

# Techno-economic analysis of integrating an on-board CCS system and a PtG technology in a heavy vehicle fleet

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## ABSTRACT

Decarbonising the heavy-duty transport sector requires switching internal combustion engine (ICE) fuel from fossil to synthetic fuels. In this context, on-board carbon capture and storage (OCCS) in ICEs could provide the CO<sub>2</sub> needed by Power-to-gas (PtG) technologies to produce synthetic natural gas (SNG), which is then consumed again by the vehicle fleet, closing in this way the carbon loop. This study presents a techno-economic analysis of a heavy-duty vehicle fleet integrating an OCCS system with a PtG plant. The OCCS system operates by temperature swing adsorption where two sorbents, PPN-6-CH<sub>2</sub>-DETA and zeolite 13X, are evaluated at carbon capture rates (CCR) of 70 % and 100 %. A fifth scenario examined the effect of varying the H<sub>2</sub>:CO<sub>2</sub> ratio in the methanation plant at 100 % CCR using PPN-6-CH<sub>2</sub>-DETA. Both systems were simulated using Aspen Plus and AVL Boost softwares. Moreover, a sensitivity analysis was conducted considering three key performance indicators: the CO<sub>2</sub> tax, natural gas (NG), and electricity prices. The results indicate that the carbon abatement cost reaches a break-even point at 150 €/tCO<sub>2</sub> for a fleet size of 400 vehicles. However, the capital expenditures do not achieve payback within 20 years due to the high operational expenditures and low incomes in the evaluated scenarios. The sensitivity analyses show that the CO<sub>2</sub> tax and the NG price must be higher than 400 €/tCO<sub>2</sub> and 160 €/MWh, respectively, to compensate for the current electricity price and allow the proposed systems to be techno-economic feasible.

## 1. Introduction

Power-to-gas (PtG) technology has emerged as a promising approach for storing renewable energy and addressing the intermittency challenge associated with many renewable energy sources [1]. PtG involves the conversion of excess renewable electricity into hydrogen or other renewable gases, which can then be stored and used as fuel for transportation, heating, or other applications [2].

Despite the significant advancements in hydrogen technologies in recent years [3], One of its drawbacks is the absence of a suitable infrastructure that is capable of meeting H<sub>2</sub> demand [4]. Consequently, developing an H<sub>2</sub> network infrastructure (encompassing production plants, storage facilities, transportation channels and endpoints to supply H<sub>2</sub>) requires significant investment and long-term planning, factors that currently hinder the feasibility of H<sub>2</sub> as a mainstream energy source [5]. However, if the PtG produces synthetic methane using CO<sub>2</sub> captured from a large emitter, this renewable fuel could be a promissory option to

take advantage of the existing and extended infrastructure used to supply natural gas. For that reason, in recent years, there has been growing interest in applying PtG technology to the transport sector to decarbonize it and reduce its dependence on fossil fuels [6].

The transport sector is one of the largest contributors to global greenhouse gas (GHG) emissions, emitting around 7.98 Gt of CO<sub>2</sub> in 2022 [7]. The transport sector emits these large amounts of GHG because it still heavily relies on fossil fuels for its propulsion and because electrification technologies to decarbonise this sector, such as battery and fuel cell battery vehicles, need more time to be widely implemented [8]. For this reason, the internal combustion engine will continue to operate in the short and medium term, especially in heavy transport [9]. Since internal combustion engines (ICE) will continue and cannot operate with biofuels due to difficulties in their production [10,11], well-known low-carbon fuels such as natural gas (NG) are gaining ground for use in the transportation sector to reduce GHG [12]. Nevertheless, the combustion of NG continues to emit CO<sub>2</sub>, but if the transport sector uses synthetic natural gas (SNG) produced by renewable

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Nomenclature			
CAPEX	Capital expenditure	LHV	Lower heating value
CAC	Carbon abatement cost	NG	Natural gas
CCS	Carbon capture and storage	NPV	Net present value
CCR	Carbon capture rate	OCCS	On-board carbon capture and storage
CNG	Compressed natural gas	ORC	Organic rankine cycle
C <sub>5</sub> H <sub>10</sub>	Cyclopentane	O&M	Operation and maintenance
DC-OCCS	Direct costs of OCCS system	OPEX	Operational expenditures
DC-PtG	Direct costs of PtG Plant	PtG	Power-to-gas
β	Electricity price	PEM	Proton exchange membrane
ETS	Emissions trading system	SNG	Synthetic natural gas
GHG	Greenhouse gas	TSA	Temperature swing adsorption
ICE	Internal combustion engine	TEC	Total equipment costs
KPI	Key performance indicator	VF	Vehicle fleet
		WF	Working fluid

PtG technologies, it could become a zero emissions sector.

One of PtG technology's main benefits is its ability to transform renewable electricity into an energy vector that can be easily stored and transported [13]. This helps balance supply and demand on the electrical grid by enabling excess renewable energy to be stored during periods of low demand and used during periods of high demand [14]. Furthermore, PtG technology holds significant potential to contribute to the decarbonization of the transport sector due to the production of SNG as a low-carbon fuel that offers an alternative to conventional fossil fuels [15]. This aligns with global efforts to reduce greenhouse gas emissions by providing a low-carbon fuel, helping the transport sector achieve its CO<sub>2</sub> 2050 targets [16].

In recent years, various research works have been conducted about carbon capture and storage (CCS) systems operating in mobile sources (ships and road freight transport) propelled by ICEs. Through simulations and experimental tests, the studies have investigated the technical, energy, and economic feasibility of integrating carbon capture and storage (CCS) systems in mobile sources. These studies encompass the evaluation of various sorbents and absorbents, as well as the configuration of CCS systems. Among the techniques assessed, amine scrubbing and temperature swing adsorption (TSA) appear to be the most suitable methods for CO<sub>2</sub> capture in mobile sources [17–21].

Regarding experimental tests research works, the maximum carbon capture rate (CCR) using amine-scrubbing as a CO<sub>2</sub> capture method has been 50 % [22]. Similar results have been achieved in experimental tests carried out using TSA as a CO<sub>2</sub> capture technique [19,23,24]. Regarding simulations, several studies have focussed on analysing the energy behaviour of CCS systems and the potential penalizations that their operation could have over the performance engine. Notable findings include evaluating a CCS system operating with TSA, which is integrated into a truck powered by a diesel engine [25]. This study demonstrated that achieving 90 % of CCR without affecting the engine performance. Other research works that also use TSA in the CCS system have yielded more realistic results [20,21,26–28]. These studies demonstrated that the CCS system penalises engine performance from 3 % to 18 % at CCR from 70 % to 100 %; this penalisation gap varies depending on the sorbent evaluated and the engine load. Previous research agrees that integrating an ORC to harness the waste heat from exhaust gases is a key addition to the CCS system [29]. This integration significantly mitigates the performance penalty imposed on the engine, primarily by the CO<sub>2</sub> compression process, which is the most energy-intensive stage of the CCS system.

Finally, techno-economic assessments of CCS systems integration in mobile sources have been developed. Regarding amine-scrubbing, the techno-economic analysis shows that the capital expenditure (CAPEX) integrating the CCS system in the vehicle is less than the CAPEX of a hydrogen fuel cell vehicle. However, it has a much higher initial

investment than battery electric vehicles, conventional diesel and NG vehicles [21]. Regarding TSA, the techno-economic assessment shows it is currently not feasible [30]. But in 2027, the transport sector must start to pay CO<sub>2</sub> emissions rights [31]. So, under this scenario, the previous study shows that a carbon abatement cost (CAC) is close to 40 €/tCO<sub>2</sub> [30], which is less than other energy intensive industries like glass and steel factories [32,33]. At this CAC price, integrating CCS systems in heavy-duty vehicles avoids the direct CO<sub>2</sub> emissions produced by heavy-duty transport with a reasonable initial investment. This kind of proposal could contribute to transforming the transport sector into a more sustainable sector.

Nevertheless, even if the transport sector incorporates CCS systems into its technologies, a bottleneck must still be overcome for this kind of technology to be entirely feasible. This bottleneck is related to the large amounts of captured CO<sub>2</sub> and its management. Therefore, utilising CO<sub>2</sub> as raw material in industrial processes is presented as a more viable solution to overcome these difficulties. One of the most promising paths is the PtG technology, which can produce synthetic natural gas (SNG) from CO<sub>2</sub> and H<sub>2</sub>. This gas can later be used as fuel for mobile sources, diversifying alternative fuel sources, enhancing energy security and establishing a closed-loop CO<sub>2</sub> cycle. Ultimately, this approach supports the dual goals of sustainability and efficiency, reinforcing the transport sector's role in a low-carbon circular economy.

The present research work makes a techno-economic assessment of a PtG plant that produces SNG using CO<sub>2</sub> as a raw material captured from a heavy-duty vehicle fleet equipped with on-board carbon capture and storage (OCCS) systems. The PtG plant uses H<sub>2</sub>, produced in a proton exchange membrane (PEM) electrolysis plant. Finally, the SNG is pressurized and fed to the vehicle fleet. The techno-economic analysis of the OCCS system in the heavy vehicle and the PtG plant was performed using Aspen Plus software. Also, a sensitivity analysis on several KPIs, such as natural gas cost, CO<sub>2</sub> tax, and electricity price, was developed. This study will contribute to closing the existing knowledge gap on the two proposed systems since the techno-economic assessment will provide detailed information on the benefits, limitations and potential to bring the transport sector closer to full decarbonisation. The findings also provide a foundation for future research and inform decisions on CO<sub>2</sub> emissions management, supporting the transition to cleaner and more efficient transportation.

## 2. Case study description

A techno-economic feasibility study of a PtG plant that uses the CO<sub>2</sub> captured from a fleet of transport vehicles with an integrated OCCS system is carried out (See Fig. 1). The vehicle fleet size is calculated based on the CAC break-even price. For this, it is necessary to obtain the capital expenditure (CAPEX), the operational expenditures (OPEX) and

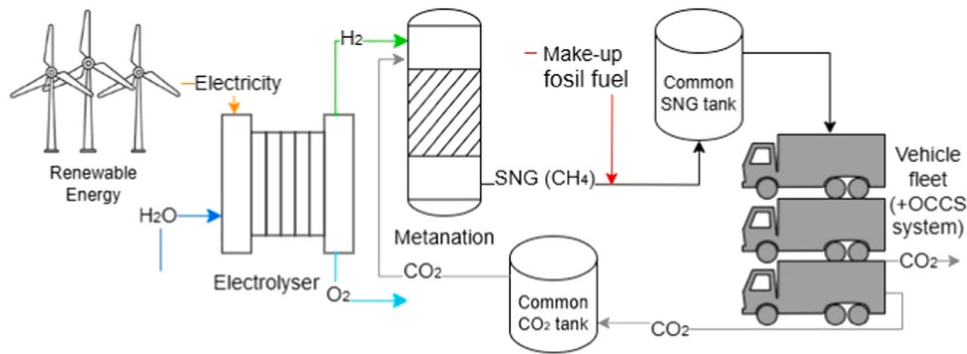


Fig. 1. Concept integration between a vehicle fleet with an OCCS system and a PtG plant.

the incomes. Each of these variables, as well as the proposed systems, are described in the following subsections.

2.1. On-board carbon capture and storage system

The process begins with modelling a heavy-duty ICE using AVL-BOOST software to determine the exhaust gas conditions required for simulating the OCCS system. The selected ICE is a turbocharged compressed natural gas (CNG) spark ignition ICE of reference M936G, which is usually used in heavy-duty road transport. This engine is commonly utilized in heavy-duty road transport applications. The engine was simulated under stoichiometric conditions for four engine loads (25, 50, 75 and 100 %) in the entire engine speed range (from 1000 to 2200 rpm). The main parameters, the engine characteristics used in the simulations and are shown in the study [28]. The model results are validated by comparing them with the engine performance curves found in the engine datasheet [34].

The design of the OCCS system used in the vehicles includes a device to develop the process of CO2 capture by TSA [30]. This device was designed to harness the waste heat of the exhaust gases in the sorbent heating and CO2 desorption stages. The sorbents selected are PPN-6-CH2-DETA (PPN onwards) and Zeolite 13X (Z13 onwards). The PPN has a high CO2/N2 selectivity (>10000), producing a CO2 purity

greater than 99.99 % [21]. Also, it can withstand small amounts of water and has a low adsorption heat (45.32 kJ/molCO2) [35]. On the other hand, The Z13 has a suitable CO2/N2 selectivity with a value of 17.1 and a low desorption heat; this sorbent is selected because it is a widely commercial sorbent.

The OCCS system is also equipped with an Organic Rankine Cycle (ORC). This takes advantage of the remaining waste heat of the exhaust gas and produces power to reduce the penalties that the CO2 compression stage imposes on the engine performance. The working fluid (WF) selected for its operation is cyclopentane, which has presented an excellent performance in previous research works on ORC in ICE [36, 37]. The ORC thermodynamics conditions for each device (pump, heaters, expander and condenser) were obtained following the procedure developed by Fatigati [38–40]. Finally, the OCCS stores the captured CO2 by compressing it until it reaches the liquid phase at 75 bar and 29.3 °C to reduce its volume and thus facilitate its storage. Further details about the ORC system and other heat exchangers also used in the OCCS system can be consulted herein [20]. Fig. 2 shows the process flow diagram of the proposed OCCS system.

2.2. Power to gas plant simulation

The power to gas plant consists of an electrolyser, a methanation

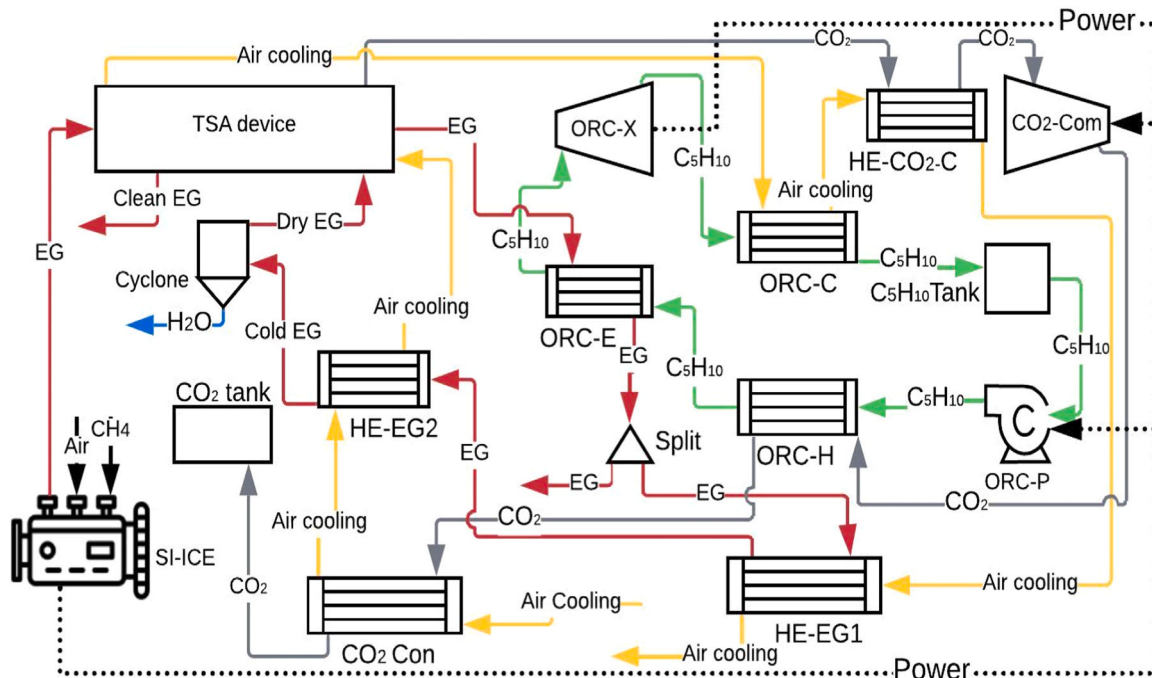


Fig. 2. Devices and mass and energy diagram of the OCCS system.

plant and a storage system, see Fig. 1. The system works continuously, storing the required gases in pressurised storage tanks. The electrolyser is a PEM type, and the energy consumption is set to 3.8 kWh/Nm<sup>3</sup>H<sub>2</sub> [41], working at 25 °C and 30 bar Eq. (1). The oxygen by-produced in the electrolyser is assumed to be sold to other industries. The methanation plant is fed with H<sub>2</sub> from the electrolyser and CO<sub>2</sub> from the CO<sub>2</sub> storage tank Eq. (2). The methanation plant consists of two isothermal fixed bed reactors working at 350 °C and 300 °C, respectively, and 30 bar, see Fig. 3. The stoichiometry of the reaction is 4 H<sub>2</sub>:CO<sub>2</sub>, with a Ni-based catalyst. An intermediate condenser is required between the two methanation reactors, to get rid of the excess water. The synthetic natural gas (SNG) is cooled to 25 °C and compressed to 100 bar to be stored in the SNG storage tank. The two storage tanks (CO<sub>2</sub> and SNG) are needed to maintain the production continuity of the PtG plant. Also, two different sets of compressors are required, one for the CO<sub>2</sub> compression (from the buses to the common CO<sub>2</sub> storage tank) and the second for the produced SNG. Both tanks operate at 100 bar.



With this configuration, at the end of the day, the buses discharge the CO<sub>2</sub> produced throughout the day in a common storage tank, while filling up with the SNG. At this point, the common CO<sub>2</sub> tank is full, and the common SNG is empty. During the night and the following day, the PtG plant continue to work, unloading the common CO<sub>2</sub> tank and filling the common SNG tank. The PtG plant (electrolyser and methanation) are supposed to work non-stop. For the storage tanks, a horizontal, carbon steel, 15.7 m<sup>3</sup> (1 m diameter, 20 m long) deposit has been chosen. The number of tanks required will be a function of the amount of CO<sub>2</sub> and SNG to store, and its pressure (100 bar).

## 2.3. Economic analysis

### 2.3.1. Capital expenditure

The economic analysis is carried out starting with the capital expenditure (CAPEX) by calculating each component of the methanation plant installation and the OCCS system. For this, correlations from the literature and values obtained of equipment given by ASPEN plus are taken. Direct costs, such as installation, control, piping, among others, and indirect costs, such as engineering and contingencies, are calculated as a percentage of the value of the equipment costs. Table 1 shows all the equipment required for the PtG plant and the OCCS system and its respective correlation to calculate its CAPEX. The variable values of the OCCS system are taken from previous research works [20,29,30].

### 2.3.2. Operational expenses

The operating expenses (OPEX) calculation considers the operating and functioning expenses of the methanation plant, as well as the OCCS system of the vehicles. Electricity cost ( $\beta$ ) is set at 84.5 €/kWh. The labor cost in this study is considered in the operation and maintenance (O&M) section. Table 2 shows the main variables and correlations to obtain the OPEX values.

In the simulations, two different CCR were used in the OCCS system, 70 and 100 %, in order to know the economic behaviour of a partial and a full CCR. All OCCS system simulations were performed in Aspen Plus software. To calculate the increase in the fuel consumption the procedure described in [30] is followed. This procedure takes into account the power penalty on the engine produced by the OCCS system, the lower heating value, and the combustion and engine efficiencies of the average operational points of the engines within the World Harmonized Transient Cycle [26].

### 2.3.3. Incomes

In this type of system, there are three different incomes: the saved natural gas, the sold oxygen, and the CO<sub>2</sub> taxes (which were approved by the European Parliament as proposed in the document "2030 Climate Objectives Plan: extension of the European Emissions Trading System (ETS) to transport emissions" [53]), which have a value of 45 €/tCO<sub>2</sub>. Table 3 shows the correlations used in the analysis to calculate these values.

### 2.3.4. Case studies and sensitivity analysis

The techno-economic analysis considers CCRs of 70 and 100 % in the OCCS system for the two sorbents mentioned above (PPN-70, PPN-100, Z13-70 and Z13-100). In addition, a H<sub>2</sub>:CO<sub>2</sub> ratio of 4:1 is considered (a fundamental ratio to optimize the conversion and guarantee the operational stability of the process) in the methanation plant. Additionally, a complementary analysis is carried out specifically for the case of PPN-100, exploring the impact of modifying the ratio H<sub>2</sub>:CO<sub>2</sub> to 3.5:1; this variation will be called PPN-100-2. This variation assesses the sensitivity of the system to changes in SNG composition and their impact on the techno-economic performance. Finally, a sensitivity analysis of key variables —electricity price, natural gas price, and CO<sub>2</sub> tax— is conducted to identify the economic factors most influencing the integration of carbon capture and utilization systems in heavy transport applications. Finally, the investment payback time of the proposed concept is determined by calculating the net present value (NPV). For this calculation, commonly used values for the interest rate and the system's lifespan were taken from the literature (an interest rate of 4 % and a system lifespan of 20 years) [57-59].

## 3. Results

### 3.1. Techno-economic assessment

Fig. 4 indicates that, at the specified electricity price, the CAC cost reaches a stable level for a vehicle fleet size of 400 vehicles. Its value is between 144.5 €/tCO<sub>2</sub> at 70 % CCR for PPN-70 and 167.3 €/tCO<sub>2</sub> at 100 % CCR for Z13-100, which is approximately two times more expensive than a traditional carbon capture facility. However, it is comparable to carbon capture solutions implemented in energy-intensive industries such as steelmaking and glassmaking [32,33]. When comparing the CAC values obtained in this research with those reported in other studies related to integrating OCCS systems in mobile sources [60-63], the results of this study are, on average, 20 % higher.

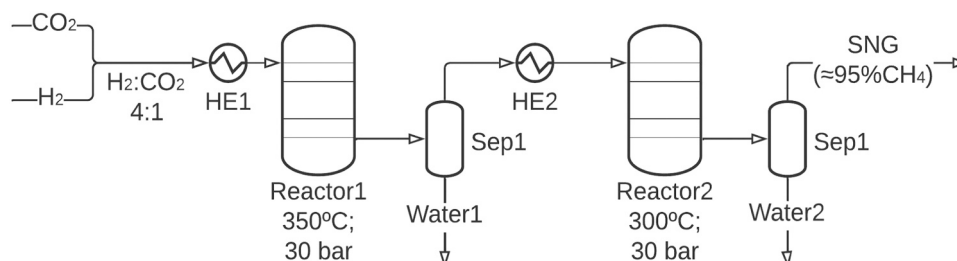


Fig. 3. Process flow diagram of the isothermal methanation plant.

**Table 1**  
CAPEX correlations and variables.

Equipment	Correlation	Variable ( $\alpha$ )	Unit	Ref.
<b>Total equipment costs (TEC)</b>				
<b>PtG plant</b>				
Electrolysis	$400 \times 10^6 \alpha$	Power	[kW]	[42]
SNG compressor	$0.267(\alpha/445)^{0.67}$	Power	[kW]	[42]
CO <sub>2</sub> compressor	$0.267(\alpha/445)^{0.67}$	Power	[kW]	[42]
Methanation Reactors	$300 \times 10^6 \alpha$	SNG power	[kW]	[43]
Catalyst	$0.1875 \alpha$	Volume of catalyst	[m <sup>3</sup> ]	[42]
SNG tank	$148 \times 10^6 \alpha$	N° tank (15.7 m <sup>3</sup> , 100 bar)	[-]	[44]
CO <sub>2</sub> tank	$148 \times 10^6 \alpha$	N° tank (15.7 m <sup>3</sup> , 100 bar)	[-]	[44]
<b>OCCS system</b>				
TSA-Device	$3397 \alpha^{0.86}$	Area	[m <sup>2</sup> ]	[30]
ORC-expander	$10 \{ 2.2476 + 1.4965 \log_{10}(\alpha) + 0.1618 [\log_{10}(\alpha)]^2 \}$	Volume (m <sup>3</sup> )	[m <sup>3</sup> ]	[45]
ORC-pump	$900(\alpha/300)^{0.25}$	Power	[kW]	[46]
ORC-C <sub>5</sub> H <sub>10</sub> tank	$31.5 + 16 \alpha$	Volume	[L]	[46]
ORC-Evaporator	$190 + 310 \alpha$	Area	[m <sup>2</sup> ]	[46]
ORC-heater	$190 + 310 \alpha$	Area	[m <sup>2</sup> ]	[46]
ORC-condenser	$190 + 310 \alpha$	Area	[m <sup>2</sup> ]	[46]
HE-EG1	$190 + 310 \alpha$	Area	[m <sup>2</sup> ]	[46]
HE-EG2	$190 + 310 \alpha$	Area	[m <sup>2</sup> ]	[46]
Cyclone	$1776.22 \alpha$	Volume (m <sup>3</sup> )	[m <sup>3</sup> ]	[47]
Fan	$900(\alpha/300)^{0.25}$	Power	[kW]	[46]
Condenser	$190 + 310 \alpha$	Area	[m <sup>2</sup> ]	[46]
Compressor	$267000(\alpha/445)^{0.67}$	Power (kW)	[kW]	[42]
CO <sub>2</sub> tank	$31.5 + 16 \alpha$	Volume (L)	[L]	[46]
<b>Other direct costs of PtG Plant (DC-PtG)</b>				
Installation	8 % $\alpha$	TEC	[€]	[48]
Instrumentation & control	4 % $\alpha$	TEC	[€]	[48]
Piping	16 % $\alpha$	TEC	[€]	[48]
Electrical	5 % $\alpha$	TEC	[€]	[48]
Building	5 % $\alpha$	TEC	[€]	[48]
Land	1 % $\alpha$	TEC	[€]	[48]
<b>Other direct costs of OCCS system (DC-OCCS system)</b>				
Installation	8 % $\alpha$	TEC	[€]	[49]
Instrumentation & control	5 % $\alpha$	TEC	[€]	[49]
Piping	1.5 % $\alpha$	TEC	[€]	[49]
Electrical	1 % $\alpha$	TEC	[€]	[49]
<b>PtG plant indirect costs (ID-PtG)</b>				
Engineering	7 % $\alpha$	TEC+DC-PtG	[€]	[48]
Legal expenses	2 % $\alpha$	TEC+DC-PtG	[€]	[48]
Construction expenses	4 % $\alpha$	TEC+DC-PtG	[€]	[48]
Contingency	7 % $\alpha$	TEC+DC-PtG	[€]	[48]
<b>OCCS system indirect cost (ID-OCCS system)</b>				
Engineering	7 % $\alpha$	TEC+DC-OCCS	[€]	[48]
Construction expenses	4 % $\alpha$	TEC+DC-OCCS	[€]	[48]
Contingency	7 % $\alpha$	TEC+DC-OCCS	[€]	[48]

**Table 2**  
OPEX correlations and variables.

Concept	Correlation	Variable	Ref.
Catalyst renovation	15 % $\alpha$	Initial catalyst cost [M€]	[50]
Electricity	Elec.Consump $\times 10^6$	Electricity cost [€/MWh]	
Water	$1.47 \times 10^{-6} \alpha$	Water consumption [m <sup>3</sup> /y]	[51]
O&M	3 % $\alpha$	Total CAPEX [M€]	[48]
PPN renovation	$2\alpha$ for PPN and $1\alpha$ for Z13	Total CAPEX [M€]	[30]
Cyclopentane	$7VF_{ax}10^{-6}$ at 70 %CCR; $5VF_{ax}10^{-6}$ at 100 % CCR	Working fluid cost [€/L]	[52]
O&M	3 % $\alpha$	Total CAPEX [M€]	[48]
Fuel consumption increasing	$\frac{3.6ABC}{DEF} \times VF \times 10^{-6}$	(A) Power penalty [kW], (B) CNG cost [€/kg], (C) time operation by year [s/year], (D) LHV [kJ/kg], (E) Combustion efficiency, (F) engine efficiency	[30]

However, the techno-economic analyses in these studies do not consider integrating a fuel production system that would enable the self-sufficiency of a transport fleet.

**Table 3**  
INCOMES correlations and variables.

Concept	Correlation	Variable	Unit	Ref.
Natural gas	$\alpha\beta$	NG saved	[MWh/y]	[54]
		NG price	[€/MWh]	
Oxygen	$80 \times 10^{-6} \alpha$	O <sub>2</sub> generated	[tO <sub>2</sub> /y]	[55]
CO <sub>2</sub> taxes	$10^{-6} \alpha\beta$	CO <sub>2</sub> saved	[tCO <sub>2</sub> /y]	[56]
		CO <sub>2</sub> tax price	[€/tCO <sub>2</sub> ]	

As seen in Fig. 4, the cases with 70 % CCR present the lowest value of CAC compared to their counterparts at 100 % CCR. Two factors mainly produce this behaviour; the first is that a larger electrolyser is required at 100 % of CCR, which increases the CAPEX when compared with the 70 % of CCR case; the second factor is a consequence of having a larger electrolyser, as also more electricity is required for its operation, increasing the OPEX. Therefore, the amount of CO<sub>2</sub> avoided at 100 % of CCR falls short to achieve a CAC lower than at 70 % of CCR. Table 1 shows the values obtained for the CAPEX, OPEX, incomes, and CAC for a vehicle fleet of 400 units. The detailed results obtained for the CAPEX, OPEX, and incomes can be seen in Appendix A, B, and C.

Table 4 shows the results of the main techno-economic variables of integrating a PtG plant with a vehicle fleet of 400 units with

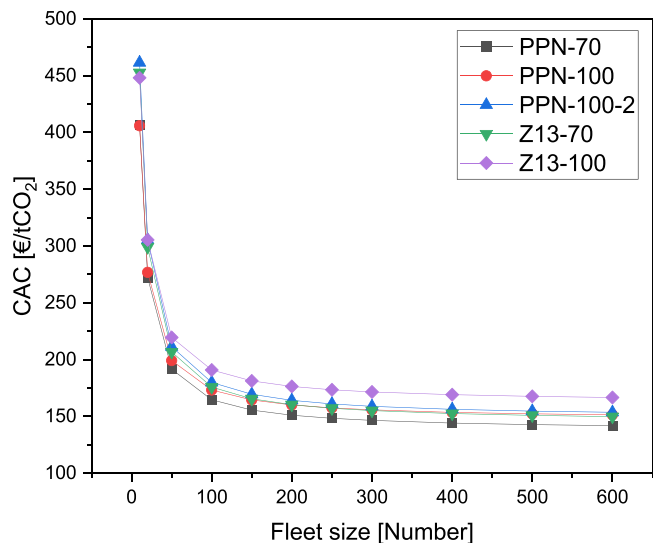


Fig. 4. Carbon abatement cost (CAC) vs vehicle number.

**Table 4**  
Cost of the main variables of the integration of a PtG plant with an OCCS system.

Cases	PPN-70	PPN-100	PPN-100-2	Z13-70	Z13-100 %
CAPEX [M€]	58.98	76.42	74.02	61.09	77.71
OPEX [M€]	14.50	22.06	21.28	14.83	23.37
INCOMES [M€]	7.27	10.40	9.23	7.28	10.40
Profits [M€]	-7.24	-11.66	-12.05	-7.55	-12.97
NPV at 20 years [M€]	-157.3	-234.9	-237.8	-163.7	-253.9
CO <sub>2</sub> avoided [tCO <sub>2</sub> /year]	70503.7	100719.5	100719.5	70503.7	100719.5
CAC [€/tCO <sub>2</sub> ]	144.5	153.7	156.4	150.4	167.3

incorporated OCCS systems. Results shows that, with PPN as sorbent, the lower values of CAPEX, OPEX, and CAC are obtained when compared to Z13. This is due to the lower selectivity of the Z13 regarding PPN, which produces impurities in the CO<sub>2</sub> captured. This leads to a lower quality of the SNG since it has 14 % less LHV. This drawback leads to larger devices, higher CO<sub>2</sub> storage pressure (81.76 bar), and higher penalties over engine performance, when compared with PPN sorbent. Consequently, it increases the CAPEX and OPEX, due to larger devices and increased fuel consumption.

In the case of PPN-100-2, Table 4 indicates that, despite having lower CAPEX and OPEX than PPN-100, it also generates lower incomes due to reduced production of SNG and O<sub>2</sub>. Consequently, PPN-100-2 exhibits a higher CAC than PPN-100. Nonetheless, this case remains more favourable in terms of CAC than Z13-100 because it presents lower values of CAPEX and OPEX. Finally, none of the five case studies achieved a positive net present value after 20 years, mainly due to high OPEX and low incomes.

### 3.2. Sensitivity analyses

Fig. 5 shows a sensitivity analysis of the CAC behaviour varying the cost of electricity. The analysis reveals that achieving a CAC of zero is feasible only in the PPN-70 scenario with an electricity price of 5 €/MWh. However, such a low electricity price is unrealistic under current market conditions, limiting the practical relevance of this scenario. In contrast, standard CAC values reported in the literature are approximately 60 €/tCO<sub>2</sub> [64]; this value can be reached with electricity prices

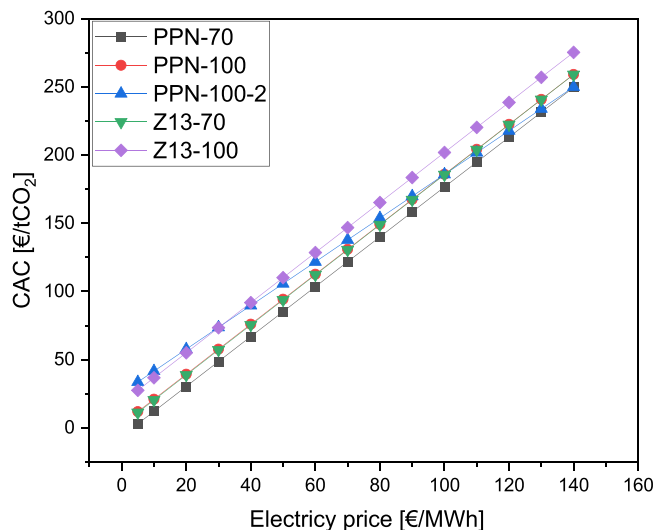


Fig. 5. Carbon abatement cost (CAC) vs Electricity price.

ranging from 20 €/MWh with PPN-100-2–40 €/MWh with PPN-70. However, these electricity prices are still low compared to the recent market trend. So, for an electricity price of 50 €/MWh (mean value up to 2021), the achieved CAC cost is between 85 and 110 €/tCO<sub>2</sub> for PPN-70 and Z13-100, respectively.

The second sensitivity analysis, depicted in Fig. 6, examines the relationship between the CAC and the CO<sub>2</sub> emission tax that the European Parliament has adopted and that is scheduled to go into effect in 2027 [31]. As can be seen in this Figure, a CAC cost of zero is achieved with CO<sub>2</sub> tax values between 680 €/tCO<sub>2</sub> for the PPN-70 and 780 €/tCO<sub>2</sub> for the Z13-100.

Although this increase achieves a CAC of zero, it implies that a tenfold increase in the CO<sub>2</sub> tax is required to mitigate the impact of electricity prices on the techno-economic analysis. This poor influence is further supported by the results obtained in the incomes related to the CO<sub>2</sub> tax (Appendix C), which clearly shows that the CO<sub>2</sub> tax only accounts for 10 % of total incomes. Therefore, it is complex that under the scenarios shown, substantial economic advantages will result from reducing CAC only through CO<sub>2</sub> tax.

Finally, the sensitivity analysis of the CAC under different natural gas prices is shown in Fig. 7. According to the results, the CAC could effectively reach zero if the NG price rises to approximately 165 €/MWh.

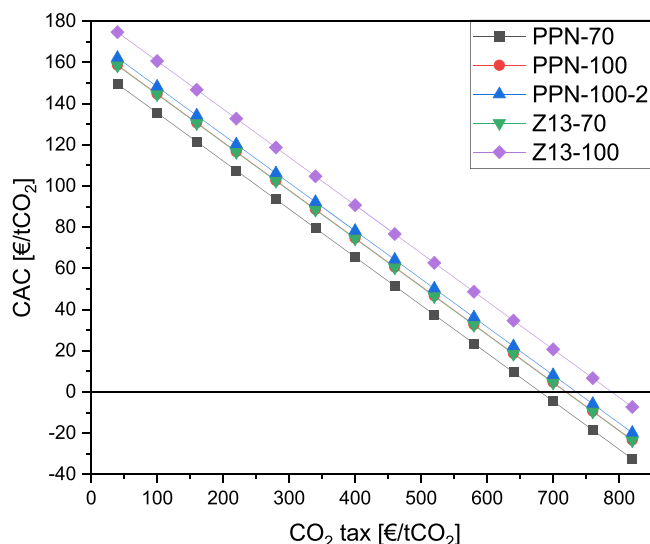


Fig. 6. Carbon abatement cost (CAC) vs CO<sub>2</sub> Tax.

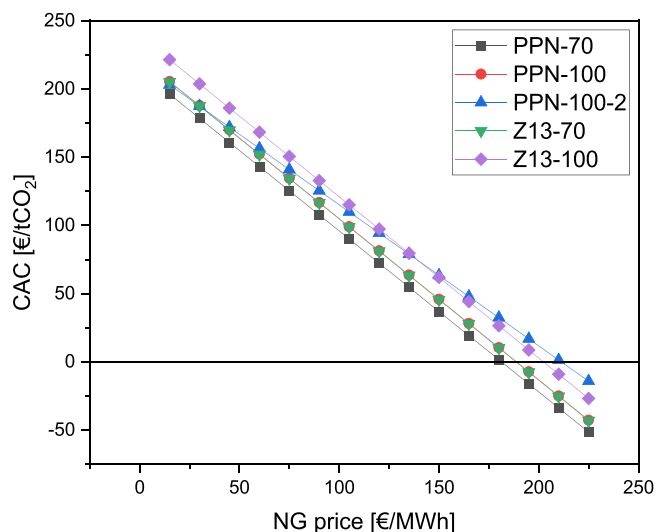


Fig. 7. Carbon abatement cost (CAC) vs NG price.

To reach a CAC similar to those documented in the literature [64], a NG price of 130 €/MWh would be enough. This represents a substantial NG price rise of nearly 270 %, compared to the reference price in December 2024 [54]. These outcomes highlight that high natural gas costs substantially enhance SNG's competitiveness, offering a pathway to carbon neutrality in energy-intensive sectors that currently use NG. However, the price found to achieve carbon neutrality could only be achieved under unsuitable geopolitical circumstances or in the face of a shortage of natural gas reserves.

### 3.3. Payback analysis

Fig. 8 shows the payback period in the analysed case studies. These payback analyses were done under three scenarios: a) vary the NG and electricity price and keep constant the CO<sub>2</sub> tax, b) vary the CO<sub>2</sub> tax and electricity price and keep constant the NG price and c) vary the NG and CO<sub>2</sub> tax and keep constant the electricity price. A similar trend is observed in all the scenarios evaluated, which allows us to identify clear patterns in the relationship between the economic factors considered.

In the first case, by keeping the price of the CO<sub>2</sub> tax constant, a direct correlation is evident between the price of electricity and the cost of natural gas. A payback of at least 20 years is achieved when the electricity price exceeds 5 €/MWh, and if the natural gas price is 90 €/MWh for PPN-70, PPN-100 and Z13-70 cases, and for Z13-100 case, the natural gas price must be 105 €/MWh. Also, it is observed that the payback period, for all cases, is less than 20 years as NG increases its value and the electricity price remains low.

When analysing the combined effect of electricity prices and the CO<sub>2</sub> tax while keeping the cost of natural gas constant, a similar trend to the one observed with natural gas and electricity prices is noted. Specifically, low electricity prices and high CO<sub>2</sub> tax values are required to achieve a payback on the initial investment in under 20 years.

The electricity price was held constant to examine how the payback period changes in response to changes in natural gas and CO<sub>2</sub> taxes. The results indicate that it is possible to get a payback of the initial investment in less than 20 years when NG and CO<sub>2</sub> tax prices are high. This relation highlights that adjustments in one or another can offset variations, provided they remain within a suitable range.

Comparing the PPN cases with Z13 cases, it is evident that PPN achieved a payback (in 20 years) with lower values for CO<sub>2</sub> tax, natural gas and electricity prices than Z13 for both CCRs. In the same way, with PPN-100 compared to PPN-70, a return on investment is achieved with lower costs associated with electricity prices, natural gas and CO<sub>2</sub> tax. This behaviour is because, in the case of PPN-100, the vehicle fleet is

entirely self-sustaining, eliminating the need to purchase additional fuel and thus reducing operating costs.

On the other hand, in cases where the OCCS system operates with Z13, the payback period is more favourable with 70 % CCR compared to 100 % CCR. This behaviour is explained by the ratio between OPEX and incomes that, at 100 % CCR, is 4.6 % higher than 70 % CCR. As mentioned above, this difference is due to the higher power penalty associated with Z13-100 compared to Z13-70. In addition, the low calorific value of the SNG produced in the methanation, caused by the impurities in the captured CO<sub>2</sub>, increases the fuel consumption of the vehicles. Thus, although the OCCS system in the Z13-100 case achieves self-sufficiency in fuel, this saving is not enough to compensate for the initial investment.

### 3.4. Discussion

This study provides a comprehensive techno-economic analysis of integrating OCCS system and methanation in a heavy-duty transport fleet; however, certain limitations should be acknowledged. The analysis assumes static electricity, natural gas, and CO<sub>2</sub> tax prices, while in reality, these values fluctuate due to market and policy changes, affecting economic viability. Additionally, the study does not consider the full life cycle assessment (LCA) of the proposed system, which could provide a broader environmental perspective. The availability and scalability of the selected sorbents, also introduce uncertainties regarding large-scale implementation. Moreover, operational constraints such as space requirements, additional vehicle weight, and potential performance impacts on the fleet have not been deeply explored. Future research should address these factors to refine feasibility assessments and further optimize system performance.

## 4. Conclusions

This research conducts a comprehensive techno-economic analysis of integrating a methanation plant with a heavy-duty vehicle fleet operating with OCCS systems. The study examines the variations in CAPEX, OPEX, incomes, CAC, and payback periods across different scenarios. These scenarios include varying CCR, the kind of sorbent used, and operational adjustments within the methanation plant. The analysis is framed around the CO<sub>2</sub> tax, electricity and NG prices.

As can be seen in the results, the proposal to have a methanation plant operating in a fleet of vehicles with a CO<sub>2</sub> capture and utilization system to produce methane and thus be self-sufficient is not yet economically viable, due to the high cost of electricity and since this sector does not have to pay a CO<sub>2</sub> emission tax. However, with the implementation of the CO<sub>2</sub> tax planned for 2027, these types of applications would become more attractive. With a specific CAC of approximately 160 €/MWh and 100 % CCR the system is profitable, and the initial investment can be amortized in a reasonable period.

The results indicate that reducing the H<sub>2</sub>:CO<sub>2</sub> ratio to 3.5 in the methanation plant does not yield significant benefits in the techno-economic analysis. While this adjustment leads to lower electricity consumption and, consequently, a reduction in CAPEX, it also produces low-quality SNG. This poor-quality SNG increases fuel consumption and harms OPEX.

Although there is a techno-economic difference depending on the type of sorbent used, this variation in the main study variables is relatively small: around 3 % when operating at 70 % CCR and 6.5 % at 100 % CCR in favour of PPN. However, PPN sorbent, despite its remarkable performance and certain technical advantages, such as the ability to operate with a small amount of water in exhaust gases, faces notable limitations in manufacturing and availability. Based on this and the small gap found in the techno-economic analyses between sorbents, Z13 can not be discarded entirely since it is a widely marketed and accessible sorbent.

Future research endeavours should focus on incorporating freight

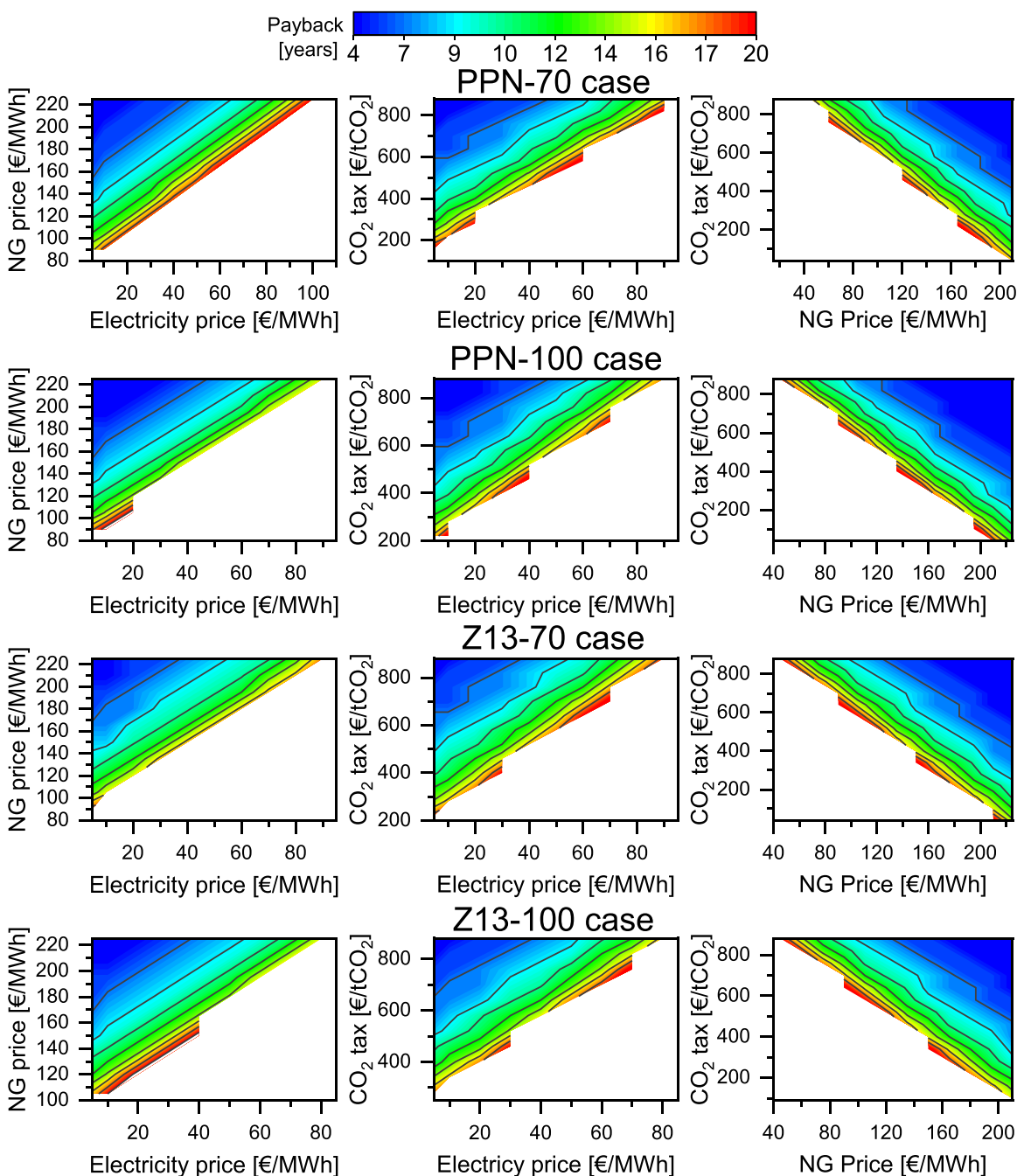


Fig. 8. Payback analyses under key performance indicators.

costs into incomes in more detail. This inclusion would allow for more representative results in techno-economic studies, and it might even make them more promising by more accurately reflecting real economic dynamics. Additionally, considering freight costs would make it possible to draw a direct correlation between these parameters and other important variables, like the CO<sub>2</sub> tax and electricity price. This method would make it easier to create all-encompassing plans that maximize the system’s techno-economic performance while considering the investments and incomes related to operation in the transport sector in various market and regulatory contexts.

This research paper presents an innovative proposal for integrating CO<sub>2</sub> capture and utilization in the heavy-duty transport sector, with the aim of covering the knowledge gap on this topic. Such efforts are crucial for achieving the ambitious CO<sub>2</sub> reduction targets set by the European Union for 2050, fostering progress toward a more sustainable and

decarbonized economy.

**CRedit authorship contribution statement**

**García Mariaca Alexander:** Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Conceptualization, Supervision. **Perpiñan Jorge:** Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Carreño Uriel:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing.

**Declaration of Competing Interest**

The authors have declared no conflict of interest.

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**Appendix A. CAPEX**

Case	PPN-70	PPN-100	PPN-100-2	Z13-70	Z13-100
<b>PtG plant TEC [M€]</b>					
Overall Cost	9.008	12.90	11.29	9.029	12.90
SNG compressor	0.123	0.157	0.154	0.132	0.167
CO <sub>2</sub> compressor	0.225	0.286	0.249	0.240	0.304
Reactors	4.455	6.378	5.579	4.465	6.379
Catalyst	0.061	0.088	0.106	0.071	0.102
SNG tank	3.036	4.048	5.060	3.542	4.554
CO <sub>2</sub> tank	0.444	0.740	0.740	0.444	0.740
<b>OCCS system TEC [M€]</b>					
TSA-device	1.24	1.826	1.826	1.370	2.145
ORC-expander	2.32	1.970	1.970	2.344	1.997
ORC-pump	0.09	0.088	0.088	0.090	0.086
ORC-C5H10 tank	0.08	0.077	0.077	0.077	0.077
ORC-Evaporator	1.09	1.017	1.017	1.062	0.966
ORC-heater	0.15	0.165	0.165	0.154	0.167
ORC-condenser	2.13	1.783	1.783	2.147	1.596
FG1	2.40	3.213	3.213	2.306	3.083
FG2	1.34	1.465	1.465	1.347	1.273
Cyclone	0.15	0.213	0.213	0.149	0.213
Fan	0.09	0.086	0.086	0.093	0.089
Condenser	0.30	0.381	0.381	0.311	0.374
Cooling	0.16	0.194	0.194	0.167	0.202
Compressor	3.51	4.658	4.658	4.085	5.090
CO <sub>2</sub> tank	2.12	3.033	3.033	2.125	3.021
<b>DC-PtG [M€]</b>					
Installation	1.74	2.46	2.32	1.79	2.51
Instrumentation & control	0.69	0.98	0.93	0.72	1.01
Piping	2.78	3.94	3.71	2.87	4.02
Electrical	0.87	1.23	1.16	0.90	1.26
Building	0.87	1.23	1.16	0.90	1.26
Land	0.17	0.25	0.23	0.18	0.25
<b>DC-OCCS system [M€]</b>					
Installing	2.75	3.23	3.23	2.85	3.26
Instrumentation	1.72	2.02	2.02	1.78	2.04
Piping	0.51	0.61	0.61	0.53	0.61
Electric installing	0.34	0.40	0.40	0.36	0.41
<b>(ID-PtG) [M€]</b>					
Engineering	1.71	2.43	2.29	1.77	2.48
Legal expenses	0.49	0.69	0.65	0.51	0.71
Construction expenses	0.98	1.39	1.31	1.01	1.42
Contingency	1.71	2.43	2.29	1.77	2.48
<b>ID-OCCS system [M€]</b>					
Engineering	2.78	3.26	3.26	2.88	3.30
Construction expenses	1.59	1.86	1.86	1.65	1.88
Contingency	2.78	3.26	3.26	2.88	3.30

**Appendix B. OPEX**

Case	PPN-70	PPN-100	PPN-100-2	Z13-70	Z13-100
Catalyst renovation	0.01	0.01	0.01	0.01	0.01
Electricity	10.89	15.59	13.64	10.94	15.63
Water	0.03	0.04	0.04	0.03	0.04
Sorbent renovation	0.59	0.70	0.70	0.31	0.35
increasing in the fuel consumption	0.985	3.267	4.521	1.490	4.843
Cyclopentane	0.22	0.16	0.16	0.22	0.16
O&M	1.77	2.29	2.22	1.83	2.33

## Appendix C. Incomes

Case	PPN-70	PPN-100	PPN-100-2	Z13-70	Z13-100
SNG generated [MWh/y]	4.62	6.62	5.79	4.63	6.62
O <sub>2</sub> generated [tO <sub>2</sub> /y]	1.90	2.72	2.38	1.91	2.72
CO <sub>2</sub> tax	0.74	1.06	1.06	0.74	1.06

## Data availability

Data will be made available on request.

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