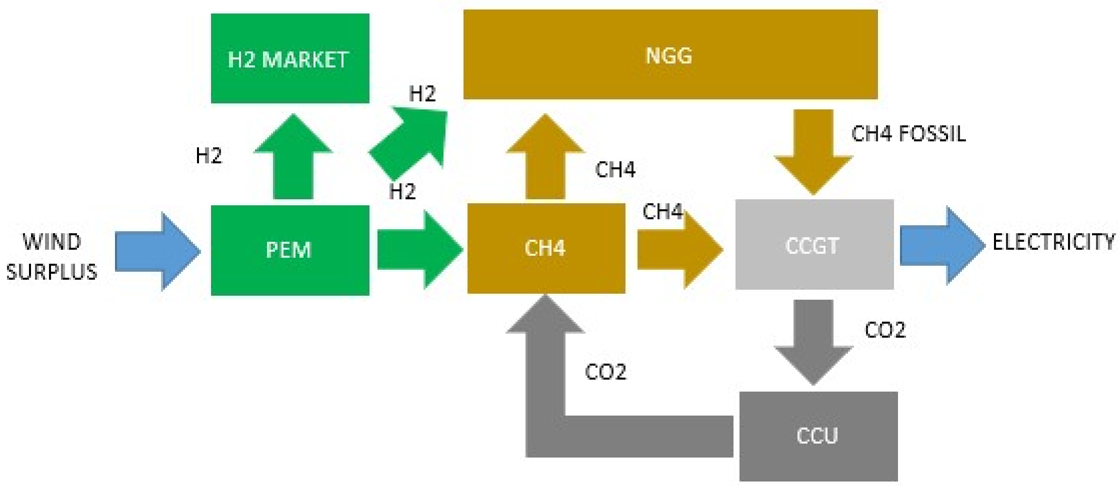
- $H_2$ industrial gas market
- UK National Gas Grid (NGG), and UK electricity market.

The relationship of the exchange flows between the model plants are described in table 1

**Table 1: Material and energy flows of each plant in the model.**

| Plant | INPUT | OUTPUT |
|---|---|---|
| PEM-Plant | Wind surplus of power market | $H_2$ to market / $H_2$ to NGG / $H_2$ to $CH_4$-Plant |
| $CH_4$-Plant | $H_2$ / $CO_2$ | $CH_4$ National Gas Grid (NGG) / $CH_4$ to CCGT |
| CCGT | CH4 / CH4 fossil | Electricity to power market / $CO_2$ to CH4-Plant |
| CCU | $CO_2$ | $CO_2$ to $CH_4$-Plant |

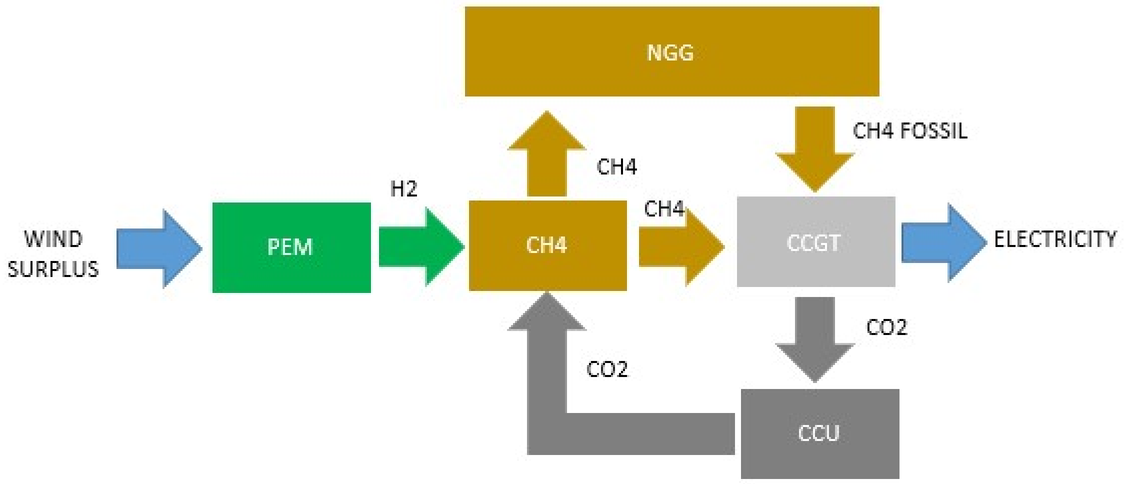
**Figure 1. Model Schem**




With the proposed model, the economic viability analysis of all the plants is performed, forming the same business unit (combined resort). The model is versatile and would allow an analysis of some of the plants independently by modifying the quantities of Green $H_2$ sold to Market. For example, if (0%) $H_2$ is not sold to the market, it implies a total integration of $H_2$ generation

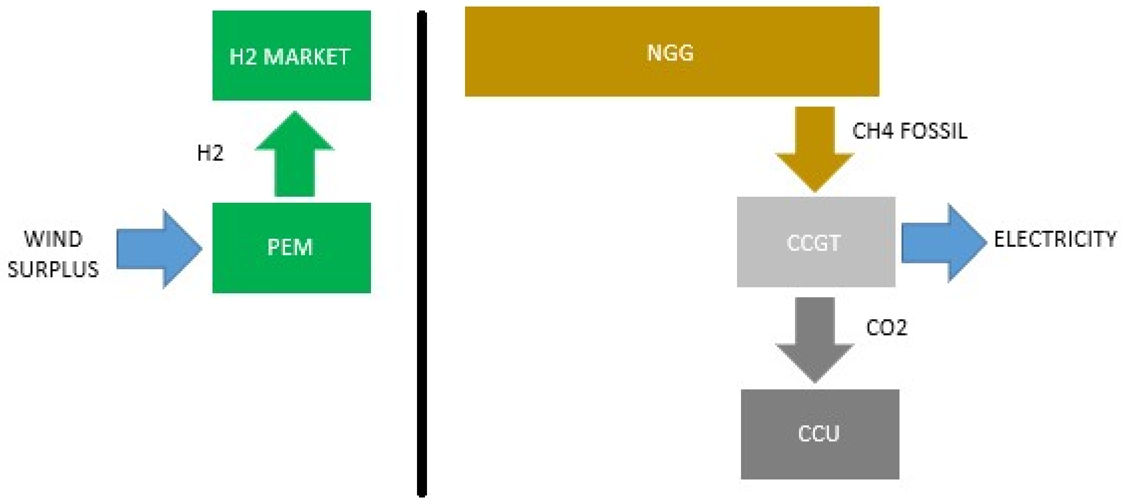
(PEM-Plant) in the combined operation strategy (see Figure 2). This improves profitability to the CCGT which would maximize the consumption of synthetic $CH_4$ instead of fossil $CH_4$.

**Figure 2. Model Schem for 100% $H_2$ sold to CH4-Plant**




On the other hand, if the PEM-Plant sold all its $H_2$ production (100%) to the market, it would be the existence of two different business models that would be neither interconnected nor coupled with each other (see Figure 3).

**Figure 3. Model Schem for 100% $H_2$ sold to Market**



## 3. Case Study.

The case study presented performs a sensitivity analysis of the NPV, IRR and payback for the hybrid Wind-Power to Gas - CCGT model. The main characteristics of each plant are identified in Table 2.

**Table 2: Main characteristics of each plant. Efficiency and Maximum Capacity**

| Plant | Plant Life (year) | Efficiency ratio | Plant Maximum Capacity |
|---|---|---|---|
| PEM-Plant | 40 | 61% | 50000 kg $H_2$ /day |
| $CH_4$-Plant | 40 | 78% | 81100 kg $CH_4$ /day |
| CCGT | 25 | 60% | 450 MW |
| CCU | 25 | 70% ($CO_2$ capture ratio) | Medium / High |

A base state is taken as the starting point for the variables that are in principle the most influential of the model. Additionally, the ranges of study of the variables that generate the greatest impact on the profitability of the model will be established, and a more detailed analysis will be made of them in conjuction with the impact on $CO_2$ emission. The variables selected for the analysis are:

- Wind Price
- Electricity Market Price
- $CO_2$ Right Price
- Gas Capacity Payment
- Green $H_2$ sold to Market
- $CH_4$ sold to Market
- $CH_4$ Fossil Price

From the economic-financial point of view, the set-up of adjustments for the analysis is the one identified in Table 3. Conservative values have been taken for the discount rate (12%), and the investment analysis period (20 years), shorter than the useful life of the plants (between 25 and 40 years). The amortization period of the plants is also conservative (10 years). It has not been considered a revaluation of the sale prices of energy, nor of the cost of supplies, because this case study is located in a scenario with surplus energy, and negative energy prices.

Conservatively, no tax exemption has been considered in the model, and therefore a tax rate of 30% has been set. But it is possible that a scenario of energy transformation could raise possible tax-payment relaxation incentives in new generation plants, such as the PEM-Plant and $CH_4$-Plant. Regarding the financing of the bank loan, an interest rate of 10% has been considered.

**Table 3: Economyc set-up**

| Parameter | Value |
|---|---|
| Analysis time | 20 year |
| Amortization time | 10 year |
| Stockholder´s Equity | 40% |
| Financing | 60% |
| Interest Rate | 10% |
| Loan payback periods | 20 year |
| Tax rate | 30% |
| Discount Rate | 12% |

### 3.1. Base state

The starting base state is characterized by:

- Negative and very low price (-30 £/MWh) of wind energy surplus. This is typical of a scenario with large surpluses.
- Sale price of electrical energy generated in the CCGT of £ 45/MWh.
- Payment for capacity for the combined cycle plant (CCGT).
- The hydrogen generation plant (PEM-Plant) and the synthetic methane generation plant ($CH_4$-Plant), make very low (residual) sales to the market.
  - The hydrogen generation plant (PEM-Plant) sells 5% of its production to the market, 6% to the National Gas Grid (NGG) and the rest (89%) is transferred to the synthetic $CH_4$ generation plant
  - The synthetic $CH_4$ plant only sells 5% of its production to the National Gas Grid (NGG) and the rest of the production (95%) is sent to the combined cycle plant (CCGT).

For the base state, the results obtained from the calculation of NPV, IRR, and payback show that the combined resort is not profitable. The NPV is -1.39E + £ 08, the IRR is 9.52%, and the payback is still higher than the analyzed investment period (20 years). It is important to note that the CCGT is the one that is the great contributor of profitability for the whole.

Regarding the balance of $CH_4$ used and the $CO_2$ emitted in the CCGT, in the base state the contribution of synthetic $CH_4$ is low (8%) compared to the contribution of CH4 fossil (92%). The CCGT plant emits 330 kg $CO_2$/MWh, with 302 kg $CO_2$/MWh associated with fossil $CH_4$ and 28 kg $CO_2$/MWh due to the combustion of synthetic $CH_4$ that will not count in the balance of $CO_2$ emission into the atmosphere.

The CCU (70% efficiency) plant recovers 231 kg $CO_2$/MWh on the total emitted by the combustion of the CCGT, and cannot recover 99 kg $CO_2$/MWh. But keep in mind that only 71 kg CO2/MWh is actually emitted into the atmosphere. This is so, because 28 kg $CO_2$ / MWh of the 99 kg $CO_2$/MWh that cannot be captured in the CCU, have their origin in synthetic $CH_4$.

In this way, the $CO_2$ capture efficiency of the combined resort increases to 78.48% and improves compared to a CCGT plant together with a CCU that only consumes $CH_4$ fossil. Table 4 includes the $CH_4$ and $CO_2$ balance values of the combined model.

**Table 4: Base state balance of $CH_4$ & $CO_2$**

| | |
|---|---|
| $CH_4$ input | 8% |
| $CH_4$ Fossil input | 92% |
| $CO_2$ Emission Intensity | 330 kg/MWh |
| $CO_2$ Emission Intensity of CH4 | 28 kg/MWh |
| $CO_2$ Emission Intensity of CH4 fossil | 302 kg/MWh |
| CCU $CO_2$ Captured | 231 kg/MWh |
| CCU $CO_2$ No Captured | 99 kg/MWh |
| $CO_2$ Emited to atmosphere | 99-28 =71 kg/MWh |

### 3.2. Results

The analysis ranges for the cost variables (wind price, electricity market price, $CO_2$ rights, gas capacity payment and $CH_4$ fossil price) have been established taking as reference possible future values in the medium term and extreme values of conservative and less conservative scenarios. Table 5 has compiled the adjustment values of the base state, and the range of variation selected for the variables.

**Table 5: Base state set-point and ranges of variations**

| Variable | Base Line Set-Point | Range of variation |
|---|---|---|
| Wind Price | -30 £/MWh | -30… 30 £/MWh |
| Electricity Market Price | 45 £/MWh | 15… 80 £/MWh |
| $CO_2$ rights | 0.0342 £/kg | 0… 0.0684 £/kg |
| Gas capacity payment | 50000 £/MW | 25000… 75000 £/MW |
| Green $H_2$ sold to Market | 5% | 0%... 100% |
| $CH_4$ sold to NGG | 5% | 0%... 100% |
| $CH_4$ fossil price | 0.02 £/kg | 0.0050… 0.1000 £/kg |

Wind Price values less than -56 £/MWh (outside the analyzed range) are required to obtain profitability. This value is outside the studied range.

The business model achieves profitability if the Electricity Market Price is greater than 50 £/MWh (Figures 4 and 5) for the electrical energy produced by the CCGT.

**Figure 4: NPV curve for Market Price variation (£/MWh)**

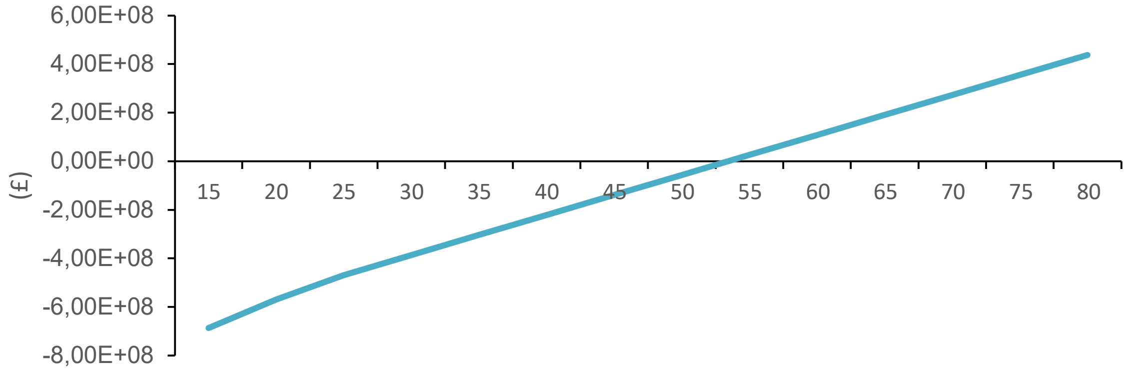
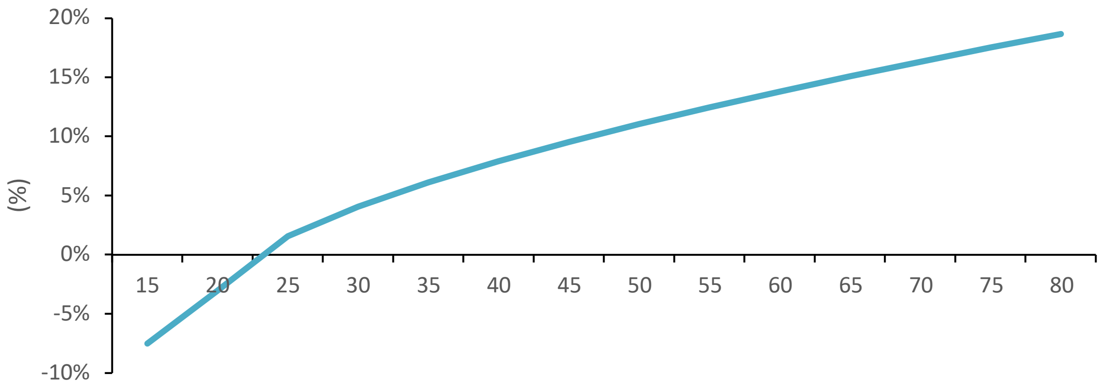



**Figura 5: IRR curve for Market Price variation (£/MWh)**




The model achieves profitability for values below 0.0085 £/kg in carbon emission allowances. This is a low value considering that the price of emission rights in the base state is set at 0.0342 £/kg. In scenarios with large surpluses of renewable energy, the prices of carbon emission rights may have a downward trend.

For the variation of the amount of $H_2$ sold to the market, if the PEM-Plant sells more than 15% of the $H_2$ generated, the business model is profitable. Figures 6 and 7 show that the increase in the sale of $H_2$ to the market has a direct impact on the profitability of the group, although it slightly penalizes the profitability of the CCGT.

The impact on the CCGT is due to the lower production of synthetic $CH_4$, and consequently the decrease in profitability by increasing the emission of $CO_2$ of fossil origin and the payment of carbon emission rights.

**Figura 6: NPV curves for % $H_2$ sold to market**

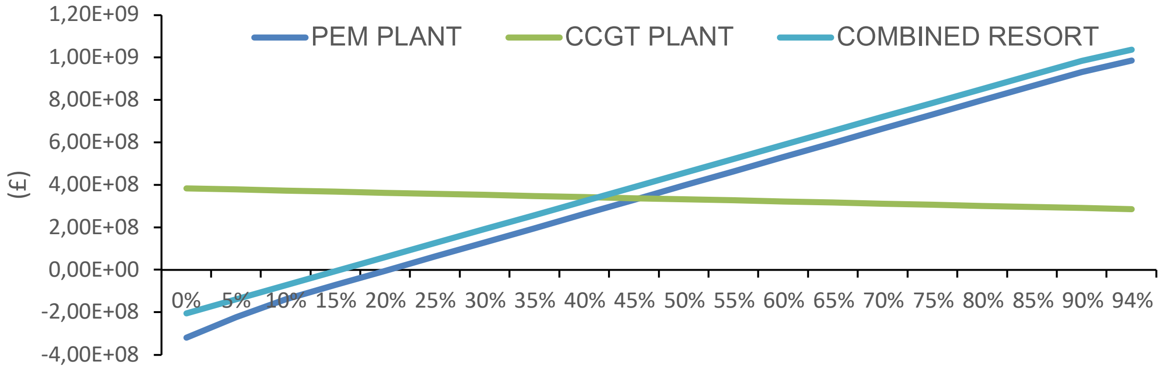
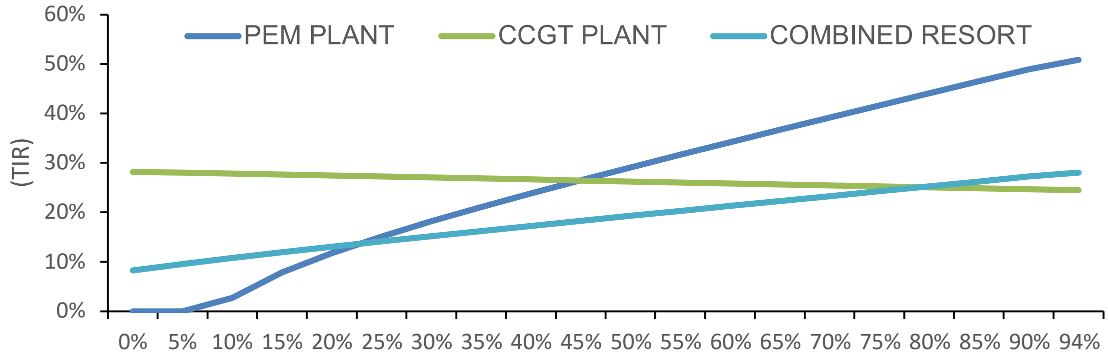
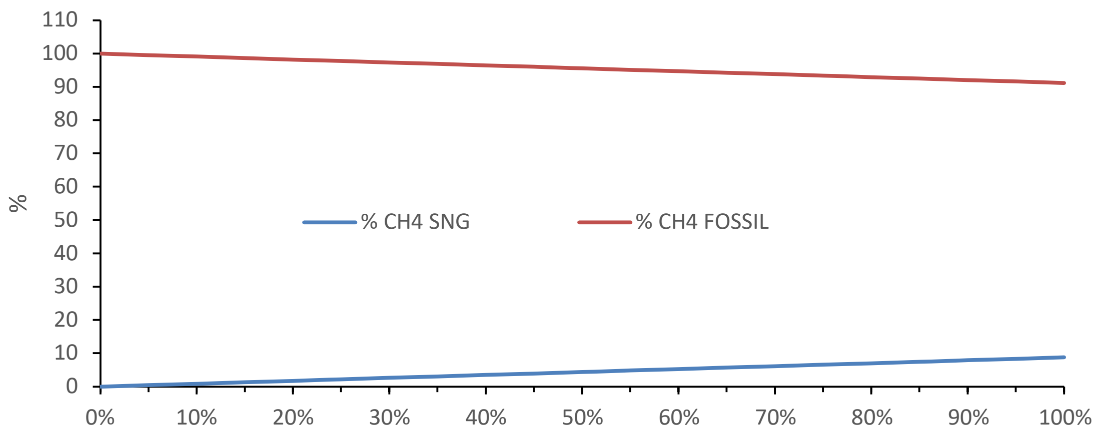



**Figure 7: IRR curves for % $H_2$ sold to market**



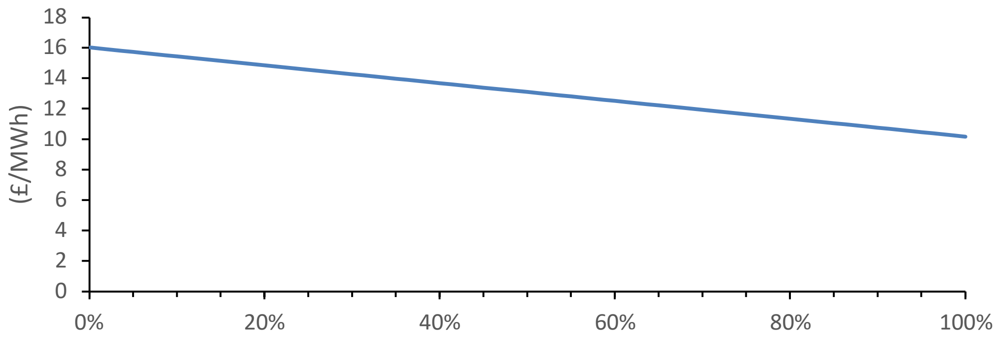

Finally, the influence of the amount of synthetic $CH_4$ that is supplied to the CCGT has been analyzed. For an extreme scenario in which the CCGT consumes all the synthetic $CH_4$ produced (100%), this only represents 8.79% of the $CH_4$ necessary to maintain the CCGT at 100% load, and it is necessary to provide the remaining 91.21% of $CH_4$ fossil. Figure 8 shows the $CH_4$ input balance curves of the CCGT.

**Figure 8: $CH_4$ input balance in CCGT**



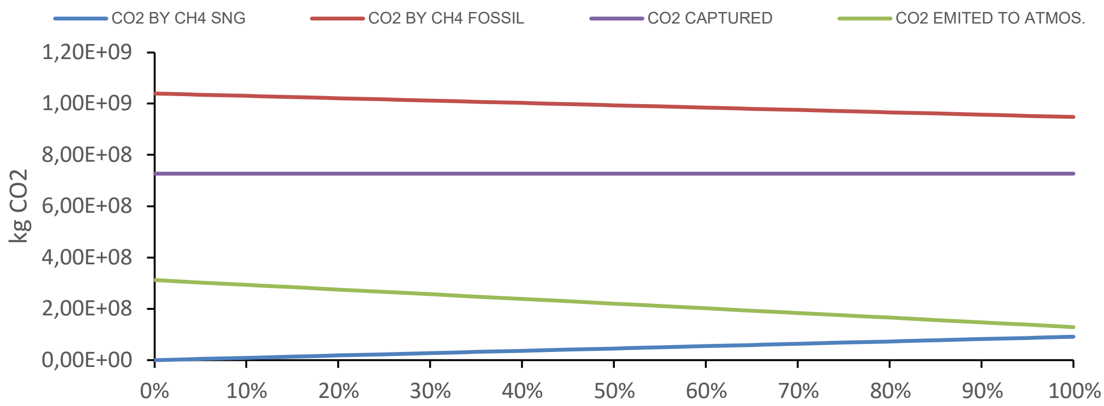
Increasing the contribution of synthetic $CH_4$ significantly reduces the cost of production in the CCGT, from 16.03 £/MWh for 100% $CH_4$ fossil, to 10.18 £/MWh if 100% of synthetic $CH_4$ is consumed (see Figure 9). This represents a 36.5% reduction in the cost of production of the CCGT.

**Figure 9: CCGT Production Cost (£/MWh) vs % $CH_4$ synthetic input to CCGT**




Lastly, it is verified (Figure 10) that the use of synthetic $CH_4$ reduces the $CO_2$ emission by 59% compared to the single use of $CH_4$ fossil in a CCGT.

**Figure 10: kg $CO_2$ Balance (CCGT + CCU) vs %$CH_4$ synthetic input to CCGT**



## 4. Conclusions

- The existence of surplus renewable energy can be used to generate energy vectors of gas (Power to gas) such as $H_2$ and $CH_4$. These gases can later be used in plants with known and reliable technologies such as CCGT.

- The use of energy vectors ($H_2$ and $CH_4$) contributes to the increase of the profitability margin in combined cycle plants (CCGT) with reductions of up to 36.5% of the production cost.

- This is achieved through a double route. On the one hand, savings in fossil fuel, and on the other hand, offsetting the payment of $CO_2$ emission rights. The results obtained endorse the above, using synthetic $CH_4$ in the CCGT reduces $CO_2$ emission by 59% compared to the single use of $CH_4$ fossil in a CCGT.

- The decrease in the cost of production places CCGT plants in an advantageous position in the electricity market, because they can offer a lower price and increase the number of production hours.

- The hybrid model generated wind-Power to Gas-CCGT is versatile and the results obtained are indicative of profitability for an independent business model for the PEM-Plant. This may be a future line of study but has to be analyzed in detail. $H_2$ production by proton exchange membrane is still a developing technology, and cost estimates may be greatly reduced

## 5. Acronym List

***CCGT.*** Combyned Cycled Gas Turbine

***CCU.*** Carbon Capture and Utilization

***CCS.*** Carbon Capture and Storage

***DAC.*** Direct Air Carbon Capture

***IRR.*** Internal Rate Return

***LCOE.*** Levelized Cost of Energy

***NGG.*** National gas grid (UK)

***NPV.*** Net Present Value

***PEM.*** Proton Exchange Membrane.

***PV.*** Photovoltaic Energy System

***P2G.*** Power to gas

***RPM.*** Renewable Power Methane

***SMR.*** Steam Methane Reform

***SNG.*** Synthetic Natural Gas

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