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Cost projection of combined cycle power plants equipped with post-combustion carbon capture

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This work aims to analyze the cost projection of natural gas combined cycles (NGCC) with post-combustion carbon capture (PCC) technology for two promising power plant configurations, namely: conventional NGCC and exhaust gas recirculation (EGR). A thermo-economic analysis was performed considering the second-law efficiency for the CO_2 separation process (η_{2nd}) and the CO_2 avoided cost (CAC) as main indicators. Several critical variables influencing the overall cost of the plant were considered, such as the work required for solvent regeneration (W_{regen}), technology maturity, learning rate, carbon tax credit, and carbon capture level (85%, 90%, and 95%). A hybrid method combining engineering-economic and experience-curve approaches was used to estimate the costs of Nth-of-a-kind (NOAK) plants. The results showed that NOAK plants could potentially decrease the levelized cost of electricity (LCOE) by 10%–11%, and the CAC by 21%–23%, compared with first-of-a-kind (FOAK) plants. EGR at 85% capture level showed the best economic performance among the study cases evaluated, with a CAC equal to \$102.5/tCO_2. At an 85% capture level, the CAC for the conventional NOAK NGCC plant is \$104.1/tCO_2; maintaining this same CAC value, the carbon capture rate could increase from 85% to 90.8% if EGR configuration is implemented. Finally, from the findings of this research, it is concluded that the CAC for NOAK plants is expected to be, in the best scenario, as low as \$69/tCO_2. Therefore, these plants might need at least a similar carbon tax value to ensure their operation during their useful life.

KEYWORDS

post-combustion, natural gas combined cycle, cost projection, learning rate, experience curves, second-law efficiency, NOAK plants, carbon tax

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Introduction

Mexico's greenhouse gas (GHG) emissions from the electricity sector were 126.6 $MtCO_{2eq}$, corresponding to 19.0% of total national emissions (INECC, 2015). This is due to the fact that around 80% of the Mexico's electricity generation comes from fossil fuels (SENER, 2018a), with NGCC plants accounting for the largest proportion (~50%) and they are expected to increase their participation in the long term (SENER, 2019; SENER, 2021). Therefore, technologies to reduce GHG emissions, especially CO_2, from current and future NGCCs are of great interest to the country.

Carbon capture and storage (CCS) is a key technological tool for CO_2 abatement in NGCC plants. One of the most promising CCS technologies is post-combustion carbon capture (PCC), which consists of separating the CO_2 contained in flue gases from the stack through a chemical process with absorption-desorption cycles using an amine-based solvent as carbon captor material. In general, PCC technology is preferred over other CCS technologies (e.g., pre-combustion and oxy-fuel combustion) mainly because it can be coupled to new and existing plants with minor modifications (Figueroa et al., 2008; Freeman and Bhown, 2011; Sanchez Fernandez et al., 2014; Pan et al., 2016) and its higher technology maturity level (Wilcox, 2012; Oh et al., 2018; Feron et al., 2019; Finney et al., 2019).

Another alternative for CO_2 mitigation in NGCC plants is the use of blending of natural gas with blue hydrogen (bH_2) or green hydrogen (gH_2). Especially, gH_2 makes sense in the Mexican context, as there are vast renewable energy and water resources available. The Federal Comission of Electricity, a state-owned utility company, has realized this local advantage and, in early 2022, announced the implementation of a pilot project for the use of blending of natural gas with gH_2 in a gas turbine (CFE, 2022). The purpose of this is to generate knowledge about the challenges and opportunities of using gH_2 in electricity generation and, based on the results, to advance towards commercial scale-up.

Due to the relevant role that CCS and hydrogen could play in the decarbonization of the Mexican electricity sector in the long term, Díaz-Herrera et al. (2021) reported the comparison between PCC technology and the use of bH_2 and gH_2 in existing NGCCs. The techno-economic analysis considers fuel costs, capital expenditure, operating cost, and the plant capacity factor. The results show that the NGCC equipped with PCC (NGCC + PCC) is a much more economical alternative to reduce CO_2 emissions ($140.4/$tCO_2$) than the use of blendings of bH_2 ($256.9/$tCO_2$) and gH_2 ($435.8/tCO_2). Although PCC technology is an excellent alternative to mitigate CO_2 emissions in NGCC plants, its high cost is the critical barrier to its commercial-scale deployment (Wilcox, 2012; DOE/NETL, 2010; Rubin et al., 2015; Irlam, 2017; Muhammad et al., 2020; Liu, 2020).

One strategy that several countries have adopted to promote the early deployment of carbon capture technologies in industrial processes that are difficult to decarbonize, such as an NGCC, is the application of a carbon tax (Shirmohammadi et al., 2020). For example, in 1991 Norway was one of the first countries in the world to introduce a carbon tax to reduce emissions from upstream oil and gas operations. This initiative prompted the development of the Sleipner project in 1996, the first large-scale carbon capture and storage (CCS) project in the world (Equinor, 2019). If we look into the North American region, in 2008, the United States implemented a carbon tax credit called 45Q, which provided $10/$tCO_2$ stored *via* enhanced oil recovery (EOR) and $20/$tCO_2$ stored in geologic formations (GCCSI, 2020). Later, in 2018, the 45Q tax credit was reformed as part of the Bipartisan Budget Act, increasing its value to $35/$tCO_2$ for EOR projects and $50/$tCO_2$ for geological storage (Jones and Sherlock, 2021). Recently, in 2022, the US Inflation Reduction Act has increased the value of the 45Q tax credit to $60/$tCO_2$ for EOR purposes and $85/$tCO_2$ for geological purposes (Bipartisan Policy Center, 2022). Canada introduced an investment tax credit for CCS deployment of $319 million over 7 years from 2021 (Government of Canada, 2021). So far, Mexico still does not have a solid regulatory framework for the financing of CCS projects; however, the recent United States-Mexico-Canada Agreement is expected to be a driver for the insertion and development of the first CCS projects in the country.

Assuming that Mexico acquires the same level of commitment in the fight against climate change as its partners in the short term and, considering that the CAC for a NGCC + PCC plant in the local context is $140.4/$tCO_2$, this value is 1.7 times higher than the 45Q tax credit for geological storage. Therefore, a substantial increase in the tax credit would have to be necessary to implement the first commercial project in the country. This could lead to a significant increase in electricity costs, which would impact the economy of the population. Nevertheless, a positive approach to the fact that PCC technology is still in the research and development phase is that it can reduce its costs through the learning-by-doing effect, so it could be successfully developed in the next few years.

As with other types of technology, it is expected that the first generation of NGCC plants using PCC technology (FOAK plants) can be significantly more costly than later or advanced generations, which are referred to as NOAK plants. This has a favorable economic impact on the technology since the carbon tax could be very high in the early years for FOAK plants and progressively decrease until NOAK plants are economically competitive in the market on their own. A clear example of this was what happened with renewable energy in Mexico. In 2014, the Mexican government implemented clean energy certificates (CECs), a legal instrument promoting investment and development of solar and wind FOAK plants on a commercial scale (DOF, 2014). The CECs were gradually reduced until their cancellation in 2022, once renewable energies reduced their costs to the point of being economically competitive (Forbes, 2022). A very interesting aspect to analyze is the extent to which NOAK plants could reduce their costs or whether they will need to be permanently subsidized to ensure their operation during their useful life. Therefore, the cost projection of the NOAK plants is a key element since it could support the planning of the portfolio of strategies for the energy transition not only in Mexico, but also in other countries that depend on natural gas for their electricity generation (e.g., Japan, the United States, and Canada).

Very few research publications focused on cost projection for FOAK and NOAK NGCC plants equipped with PCC are available in the literature. One of them was published by Rubin et al. (2007), who performed a sensitivity analysis varying different technic-economic parameters for estimating NOAK NGCC power plants equipped with CO_2 capture systems. In the case of NGCC + PCC plants, the results show that LCOE of a NOAK plant could be between 12% and 20.4% cheaper compared to a FOAK one. Additionally, (Irlam, 2017) reported the costs of NOAK plants for different industries (power, cement, iron, and steel). In the case of NGCCs, they conclude that the CAC for a FOAK and NOAK plant is \$89 and \$43/tCO_2, respectively. This represents a cost reduction equal to 51.7%. Although both studies explain in-depth the economic assumptions that were considered to arrive at these results, they did not consider the fact that technology costs could also be constrained by thermodynamic principles. This is especially important to analyze, as the PCC plant currently demands a lot of energy for its operation, technological improvements will make it more and more efficient, which in turn will increase its economic performance, here a key question arises: to what extent can the NOAK NGCC + PCC plant be really efficient?

A key indicator to respond the above question is the second-law efficiency for the CO_2 separation process (η_{2nd}), since it allows us to know the thermodynamic limits of the PCC technology and to recognize which sub-processes present the best areas of opportunity for energy savings (Wilcox, 2012). Sanchez Fernandez et al. (2014) reported that the net efficiencies of conventional NGCC and coal-fired power plants with PCC are reduced by 8.4% and 11.7% points, respectively. In the case of NGCC + PCC plants, Bolland and Undrum (2003) mentioned that the work required for solvent regeneration (W_{regen}) represents the highest energy penalty, with a loss of 4.5% points in the power plant efficiency, while the penalty associated with the use of mechanical power and CO_2 compression is 1.8% and 2% points, respectively. In addition, W_{regen} has a much lower technological maturity than the mechanical power and CO_2 compression processes, which means, in theory, a larger energy-saving opportunity window. Therefore, several studies have focused on innovative energy-saving pathways.

Oh et al. (2018) focused on heat integration and the design process for the energy penalty reduction in a coal-fired power plant integrated with an amine-based PCC plant. Simulation results show that the net efficiency of the plant is reduced by 9.7% points (3.1% points less than the conventional PCC technology). Saleh et al. (2019) proposed a novel conceptual NGCC configuration integrated with a lithium-based PCC technology, which shows a reduction in its net efficiency equal to 9.2% points, being this value close to the energy penalty of the amine-based PCC technology published elsewhere (Sanchez Fernandez et al., 2014; Díaz-Herrera et al., 2021). Other studies reported the use of thermal solar energy to compensate for the energy penalty of the PCC plant (Li et al., 2012; Lambert et al., 2014; Wang et al., 2015; Liu et al., 2017; Shirmohammadi et al., 2021). A very interesting study on this subject is the one published by Zhai and co-workers (Zhai et al., 2018), who mentioned that a coal-fired power plant with a solar-assisted PCC plant shows a higher LCOE than the conventional PCC technology, mainly because of the increase in the CAPEX associated with the solar farm. Other authors evaluated the energy performance of novel power plant configurations; for example, Lindqvist et al. (2014) notified that an NGCC + EGR has a lower energy penalty than the conventional NGCC plant (7.6% vs. 8.7% points), mainly because its higher CO_2 concentration in the flue gas.

Capture level is another strategy to reduce the energy penalty of the power plant and reduce the CAPEX of the PCC (Hildebrand and Herzog, 2009; Wilcox et al., 2017; Feron et al., 2019). This consists of capturing an amount of CO_2 at lower rates or partially capturing it to reduce the cost. Several studies focus on the technical and economic implications of the use of the capture level in the PCC plant; one of these is published by Wilcox et al. (2017), who mentioned that there is a direct relationship between the carbon capture level and the minimum thermodynamic work for the CO_2 separation (W_{min}). Normann et al. (2017) presented a techno-economic analysis of the capture level of a PCC plant considering key design parameters, such as gas flow, load hours, and CO_2 concentration. For a capture level of 22.5%, the CAC is 80 €/tCO_2, representing an 11.1% cost reduction compared to the 90% capture level. Díaz-Herrera et al. (2020) performed an economic analysis of the capture level design for an NGCC + PCC plant using novel configurations. At 90% capture, the CAC for conventional NGCC + PCC is 117.7 \$/tCO_2. This cost could be reduced by around 3% if the EGR configuration is implemented. Despite these savings, the CAC is still high, mainly due to the CAPEX associated with the PCC plant.

As can be seen, there is a lot of information in the literature focused on reducing the energy penalty of the PCC plant, as well as its capital cost; nevertheless, very few papers paying attention to the effect of the W_{regen} on the η_{2nd} have been published. Also, to the authors' knowledge, no work has been reported on the combination of the η_{2nd} with CAC applied to NGCC plants. The relationship between these two indicators is key because they

TABLE 1 Study cases assessed in this work.

Cases	Technology	Type of plant	Capture level (%)
NF_85%	NGCC	FOAK	85
NF_90%	NGCC	FOAK	90
NF_95%	NGCC	FOAK	95
NN_85%	NGCC	NOAK	85
NN_90%	NGCC	NOAK	90
NN_95%	NGCC	NOAK	95
EF_85%	EGR	FOAK	85
EF_90%	EGR	FOAK	90
EF_95%	EGR	FOAK	95
EN_85%	EGR	NOAK	85
EN_90%	EGR	NOAK	90
EN_95%	EGR	NOAK	95

allow estimating costs for NOAK plants based upon scientific limits. This is mainly important for Mexican decision makers, since knowing information about cost scenarios for NOAK plants would allow them to design appropriate public policies on energy and climate change.

This study aims to analyze the cost projection of FOAK and NOAK type plants for two promising NGCC configurations, namely: conventional NGCC and EGR. A thermo-economic analysis was performed considering the η_{2nd} and CAC as main indicators. Several essential variables influencing the overall cost of the technology were considered, such as W_{regen}, technology maturity, learning rate, carbon tax credit, and carbon capture level. Most of the related work published in the literature has considered these variables separately. Our contribution is the first attempt to establish and carry out an integral effort to consider the different inputs reported by other authors to project the cost of carbon mitigation in NGCCs taking into account the thermodynamic constraints of the PCC technology.

The work is organized as follows. First, the methodology is described. Then, the results are presented and discussed. Finally, a conclusion is reached.

Methodology

Study cases

Twelve study cases were evaluated in this work: Conventional NGCC (NGCC) and NGCC with exhaust gas recirculation (EGR), considering two technological maturity statuses, FOAK and NOAK plants, at different carbon capture levels (see Table 1). A thermo-economic analysis was performed considering the η_{2nd} and CAC as main indicators. For this purpose, the results reported in a previous study published by the authors were used (Díaz-Herrera et al., 2020) (see Supplementary Tables S1, S2).

A brief description of the configuration and operation of the conventional NGCC and EGR power plants is given below:

1. Conventional NGCC. The configuration includes two gas turbine trains in parallel, with a heat recovery steam generator (HRSG) for each gas turbine, and one steam turbine for both HRSG, as shown in Figure 1. The steam produced in the HRSGs goes to the steam turbine to generate power. Three levels of steam are generated in the HRSG: high, intermediate, and low steam pressures.
2. Exhaust Gas Recirculation (EGR) is presented in Figure 2. This alternative has the same configuration as the conventional NGCC case, but with a cooler and a liquid-vapor separator incorporated in each train to cool and remove water from the flue gas recirculated to the gas turbine. The exhaust gas is recirculated at a rate of 35% and subsequently cooled at 40°C before being fed to the compressor (Li et al., 2011; Vaccarelli et al., 2014).

In both power plant configurations, low-pressure steam is extracted and sent out to the capture plant reboiler to cover the thermal energy demand for solvent regeneration. At the same time, the power plant supplies the electrical demand of process equipment (e.g., pumps, fans, compressors, among others).

Method to calculate the η_{2nd} for the CO_2 separation process

The second-law efficiency (η_{2nd}) for the CO_2 separation process can be expressed as follows (Wilcox, 2012; Wilcox et al., 2017):

$$\eta_{2nd} = \frac{W_{min}}{W_{real}} \tag{1}$$

where W_{min} is the minimum thermodynamic work calculated for the CO_2 separation and the W_{real} is the actual work for the same process, both expressed in kJ/mol of CO_2 captured. W_{min} was calculated by combining the first and second laws of thermodynamics (Wilcox et al., 2017):

$$\begin{aligned} W_{min} = RT\Big[&\left(n_{r,CO_2} \ln X_{r,CO_2} + n_r \ln X_r\right) \\ &+\left(n_{p,CO_2} \ln X_{p,CO_2} + n_p \ln X_p\right) \\ &-\left(n_{i,CO_2} \ln X_{i,CO_2} + n_i \ln X_i\right)\Big] \end{aligned} \tag{2}$$

where n_{x,CO_2} and n_x represent the number of moles of CO_2 and non-CO_2 components in stream x, respectively; likewise, X_{x,CO_2} and X_x represent the mole fractions of CO_2 and non-CO_2 components in stream x, respectively, while, the real work required for the CO_2 separation can be expressed as follows (Wilcox, 2012):

$$W_{real} = W_{fan} + W_{pump} + W_{regen} \tag{3}$$

where W_{fan}, W_{pump}, and W_{regen} are electrical penalties associated with fan, solvent pumping, and solvent

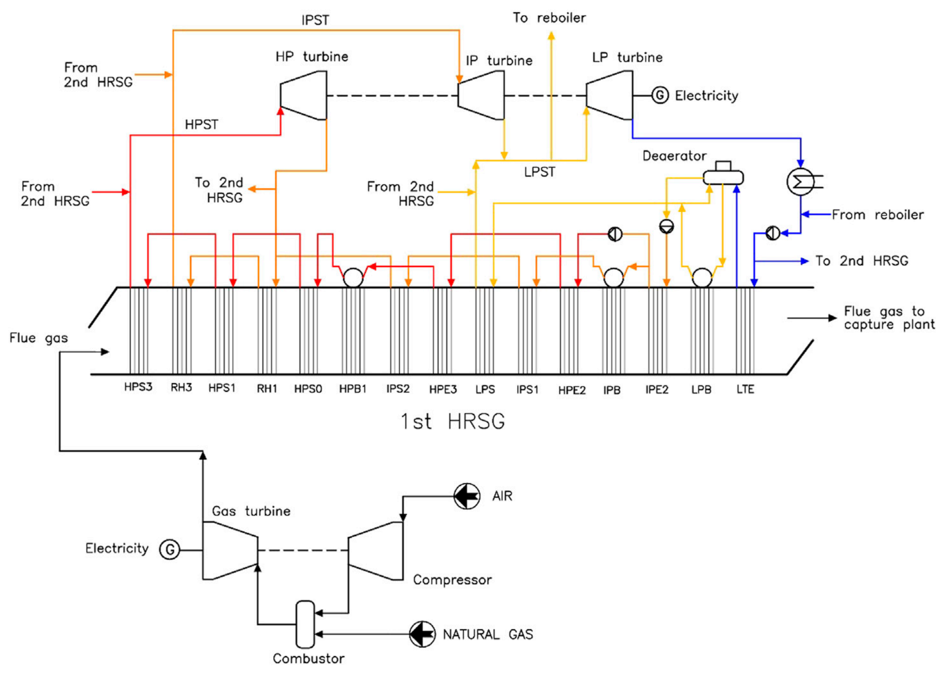

FIGURE 1
Conventional case: Natural gas combined cycle. Extracted from (Díaz-Herrera et al., 2020).

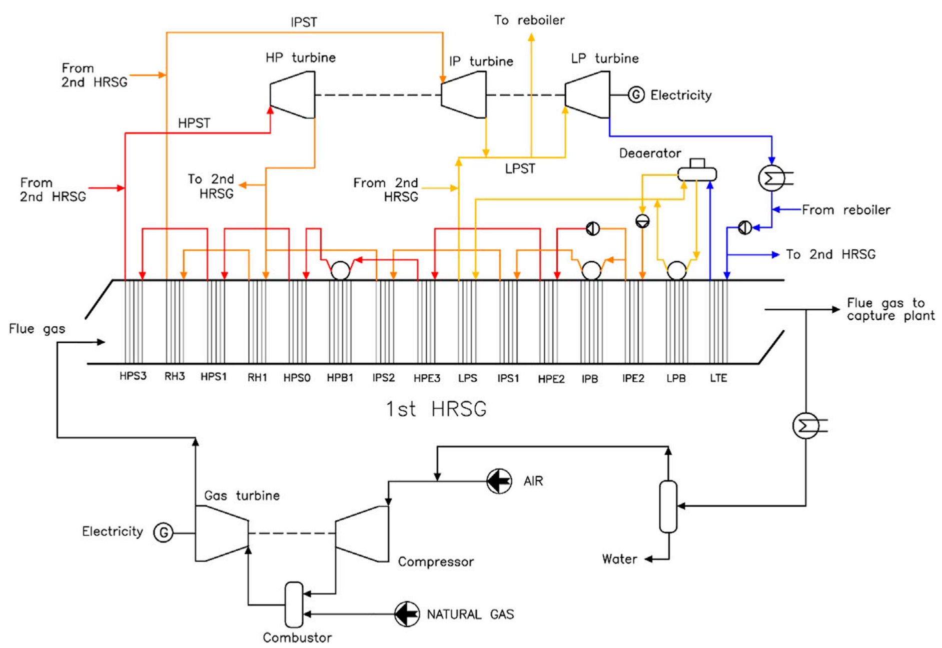

FIGURE 2
Exhaust Gas Recirculation combined cycle. Extracted from (Díaz-Herrera et al., 2020).

TABLE 2 Learning rates (LR) used for each major technology sub-section.

Major technology sub-sections	LR (%)	References
Power plant package		
Gas turbine	1	NETL (2014)
Steam turbine	1	NETL (2014)
HRSG	1	NETL (2014)
EGR gas turbine	4	NETL (2014)
PCC package		
Absorber	11	Rubin et al. (2007)
Stripper	11	Rubin et al. (2007)
CO_2 compression package		
Compressors	0	IEAGHG (2006)
Intercooling system	0	IEAGHG (2006)

regeneration, respectively. It is worth mentioning that the electricity consumption for compression is not included, since this is not considered in the minimum work for the CO_2 separation.

On the other hand, the effect of the W_{regen} on the efficiency of the CO_2 capture process was assessed in this study. Based on a previous simulation template built-in Thermoflex™ (Díaz-Herrera et al., 2020), the mass flow of steam extracted from the NGCC to the reboiler varied from 100% (business-as-usual, BAU value) to 0% (thermodynamics limit), by steps of 10%. W_{fan} and W_{pump} were not assessed because their contribution to the W_{real} is much lower than the solvent regeneration process (Wilcox, 2012; Lindqvist et al., 2014; Liu, 2020). In addition, blowing and pumping have a much higher technological maturity than the solvent regeneration process, which means a higher energy efficiency; therefore, W_{fan} and W_{pump} show a lower energy-saving opportunity in the PCC plant compared to W_{regen}.

Capital cost projection for a nth-of-a-kind plant

The method selected to calculate the CAPEX for a NOAK NGCC-CCS plant is based on Ref. (Roussanaly et al., 2021), which consists of a hybrid method combining the engineering-economic and the experience curve approaches.

First, the overall plant is decomposed into major technology sub-sections and the capital cost estimation for each one is calculated. For each case, the total CAPEX of all sub-sections corresponds to a FOAK plant. Then, appropriate learning rates (LR) are selected for each major technology sub-section. Table 2 shows the learning rates used for each sub-section. As learning rates are related to technology maturity, each sub-section has different values. For well-known technologies, learning rates are very low (1% ≤), e.g., conventional gas turbine, steam turbine, and HRSG. In contrast, processes with low technological maturity show a higher learning rate, e.g., PCC technology and advanced combustion turbines (EGR gas turbines). It is worth mentioning that there are no measured learning rates for PCC amine-based systems for CO_2 capture yet, as only a few plants have been built so far. Thus, learning rates for flue gas desulfurization (FGD) systems were used as a proxy for PCC technology (LR = 11%).

After the CAPEX and the learning rate of each technology sub-section were estimated, the starting and end points of the experience curves were set. Applying an experience curve using the hybrid method requires assumptions for when cost reductions begin and how long will they continue at the specified learning rate. The guidelines for such assumptions depend on the current maturity of each technology sub-section. For pre-commercial technologies, e.g., PCC plant and EGR gas turbine, the size of the power plant represents the starting point (initial capacity = 800 MW). In contrast, the end point of the cost curve (the point at which the technology can be labeled as mature) can be proxy equal to 20 replications of its initial capacity (Roussanaly et al., 2021). Therefore, in this work, it is assumed that the starting and end points, both for the EGR gas turbine and the PCC plant, are equal to 800 and 16,000 MW, respectively (800 MW * 20 = 16,000 MW). For the commercial technologies sub-sections, we assume the following starting points based on its estimated current capacity (MW) (IEAGHG, 2006): 10,000 MW for CO_2 compression; and 240,000 MW for gas turbine, steam turbine, and HRSG; while the end point for each one is estimated adding the end point capacity of the pre-commercial technology component to its estimated current capacity (e.g., gas turbine = 240 GW + 16 GW = 256 GW).

Once all sub-section learning rates and starting/end points for experience curves were specified, Eqs 4, 5 were used to project the future CAPEX for a NOAK plant ($/kW) (Bui et al., 2018):

$$b_n = \frac{-log\ (1 - LR_n)}{log\ (2)} \tag{4}$$

$$CAPEX = \sum_{i=1}^{n} a_n x^{b_n} \tag{5}$$

where n is a specified technology sub-section; b_n is the learning curve exponent for technology sub-section n; LR_n is the learning rate for the technology sub-section n; a_n is the CAPEX per unit for the FOAK plant for technology sub-section n ($/kW); x is the ratio of cumulative to initial capacity of the technology sub-section n. Supplementary Table S3 provides detailed information on the calculation method used to estimate the CAPEX for NOAK plants.

Economic indicators

The economic indicators used in this study were the LCOE and the CAC, both reported in 2022 constant-dollar. The LCOE was calculated using Eqs 6, 7 (Rubin et al., 2015):

$$\mathrm{LCOE} = \frac{\mathrm{CAPEX} \times \mathrm{FCF} + \mathrm{FOM}}{\mathrm{MW} \times \mathrm{CF} \times 8760} + \mathrm{VOM} + \mathrm{HR} \times \mathrm{FC} + \mathrm{TCO_2} + \mathrm{SCO_2} \tag{6}$$

$$\mathrm{FCF} = \frac{\mathrm{r} \times (1+\mathrm{r})^{\mathrm{T}}}{(1+\mathrm{r})^{\mathrm{T}} - 1} \tag{7}$$

where the LCOE is in units of \$/MWh; FCF is the fixed charge factor (dimensionless); CAPEX is the capital expenditure (\$); FOM is the annual fixed O&M costs (\$/year); MW is the net power output (MW); CF is the plant capacity factor (%); VOM is the variable O&M costs (\$/MWh); FC is the fuel cost per unit of energy (\$/MJ); HR is the net power heat rate (MJ/MWh); TCO_2 is the CO_2 transport cost (\$/MWh), SCO_2 is the CO_2 storage cost (\$/MWh); r = interest rate (%); and T is the economic life of the plant (years).

The CAC is an indicator that compares a power plant with a carbon mitigation technology to a "reference plant" without CO_2 reduction technology and quantifies the average cost of avoiding a unit of atmospheric CO_2 emissions per MWh (Metz B et al., 2005). For all cases, the CAC is calculated using Eq. 8. For this work, conventional NGCC without capture (base case) is the reference plant.

$$\mathrm{CAC}\ (\$/\mathrm{tCO_2}) = \left[\frac{(\mathrm{LCOE})_{\text{with capture}} - (\mathrm{LCOE})_{\text{without capture}}}{\left[\frac{\mathrm{tCO_2}}{\mathrm{MWh}}\right]_{\text{ref}} - \left[\frac{\mathrm{tCO_2}}{\mathrm{MWh}}\right]_{\text{with capture}}}\right] \tag{8}$$

The main assumptions for the economic analysis are shown below:

- The baseline fuel cost (FC) for this analysis is \$5.8 per million British thermal units (\$/MMBtu) based on historical data from Ref. (EIA, 2020; Natural Gas Prices, 2020) (see Supplementary Figure S1).
- For all cases, the CAPEX, FOM, VOM, and, TCO_2 are obtained based on a previous work (Díaz-Herrera et al., 2020). The CAPEX and TCO_2 were updated from 2017 to 2022 using the Chemical Engineering Plant Cost Index (CEPCI) (ToweringSkills, 2022). While, for the FOM and VOM, we escalated costs from 2017 to current 2022 dollars according to the Mexican Producer Price Index (PPI) normalized to 60 in the year 2008 (INEGI, 2022).
- The SCO_2 assumed in this work is \$8.1/tCO_2 (updated from €2010 4/tCO_2 (IEAGHG, 2011) using the CEPCI).
- The economic life of the plant was assumed to be 30 years (SENER, 2018a; SENER, 2018b) with a capacity factor (CF) equal to 85%.
- For NOAK plants, the learning rate was only applied to CAPEX. The projection costs of FOM, VOM, and TCO_2 are assumed to be fixed over time because the learning rates for O&M in CCS projects show a very low effect on the overall capture cost (Roussanaly et al., 2021).
- The present work is limited to assessing the CO_2 capture and geological storage cost in NGCC plants. The CO_2 industrial utilization for commercial purposes (e.g., EOR, synthetic fuel production, beverages carbonation, etc.) is out of the scope of this paper.

Results and discussions

Table 3 shows the η_{2nd} values for NGCC and EGR configuration at different capture levels. For each case, η_{2nd} increases as a function of the carbon capture level. The η_{2nd} ranges from 14.2% to 15.2% and 13.3%–14.2% for NGCC and EGR cases, respectively. This result is in good agreement with those published in the literature (Bolland and Undrum, 2003; Lindqvist et al., 2014; Liu et al., 2017). The increments on η_{2nd} are because the W_{real} required for the CO_2 separation is reduced as a function of the capture level. Additionally, at a specific capture rate, we can see that EGR shows a lower W_{fan} values than NGCC. This is because of the lower amount of flue gases to be treated in the PCC plant. Meanwhile, W_{regen} and W_{pump} presents similar values for both cases, which is due to optimization work done for sizing the absorber and stripper columns (Díaz-Herrera et al., 2020), which results in similar values in the reboiler duty and power consumption for solvent pumping, respectively. For example, the reboiler duty for NGCC and EGR cases is 3.76 and 3.74 MJ per kg of CO_2 desorbed, respectively. Since W_{regen} does not significantly change for both cases and contributes to most of the energy consumption required for the CO_2 separation process (~83%–88% of W_{real}), the η_{2nd} does not show significant variations.

Figures 3, 4 show the CAPEX for conventional NGCC and EGR power plants with PCC technology classified by type of plant at different carbon capture levels, respectively. As expected, the PCC package is the technology with the highest cost reduction, with a total CAPEX reduction of around 40% for a NOAK compared to the FOAK plant. While, for the power plant and CO_2 compression packages, the CAPEX reduction is marginal. This is because the PCC's learning technology rate is higher compared to the power plant and the CO_2 compression system (see Table 2). For FOAK plants, PCC shows, in general terms, a higher cost than the power plant package. However, it is estimated that the cost of the PCC plant could decrease in the future (NOAK plants), even making it potentially cheaper than the power plant package (see more details in Supplementary Table S4).

TABLE 3 Second-law efficiency values for NGCC and EGR configuration at different capture levels (%).

Work required for PCC plant	Units	Conventional NGCC			EGR		
		85%	90%	95%	85%	90%	95%
W_{fan}	kJ/mol	9.9	9.4	8.9	6.4	6.0	5.7
W_{pump}	kJ/mol	0.5	0.5	0.5	0.5	0.5	0.5
W_{regen}	kJ/mol	49.7	49.7	49.7	49.4	49.5	49.3
W_{real}	kJ/mol	60.2	59.6	59.1	56.4	56.0	55.6
W_{min}	kJ/mol	8.6	8.7	9.0	7.5	7.7	7.9
η_{2nd}	%	14.2	14.7	15.2	13.3	13.7	14.2

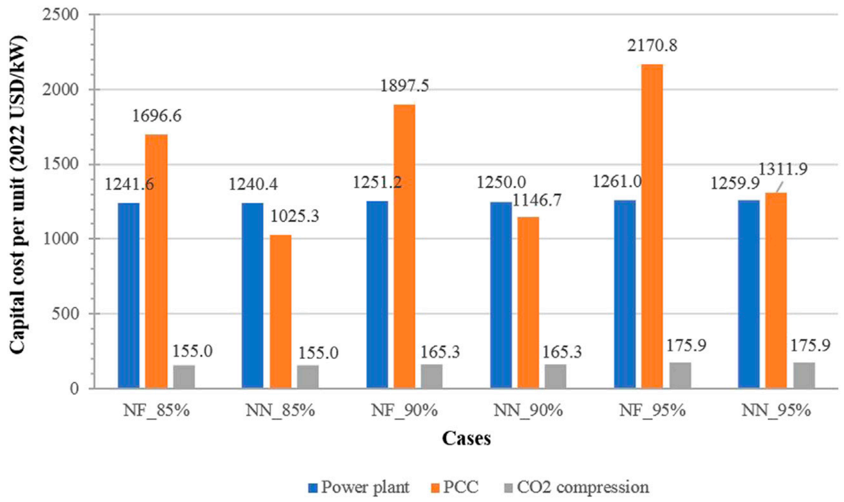

FIGURE 3
Capital cost for conventional NGCC power plant with PCC technology by type of plant (FOAK and NOAK) at different capture levels.

The CAPEX reduction in the PCC technology has a significant effect on LCOE. From Figure 5, we can see that CAPEX is one of the most crucial component cost. The estimated CAPEX reduction for a NOAK plant (mainly due to PCC technology) could potentially decrease the LCOE by 10%–11% in comparison with the FOAK plant type. For example, a NOAK NGCC plant with a 90% carbon capture level (NN-90%) has an LCOE equal to $92.5/MWh, which is 10.4% lower than a FOAK plant type (NF-90% = $103.1/MWh). This percentage of the reduction in the LCOE is in good agreement with the results published by Rubin et al. (Rubin et al., 2007).

On the other hand, Figures 6, 7 show the effect of the W_{regen} on the overall efficiency of the CO_2 capture process (η_{2nd}) and CAC for conventional NGCC and EGR cases, respectively. For each curve, the initial point represents the BAU value for solvent regeneration (100% typical or traditional energy consumption), and consequent points represent steps of 10% decrement in the reboiler energy requirements, until reaching 0% (theoretical value). Considering that η_{2nd} typically ranges from 5% to 40% for real-world separation processes (House et al., 2011), the block in yellow represents the probable future cost scenario for each case. In general, it can be seen that lower values of the W_{regen} represent lower CAC values and a higher percentage of the efficiency of the CO_2 capture process (η_{2nd}). For example, in the NF-90% case, the effect of reducing the percentage of the steam consumption in the reboiler from

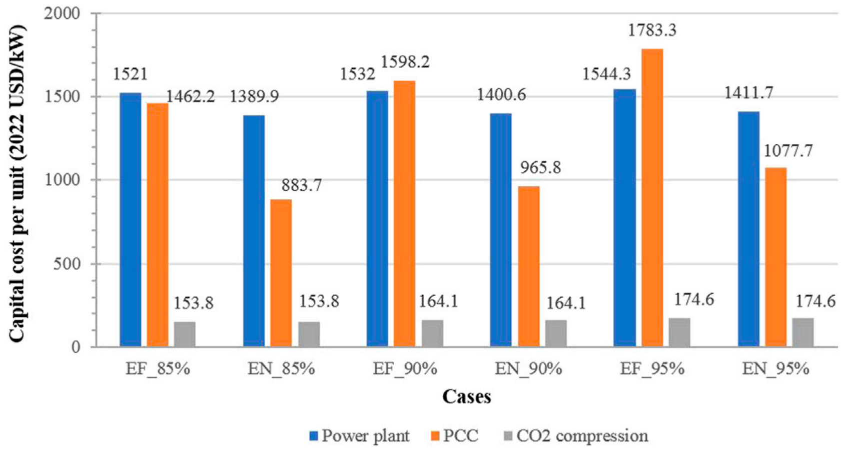

FIGURE 4
Capital cost for EGR power plant with PCC technology by type of plant (FOAK and NOAK) at different capture levels.

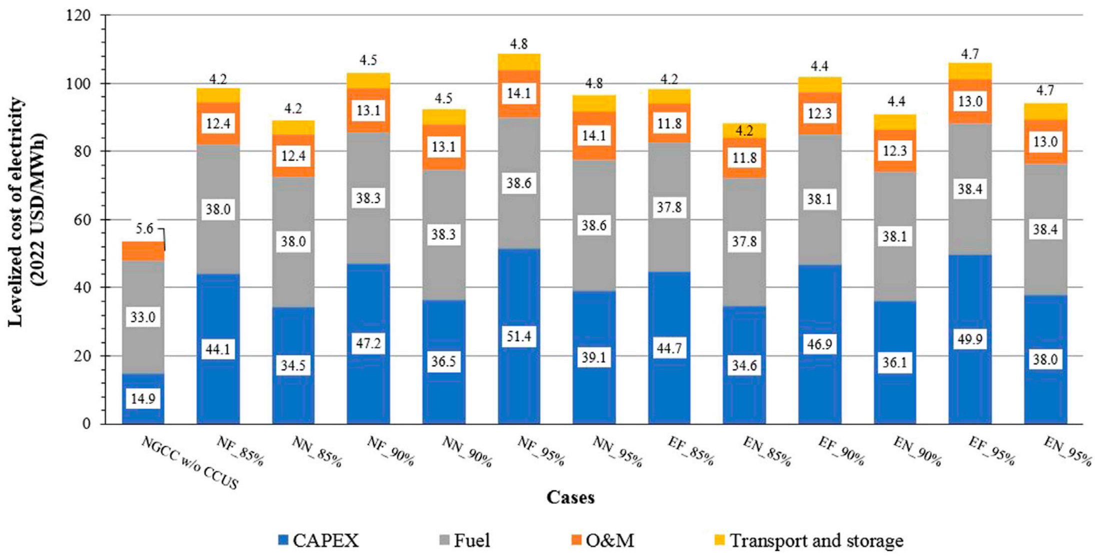

FIGURE 5
LCOE for NGCC and EGR power plants with PCC technology by type of plant at different capture levels.

100% to 0%, reduces the CAC from \$169.0 to \$132.9/tCO_2 (21.4% cost reduction), while the η_{2nd} increases from 14.7% to 88.0% (see Supplementary Table S5 in the Supplementary Information section). Nevertheless, 0% of steam consumption is thermodynamically impossible; thus, this value represents the theoretical CAC value for a FOAK NGCC power plant at a 90% capture level. For EGR cases, note that η_{2nd} reaches values higher than 100%. This is because the W_{min} has a higher value than the sum of W_{fan} and W_{pump} (see Table 3). Unfortunately, this is not possible, as the theoretical value is limited to a η_{2nd} equal to 100%, resulting in CAC values between \$128.9 and \$134.0/tCO_2 for FOAK EGR plants.

In addition, we can observe significant changes in the CAC value between FOAK and NOAK plants. For example, for a conventional NGCC plant with a 90% carbon capture rate (NF-90%), the BAU value for a FOAK plant is \$169.0/tCO_2 compared to the \$132.4/tCO_2 for a NOAK plant (NN-90%), which represents a cost reduction equal of 21.6% (see Supplementary Table S5 in the Supplementary Information

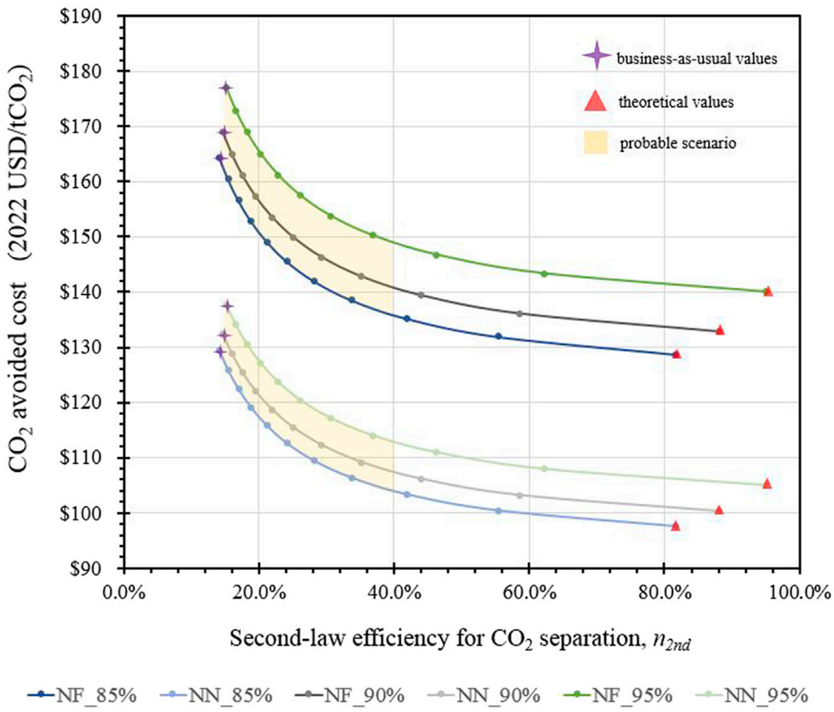

FIGURE 6
Effect of the W_{regen} on the η_{2nd} and CAC for conventional NGCC power plant with PCC by type of plant (FOAK and NOAK) at different capture levels.

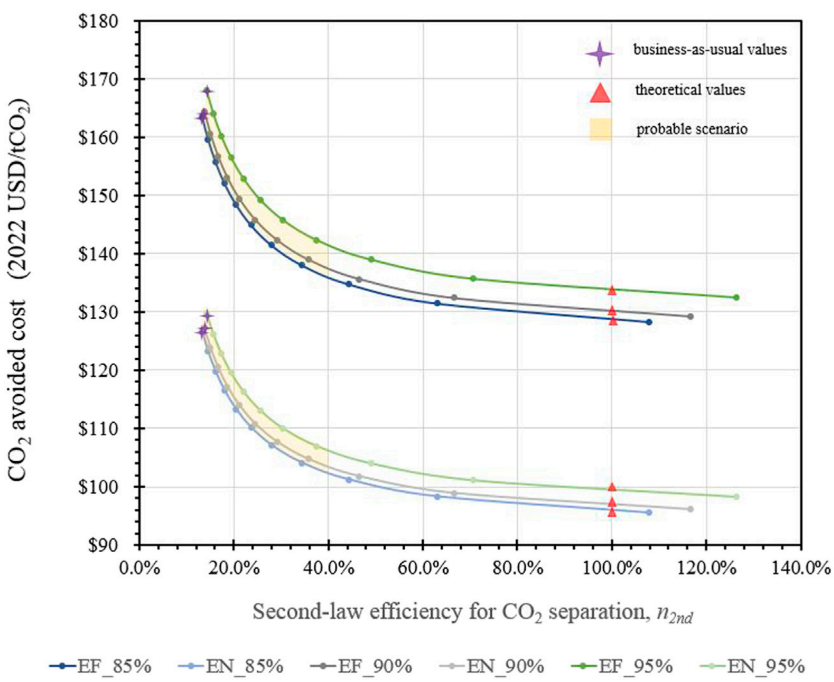

FIGURE 7
Effect of the W_{regen} on the η_{2nd} and CAC for EGR power plant with PCC by type of plant (FOAK and NOAK) at different capture levels.

section). A similar percentage in the cost reductions shows the EGR cases; for example, in an EGR plant with a 90% carbon capture level, the BAU value for a FOAK plant (EF-90%) is \$164.5/tCO_2 compared to the \$127.3/tCO_2 for a NOAK plant (EN-90%), representing a cost reduction of 22.6%.

Regarding NOAK-type plants, Figure 8 shows the expected carbon mitigation cost for future NGCC and EGR power plants as a function of the capture rate at η_{2nd} = 40%. Using the assumed value, it is observed that EGR shows a better economic performance than NGCC, with a minimum value of \$102.5/tCO_2. This is equivalent to a CAC reduction of 37.3% compared to the BAU value for a similar FOAK plant (EF_85% = \$163.5/tCO_2). At 85% capture, the CAC for the conventional NOAK NGCC plant is \$104.1/tCO_2. Maintaining this same CAC value, the carbon capture rate can increase from 85% to 90.8% if the EGR configuration is implemented.

One of the thermodynamic implications of assuming a value of η_{2nd} equal to 40% is much higher energy efficiency in the reboiler duty, estimated at a value between 1.1 and 0.8 MJ/kg of CO_2 desorbed. This is equivalent to a reduction in the energy penalty ranging from 72% to 78% of the BAU value of W_{regen}. If we place this number in perspective, most of the current innovative solvent-based PCC configuration plants reach reboiler duties between 2.3 and 2.9 MJ/kg CO_2 (Liu, 2020; Muhammad et al., 2020; Vega et al., 2020).

Considering a PCC's learning rate equal to 11% and an η_{2nd} = 40%, the results show that the estimated CAC for NOAK plants could be around \$100–110/tCO_2. Despite the fact that NOAK plants considerably reduce the CAC compared to the FOAKs, it is noted that the cost of carbon mitigation is higher than the 45Q tax credit for geological purposes (\$85/tCO_2). One possible way that could help to reduce PCC plant costs, without increasing the carbon tax credit, is through a higher learning rate. It is valid to assume that PCC technology could achieve learning rates similar to those of other energy technologies in the short term. The historical learning rate for wind power deployment in the United States (1985–1994 period) is estimated to be 32%, and that for solar PV in the EU region (period of 1985–1995) is 35% (McDonald and Schrattenholzer, 2001). For this purpose, the NF-90% case was considered and the value of the PCC technology learning rate varied from 0% to 35% (see Figure 9). It can be seen from this graph that the NOAK NGCC plant could reach the value of 45Q carbon tax credit from a learning rate close to 25%. This could have positive impact on the deployment of CCS at an early stage of the technology. Additionally, it can be observed that the NOAK plant could reduce its CAC to a value, in the best scenario, as low as \$69/tCO_2 (59.2% lower than the BAU value for the NF-90% case = \$169/tCO_2). This indicates that the NOAK plants, even with the technological and energy improvements assumed in this work, would have to be supported with an equivalent carbon tax to guarantee their operation during their useful life.

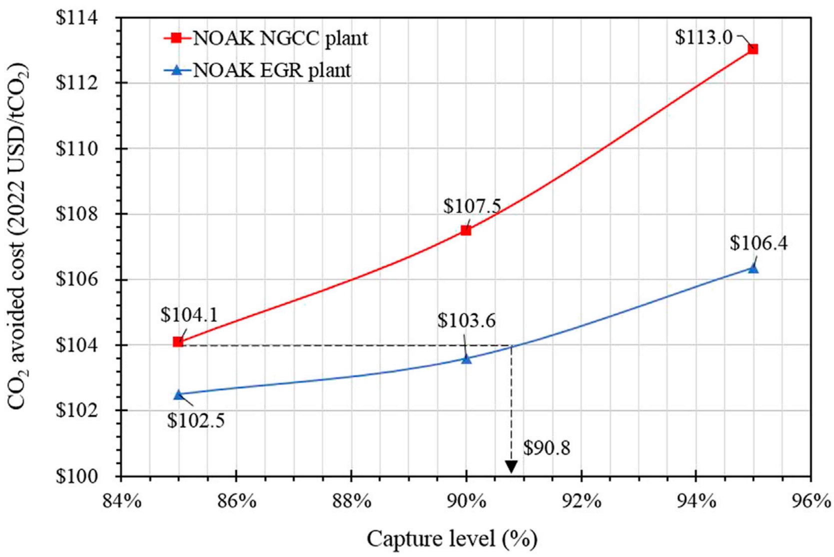

FIGURE 8
Carbon mitigation cost estimation for future NGCC and EGR power plants as a function of the capture level at η_{2nd} = 40%.

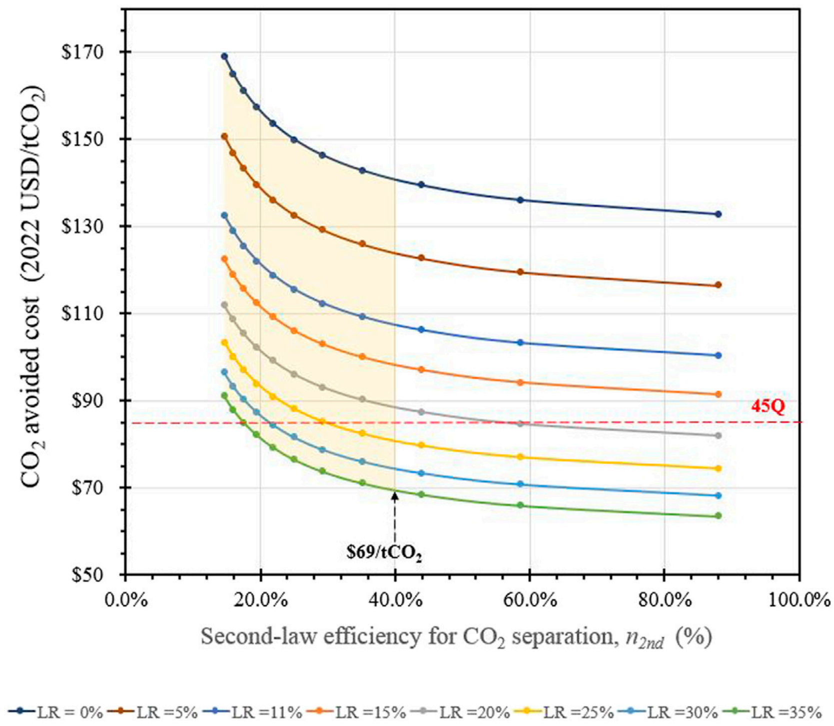

FIGURE 9
Effect of the variation of the learning rate of the PCC technology on the CAC. Note: The curves with learning rate values equal to 0% and 11% correspond to the cases NF_90% and NN_90%, respectively.

Conclusion

This study performed a scenario analysis for estimating the cost of FOAK and NOAK combined cycle plants equipped with PCC. Cost projections for conventional NGCC and EGR configurations were evaluated considering the η_{2nd} and the CAC as main indicators. Several critical variables influencing the overall cost of the technology were considered, such as W_{regen}, technology maturity, learning rate, carbon tax credit, and carbon capture level. From the results obtained, the following remarks can be made:

- Among the major technology sub-sections involved in a CCS project, PCC shows the highest cost reduction, with a total CAPEX reduction of about 40% for a NOAK compared to a FOAK plant. While, for the power plant and CO_2 compression technology sub-sections, the CAPEX reduction is marginal. This CAPEX reduction for NOAK plants potentially represents a decrease in the LCOE by 10%–11%, and the CAC by 21%–23% compared with the BAU values for FOAK plants in similar conditions.
- Considering an η_{2nd} = 40% could be the most probable energy-efficiency scenario for PCC technology in the future, the reboiler duty could be reduced from 3.7 (BAU value) to 1.1–0.8 MJ/kg of CO_2 desorbed, equivalent to an energy reduction of ~72%–78%. However, most current solvent-based PCC technologies reach reboiler duties between 2.3 and 2.9 MJ/kg of CO_2. To achieve higher energy efficiency of the PCC technology, and reduce its overall cost, more economical and technical efforts focused on research and development of new materials are needed.
- Assuming a scenario where NOAK plants achieve an η_{2nd} as low as 40%, the CAC could be reduced by about 37% compared to the BAU value for similar FOAK plants. At 85% capture level, the NOAK EGR type plant shows the lowest expected CAC value among all cases evaluated, with a value of $102.5/t$CO_2$.
- At 85% capture, the CAC for the conventional NOAK NGCC plant is $104.1/t$CO_2$. Maintaining this same CAC value, the carbon capture rate could increase from 85% to 90.8% if the EGR configuration is implemented.

- Considering a PCC's learning rate equal to 11% and an η_{2nd} = 40%, the results show that the estimated CAC for NOAK plants could be around \$100–110/tCO_2. Assuming that the PCC could achieve learning rates similar to those of other energy technologies in the short term (e.g., solar), the CAC could be, in the best scenario, as low as \$69/tCO_2. Therefore, NOAK plants are expected to need at least a similar carbon tax to operate during their lifetime.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

PD-H and GA contributed to the conception and design of the study. AR-M organized the database. PD-H, GA, and AR-M performed the data analysis and interpretation. PD-H wrote the first draft of the manuscript. GA and AR-M wrote sections of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenrg.2022.987166/full#supplementary-material

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Nomenclature

BAU business-as-usual

CAC CO_2 avoided cost

CAPEX capital expenditure

CCS carbon capture and storage

EGR exhaust gas recirculation

EOR enhanced oil recovery

FOAK first-of-a-kind plant

LCOE levelized cost of electricity

LR learning rate

NGCC natural gas combined cycle

NOAK Nth-of-a-kind plant

O&M operating and maintenance

PCC post-combustion carbon capture.