energy&fuels Article
Cite This: *Energy Fuels* XXXX, XXX, XXX−XXX pubs.acs.org/EF

Exergoeconomic Analysis of the Allam Cycle

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Supporting Information

ABSTRACT: Greenhouse gas emissions from fossil fuel combustion is one of the main causes of global warming. Carbon capture, storage, and/or utilization consists of technologies and measures focused on diminishing anthropogenic emission of carbon dioxide (CO_2), an important contributor to the greenhouse effect. One of the most promising methods for carbon capture is oxy-combustion, for which several innovative alternatives have been proposed in recent years. This paper evaluates a thermodynamic cycle known as the Allam cycle. The novelty of this plant lies in the fact that the cycle uses supercritical CO_2 as the working fluid of the process. The evaluation is performed using exergetic, economic, and exergoeconomic analyses. The election of an exergy-based methodology rather than a conventional energy-based analysis is motivated by the better characterization of the thermal system achieved by the first. The goal is to assess the cost effectiveness of the cycle and to determine a way to optimize it by design changes and other modifications. Overall, we find that the calculated efficiency and cost of electricity can compete with other low-emission technologies, but they are higher than those of the currently operating combined cycle plants.

1. INTRODUCTION

Climate change, driven by the current exponential increase of CO_2 accumulation, is a significant challenge to life on earth. The Intergovernmental Panel on Climate Change (IPCC) expressed the urge to implement measures aimed to limit global warming generated by the emission of greenhouse gases (GHGs) to 1.5 °C with respect to preindustrial levels.[1] To achieve this, the GHG emission needs to be cut down by 2050 to 40−70% the 2010 values. There are various approaches to mitigate the negative impact of climate change, such as the enhancement of energy efficiency in both the production and consumption ends; the reduction of fossil fuel use; carbon capture, utilization, and/or storage (CCS/CCUS/CCU); and the deployment of renewable energy at the commercial scale. However, none of these approaches are enough to achieve the IPCC goals individually.

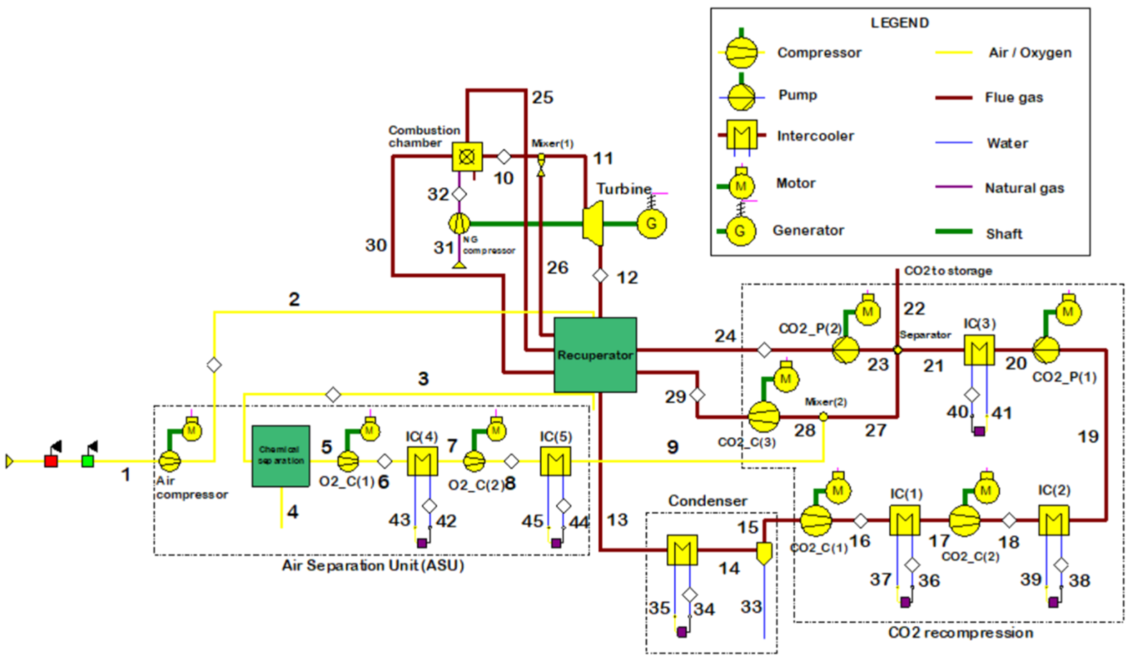
In this context, since the production of electricity contributes to a quarter of the GHG global emissions and CO_2 accounts for three quarters of the total GHG emissions,[2] the decarbonization of the power sector constitutes a primary target. This makes technologies focused on the reduction of CO_2 emission, such as CCS, crucial for the future development of the energy sector.[3] CCS technologies include the separation and capture of CO_2 and transport, storage, or utilization of CO_2.

The capture processes can be split into three main types: post-combustion, pre-combustion, and oxy-combustion. Post-combustion separates the CO_2 after the combustion takes place. This is the most mature technology, and it can be implemented in the construction of new plants or retrofitted in existing ones. Two important drawbacks of this type of technology are, first, the need of a relatively high CO_2 concentration in the exhaust gases stream and, second, the strong reduction of efficiency for elevated capture rates.[4] In pre-combustion systems, the fuel undergoes a gasification process to obtain a synthesis gas, mainly CO and H_2, with CO_2. The relatively high concentration of CO_2 (>20%) and, thus, its high partial pressure facilitate its subsequent separation. Finally, the gas rich in H_2 can be used for different purposes, such as a primary fuel in conventional combustion processes and fuel cells. This technology can also be combined with integrated gasification combined cycle plants.[5] Although pre-combustion is less energy intensive than other options, it has several disadvantages, like the required vapor in water−gas shift reactions, the low-temperature capture, and the reduced gas turbine efficiency.[6] The last capture option, i.e., oxy-combustion, is based on the realization of the combustion process with almost pure oxygen. The main advantage of this technique is that separation is inherent to the combustion, making further capture treatments unnecessary. Nevertheless, the process to obtain oxygen from atmospheric air is energy intensive. Another characteristic of this kind of technology is the need for flue gas recirculation to moderate the temperature of the combustion chamber.[4,7]

The development of carbon capture technologies has been relatively stagnant since the 2010s. The strategic plan published by the International Energy Agency (IEA) in 2009 forecasted 100 operating commercial plants by 2020,[8] when only 17 plants were in operation in 2017.[9] The problem resides in the lack of international coordination, cooperation and commitment, from both technoeconomic and regulatory points of view. To achieve commercial-scale implementations of carbon capture technologies (on the order of 300 MWe and 1 million metric tons of CO_2 stored), it is essential to use lessons learnt from the evaluation of existing pilot and demonstration plants.[10]

Received: April 30, 2019
Revised: July 2, 2019
Published: July 2, 2019

Scheme 1. Diagram of the Simulated Plant



Existing applications show that carbon capture does not imply major technical challenges. However, its biggest drawbacks are the high investment cost and strong efficiency reduction (e.g., the performance comparison carried out in ref 11 shows that while the low heating value (LHV)-based efficiency of a reference natural gas combined cycle plant is about 58.8%, oxy-combustion alternatives do not reach 50%, with the exception of the Allam cycle) that ultimately increase the cost of the generated electricity (levelized cost of electricity—LCOE). This hinders investments and creates a strong barrier to the wider incorporation of the technology to the energy sector. Hence, the viability of these projects is currently subject to regions where economic incentives enable additional revenue. For example, the sale of CO_2 for enhanced oil recovery in North America due to carbon taxes or the trade in carbon emission market in Europe.

This study evaluates the thermodynamic, economic, and exergoeconomic performance of the Allam cycle, a novel approach to capture CO_2 using oxy-combustion. It uses supercritical carbon dioxide (sCO_2) as a working fluid in a semiclosed regenerative gas turbine thermodynamic cycle. We chose the Allam cycle because of its promising features like its relatively high net electrical efficiency (according to the developers, it can reach 59%[12]) and its relatively lower cost of electricity, when compared to those of other capture options.[11,13] The Allam cycle tries to solve the issue of the energy-intensive air separation process presented earlier by maximizing the electric efficiency. For doing this, it uses the waste heat byproduct generated to heat up the recycled working fluid.

The Allam cycle evaluated here is a large-scale 300 MWe commercial plant, as proposed by its developers.[12] The model is simulated using the software EBSILONProfessional 13.00. The novelty and importance of this work lie in the fact that it presents an exergy-based analysis not been realized before, allowing a more precise evaluation of the process and deeper insight into the detailed design and operation of the system. The exergoeconomic analysis (combination of exergetic and economic analyses) realized for the purpose of this study provides detailed information about the operation and costs of the system and shows how the structure of the plant should be modified or adjusted to improve its cost effectiveness.[14,15]

2. DESCRIPTION OF THE PLANT

In the natural gas Allam cycle, the fuel (97.1% molar fraction of methane, stream 32 in Scheme 1) is burnt in the combustion chamber in the presence of two streams: stream 30 and stream 25. Stream 30 is formed by mixing oxygen (stream 9, 99.5% molar fraction) produced in an air separation unit (ASU) with recompressed supercritical CO_2 (stream 27). Stream 25 is used as a temperature moderator, and it is another fraction of the recompressed sCO_2. Both streams are preheated to 720 °C in the recuperator (the regenerative heat exchanger) and introduced in the combustion chamber.

The exhaust gases (stream 11), mainly CO_2 (95.6% molar fraction) and some water vapor (~2% molar fraction), exit the combustor at a temperature around 1150 °C and a pressure of 300 bar and are expanded in the turbine down to 30 bar. The pressure at the turbine inlet and the pressure ratio (10) are defined parameters in the simulation, while the combustion exit temperature is a result of the calculations. For turbine cooling, a fraction of the sCO_2 (stream 26) at 400 °C is used. Then, the expanded gases transfer their heat to the oxidant, moderator, and refrigeration streams in the recuperator. As the heat ceded is lower than that required to preheat these streams, an additional heat source is needed. In this work, this necessity is covered by the hot-compressed air stream coming from the main ASU air compressor (stream 2). The exhaust gases (stream 13) are further cooled down to condense the included water vapor and separate it from the sCO_2. The circulating working fluid is recompressed to 300 bar through a series of intercooled compressors and pumps. Once the sCO_2 is pressurized up to 100 bar, a small fraction is extracted from the cycle for storage (stream 22).

To achieve a more realistic model and given the thermodynamic properties of the supercritical CO_2, the

DOI: 10.1021/acs.energyfuels.9b01348
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Peng–Robinson equation of state has been selected. This cubic model allows for a precise characterization of the properties of the sCO_2 in the simulation, as it enables an accurate prediction of nonpolar fluid (such as CO_2) densities and shows good applicability to mixtures with one supercritical fluid at high pressures.[16−18] The majority of the components of the plant have been modeled using predefined components of the software EBSILONProfessional. The recuperator and the chemical separation unit of the ASU were simulated as blackboxes using data provided in refs 11, 19. The mechanical and isentropic efficiencies for the different turbomachinery are shown in Table 1.

Table 1. Selected Efficiencies of the Different Plant Components[21,22]

efficiency	value (−)
turbine isentropic efficiency	0.90
turbine mechanical efficiency	0.99
compressors isentropic efficiency	0.85
compressors mechanical efficiency	0.99
pumps isentropic efficiency	0.85
pumps mechanical efficiency	0.998
generator electric efficiency	0.985
motors electric efficiency	0.95

The recuperator is a regenerative heat exchanger with high heat duty, managing multiple hot and cold streams, withstanding high temperatures (above 700 °C), and significant pressure differences between hot and cold sides (200–300 bar).[19] According to the developers,[12] a printed circuit heat exchanger[20] is the most suitable option for such a recuperator. The sCO_2 gas turbine is subject to considerably demanding inlet conditions (above 1100 °C and about 300 bar), similar to those of commercial E-class turbines.[11]

The design of these two components plays a very important role in the efficiency of the plant. To maximize the operational efficiency, elevated turbine inlet temperatures are required. However, this temperature is restricted from the maximum thermal stress that the materials of the turbine and the recuperator can withstand, which today is usually not higher than approximately 1200 °C[13] (although with thermal barrier coating, the temperature can go higher, in some cases up to 1500 °C).

To properly simulate the Allam cycle, most of the defined parameters introduced into the simulation are taken from papers published by the developers of the cycle.[12,13,23] Nevertheless, due to a lack of some specific details, other works have been consulted as well.[11] The results of the simulation can be seen in Table 2.

3. METHODS

3.1. Exergetic Analysis. The exergetic analysis is based on the concept of exergy. Unlike energy that is always conserved, exergy can be destroyed. Thanks to this feature, thermodynamic irreversibilities that remain hidden in the conventional energy-based analysis are revealed using exergy-based methods. Exergy is an extensive property, quantified with respect to a set of reference conditions (definition of a dead state). The chemical reference model used here is that of Ahrendts.[24] To perform this analysis, criteria and guidelines presented in refs 14, 15, 25 are followed.

The analysis is realized at the component level. The exergy rates of fuel and product as well as the exergy destruction rate are thus defined for each k plant component ($\dot{E}_{F,k}$, $\dot{E}_{P,k}$, $\dot{E}_{D,k}$) and the overall plant ($\dot{E}_{F,total}$, $\dot{E}_{P,total}$, $\dot{E}_{D,total}$). The exergy loss is only defined for the overall system ($\dot{E}_{L,total}$). One important variable obtained through this analysis is the exergetic efficiency, defined by eq 1 for individual components and eq 2 for the overall plant. The exergetic efficiency shows the effectiveness of converting the exergy of a fuel into a useful product.

$$\varepsilon_k = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k}} = 1 - \frac{\dot{E}_{D,k}}{\dot{E}_{F,k}} \tag{1}$$

$$\varepsilon_{total} = \frac{\dot{E}_{P,total}}{\dot{E}_{F,total}} = 1 - \frac{\sum \dot{E}_{D,k} + \dot{E}_{L,total}}{\dot{E}_{F,total}} \tag{2}$$

Other useful variables are the exergy destruction and exergy loss ratios. These parameters measure the influence of both exergy and losses with respect to the total input of fuel exergy, as it can be seen by eqs 3 and 4, respectively.

$$y_{D,k} = \frac{\dot{E}_{D,k}}{\dot{E}_{F,total}} \tag{3}$$

$$y_{L,total} = \frac{\dot{E}_{L,total}}{\dot{E}_{F,total}} \tag{4}$$

3.2. Economic Analysis. The total revenue requirement (TRR) method has been applied in this work.[14] The first step of the method is associated with estimating the fixed capital investment (FCI), for which the estimation of the equipment's capital costs is the most critical issue.[20,26−32] The Chemical Engineering Plant Cost Index (CEPCI)[33] has been employed to escalate the costs to 2017, the reference year used in this paper (eq 5).

$$\text{reference year cost} = \text{original cost} \cdot \frac{\text{CEPCI (reference year)}}{\text{CEPCI (original year)}} \tag{5}$$

The annual expenses related to operation and maintenance (O&M), which are composed of a fixed part (salary, maintenance, and administrative costs) and a variable part (fuel and CO_2 transport and storage costs), are calculated throughout the whole expected plant life (see Table 3 for the main assumptions of the economic analysis). Then, the total annual revenue requirements are obtained as the sum of all aforementioned expenses incurred by the construction and use of the plant on a year-to-year basis. These results are first converted to

Table 2. Results Obtained from the Simulation

parameter	value
input fuel thermal energy (MW_{th})	552.7
ASU power consumption (MW_e)	64.4
CO_2 recompression power consumption (MW_e)	87.2
net power output (MW_e)	298.1
net electric efficiency, LHV-basis (%)	53.94
mass flow rate, pressure and temperature at turbine outlet (kg/s/bar/°C)	923.4/30/767
O_2 consumption (kg/s)	44.5

DOI: 10.1021/acs.energyfuels.9b01348
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Table 3. Main Selected Parameters for the Economic Analysis

parameter	value	refs
general inflation rate (%)	3	11, 26
nominal escalation rate for natural gas (%)	4	11
nominal escalation rate for other costs (%)	3	11, 26
real cost of opportunity (%)	10	14
plant economic life (years)	25	11
capacity factor (%)	90	11
cost of natural gas, LHV-based (€/MJ)	0.007	21, 22
cost of transport and storage of CO_2 (€/tCO_2)	10	11
number of employees	30	11, 26
average working time (h/year)	2080	11, 26
average salary (€/year)	60.000	11, 26

present value (TRR_{PV}) and then levelized (TRR_L) according to eq 6, where i_c is the real cost of opportunity and n is the plant economic life.

$$TRR_L = TRR_{PV} \cdot \frac{i_c \cdot (1 + i_c)^n}{(1 + i_c)^n - 1} \qquad (6)$$

Finally, the levelized cost of electricity (LCOE) is calculated by eq 7, dividing the levelized total annual revenue requirement (TRR_L) by the amount of electricity generated in a year (multiplication of the net electrical power of the cycle, W_{net}, by the number of operating hours, OH).

$$LCOE = \frac{TRR_L}{W_{net} \cdot OH} \qquad (7)$$

3.3. Exergoeconomic Analysis. The exergoeconomic analysis combined the results of the exergetic and economic analyses. The objective is to comprehend the cost formation process of the thermal system, identify the main inefficiencies from a thermoeconomic viewpoint and propose design changes that potentially optimize the cost effectiveness of the plant.[14,15,25]

Specific costs are assigned to each exergy stream of the plant. These costs are computed by cost balances defined at the component level, as shown in eq 8, where $\dot{C}_{P,k}$ is the product cost rate, $\dot{C}_{F,k}$ is the fuel cost rate, $\dot{Z}_k$ is the investment cost rate of component k calculated in the economic analysis, and $\dot{C}_{D,k}$ is the cost rate of exergy destruction within the same component. In addition, depending on the operation of each component, auxiliary relations may be needed to complete the system of equations.

$$\dot{C}_{P,k} = \dot{C}_{F,k} + \dot{Z}_k + \dot{C}_{D,k} \qquad (8)$$

There are two important parameters obtained through this analysis: the relative cost difference (r_k) and the exergoeconomic factor (f_k). The corresponding formulas are shown with eqs 9 and 10. The first one shows the relative increase of the product specific cost ($c_{P,k}$) with respect to the fuel specific cost ($c_{F,k}$). The second one shows the relative importance between the two different cost components: (1) the non-exergetic, i.e., the investment-related cost rate ($\dot{Z}_k$), and (2) the exergetic, i.e., the cost of exergy destruction ($\dot{C}_{D,k}$).

$$r_k = \frac{c_{P,k} - c_{F,k}}{c_{F,k}} \qquad (9)$$

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + \dot{C}_{D,k}} \qquad (10)$$

For the exergoeconomic evaluation, the components are listed in a descending order of cost importance, according to the $\dot{Z}_k + \dot{C}_{D,k}$ parameter, and design changes are proposed based on that sum and their r_k and f_k values.

4. RESULTS AND DISCUSSION

4.1. Exergetic Evaluation. The results of the exergetic analysis at the component level are shown in Table 4. The stream-level results can be found in the Supporting Information of the paper.

As can be seen in Table 4, most of the exergy destruction takes place in the combustion chamber ($y_D^* = 56.7\%$), reaching almost one quarter of the total fuel exergy ($y_D = 24.8\%$). This

Table 4. Results of the Exergetic Analysis at the Component Level

component	$\dot{E}_F$ (MW)	$\dot{E}_P$ (MW)	$\dot{E}_D$ (MW)	y_D (%)	y_D* (%)	ε (%)
natural gas compressor	3.57	3.11	0.46	0.08	0.18	87.21
combustion chamber	579.62	436.73	142.89	24.76	56.72	75.35
turbine	478.88	454.79	24.08	4.17	9.56	94.97
recuperator	435.35	420.20	15.15	2.63	6.01	96.52
condenser	4.48		3.94	0.68	1.56	
CO_2 compressor (1)	37.73	25.40	12.33	2.14	4.90	67.31
intercooler (1)	5.83		5.25	0.91	2.08	
CO_2 compressor (2)	32.47	17.86	14.61	2.53	5.80	55.00
intercooler (2)	11.89		10.24	1.77	4.06	
CO_2 pump (1)	3.91	2.76	1.15	0.20	0.46	70.56
intercooler (3)	0.80		0.62	0.11	0.24	
CO_2 pump (2)	17.70	17.40	0.30	0.05	0.12	98.33
CO_2 compressor (3)	9.95	8.08	1.87	0.32	0.74	81.20
air compressor	42.29	38.49	3.80	0.66	1.51	91.02
chemical separation unit	11.42	9.01	2.41	0.42	0.96	78.91
O_2 compressor (1)	11.82	10.88	0.95	0.16	0.38	91.99
intercooler (4)	3.55		3.43	0.59	1.36	
O_2 compressor (2)	6.51	5.83	0.67	0.12	0.27	89.65
intercooler (5)	1.47		1.40	0.24	0.56	
mixer (1)	6.31	5.09	1.22	0.21	0.48	80.72
mixer (2)	6.14	0.97	5.17	0.90	2.05	15.80
separator	464.17	464.17	0.00	0.00	0.00	100.00
total ($\dot{E}_L$ = 36.31 MW)	577.08	288.85	251.92	43.65	100	50.05

DOI: 10.1021/acs.energyfuels.9b01348
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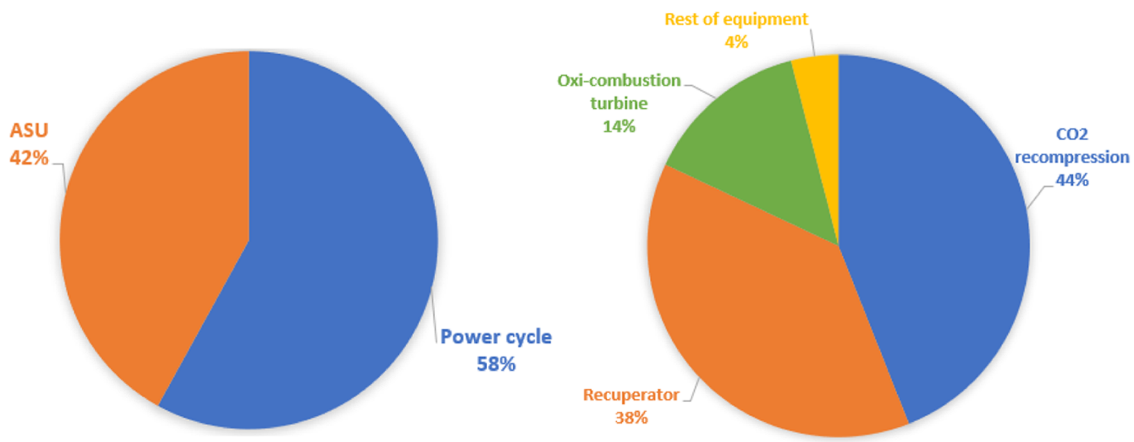
Chart 1. Distribution of the FCI[a]



[a]Left panel: FCI distribution of the total plant; right panel: FCI distribution of just the power cycle.

is expected, as phenomena related to chemical reaction and heat transfer are the main sources of thermodynamic irreversibilities.[14] The expander is the component with the second highest exergy destruction ($y_D^* = 9.60\%$). However, it presents a rather high exergetic efficiency ($\varepsilon = 95.00\%$), when compared to that of the combustion chamber ($\varepsilon = 75.40\%$). The recuperator presents the third highest exergy destruction ($y_D = 6.00\%$). Its contribution to exergy destruction is found to be relatively small for a component with such a high heat duty and considering the large mass flow rates it manages. This is also seen with its relatively high exergetic efficiency ($\varepsilon = 96.50\%$). The sCO_2 compression/pumping groups follow the pattern that the higher the pressure ratio, the higher the exergetic efficiency of the component.

Evaluating the overall plant, it is found that the total exergy destruction is 251.90 MW and the exergy loss represents a relatively small portion of the fuel input ($y_L = 6.29\%$). Finally, the exergetic efficiency of the overall plant is found to be 50.10%.

4.2. Economic Evaluation. The contribution of the different blocks of components to the total FCI of the plant is shown in Chart 1. The left chart displays the FCI cost distribution of the whole plant, while the right one shows the FCI distribution of the different equipment over the total of the power cycle, not taking into account the ASU. As observed, the ASU is the most expensive unit, representing almost half of the total FCI. It is followed by the recuperator and the oxy-combustion turbine group (combustion chamber and turbine). These results are in accordance with those presented in refs 11, 32, where the cost contribution between the power cycle and the ASU is approximately 60−40%. We find that the recompression block is associated with approximately 50% of the FCI of the power plant and that the recuperator and the oxy-combustion turbine blocks together constitute about 50% of the plant's FCI.

The results of the TRR method are shown in Table 5. The LCOE calculated (91.7 €/MWh) for the simulated Allam cycle is close to that reported in refs 11, 32 (around 80−90 €/MWh). It is, however, higher than the one reported by the developers of the Allam cycle (73.8 €/MWh).[12,13] Nevertheless, the cost of the developers of the cycle is based upon proprietary undisclosed knowledge and technology, so it is not possible to properly compare the calculations. In any case, we see that the LCOE for the Allam cycle is still higher than that of typical natural gas combined cycle plants (62.5 €/MWh).[11]

Table 5. Results of the Economic Analysis in 2017€[a]

parameter	value
specific fixed capital investment (€/kW)	1229.1 (923.5)
levelized cost of fuel (M€/year)	184.9
levelized other O&M costs (M€/year)	29.0
levelized carrying charges (M€/year)	73.0
levelized revenue requirements (M€/year)	286.8
LCOE (€/MWh)	122.0 (91.70)

[a]The values in parentheses are escalated down to 2014€ for comparison purposes.

The specific cost of FCI calculated in this paper (923.5 €/kW) is lower than the one presented in ref 11 (1320 €/kW) and that of shown by the developers of the Allam cycle (992 €/kW).[12,13] Thus, it is seen that the reason for the higher costs found in this study may be related to the relatively high fuel costs or basic assumptions of the economic analysis that can influence the outcome (overestimating or underestimating determined costs and parameters, shorter or longer periods of time, etc.). Given the significant impact of fuel costs on the results of the economic analysis, a sensitivity analysis has been carried out to measure their influence on the LCOE, as displayed in Chart 2. A linear dependence is observed where a unit percentage increase in fuel costs leads to an increase in LCOE of about 1.5%.

4.3. Exergoeconomic Evaluation. The results of the exergoeconomic analysis are shown in Table 6. The specific fuel and product costs for the overall plant are found to be 1.13 and 3.50 cents/MJ, respectively.

The ranking of the components according to their total costs (including cost of exergy destruction and investment cost) shows which components should be given priority in enhancement measures to achieve the improvement of the whole system.

The component with the highest priority is found to be the combustion chamber with a relatively low exergoeconomic factor ($f_k = 7.80\%$). This low value of the exergoeconomic factor is due to relatively high thermodynamic irreversibilities (and thus the cost of exergy destruction) in the component. Low values of f_k indicate the necessity of increasing capital investment to reduce thermodynamic inefficiencies. This

DOI: 10.1021/acs.energyfuels.9b01348
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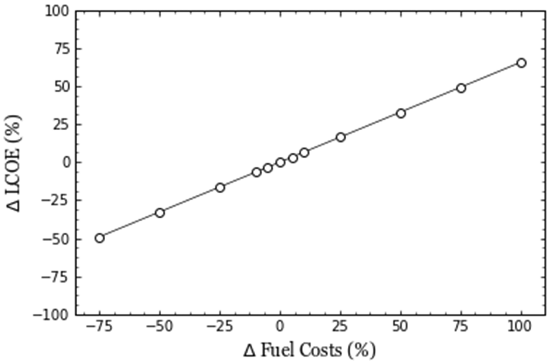
Chart 2. Sensitivity Analysis of the Influence of Fuel Costs on LCOE



means higher investment in materials, technology, and processes that can ultimately improve the efficiency of the component. In this particular case, however, the plant already includes preheating of the reactants and excess air reduction for improved performance of the combustion chamber.

The next component in order of improvement priority is the chemical separation unit of the ASU. The ASU presents rather high values for both factors r_k and f_k. The explanation for this can be found in the combination of the considerably expensive nature of ASU technology and the relatively simple model designed for this work. As a general rule, high values of the exergoeconomic factor call for a potential tradeoff among capital investment and component efficiency.

The other top-ranked components are the recuperator and the turbine of the plant. The first shows an exergoeconomic factor higher than typical values for heat exchangers (<55%).[14] However, this is expected considering the novelty of the equipment and its elevated exergetic efficiency. The turbine presents a relatively low f_k value compared to typical values for expanders (35−75%).[14] This could allow the increase of the investment for this particular component to somewhat decrease its cost of exergy destruction.

The compressors and pumps used in the sCO_2 cycle present high values of r_k and low values of f_k. This is due to their relatively poor efficiencies. In contrast, the air and oxygen compressors in the ASU show mostly better efficiencies and higher exergoeconomic factors, given that their exergy destruction is considerably lower. Thus, further efficiency enhancement actions could be considered for the CO_2 compressors.

5. CONCLUSIONS

In this paper, a novel oxy-fuel sCO_2 power cycle within carbon capture known as the Allam cycle was studied from an exergoeconomic perspective. The plant was found to have a promising net electric efficiency of 53.9% and an exergetic efficiency of 50.1%, values higher than those reported for other capture technologies. The major drawback of the plant that could be considered is its relatively high cost of electricity (91.7 €/MWh), when compared to that of combined cycle power plants. The exergoeconomic evaluation provided insight into tradeoffs between costs and inefficiencies of the plant components, and it helped to rank the different components in order of highest importance for plant improvement. It was found that the components with the greatest potential for improvement were the combustion chamber, the chemical separation unit of the air separation unit, the recuperator, and the CO_2 compression/pumping groups.

Carbon capture in power plants involves complex technologies and expensive processes. Nonetheless, the Allam cycle exhibits appealing features that could support its candidacy for large-scale implementation, provided that the economic viability of not yet commercial components is achieved.

Table 6. Results of the Exergoeconomic Analysis

component	(%)	c_F (cent/MJ)	c_P (cent/MJ)	$\dot{C}_D$ (cent/s)	$\dot{Z}$ (cent/s)	$\dot{C}_D + \dot{Z}$ (cent/s)	r (%)	f (%)
combustion chamber	5.35	1.15	1.55	163.88	13.88	177.76	34.78	7.79
chemical separation unit	78.91	3.21	16.05	7.73	107.44	115.17	400.00	93.28
recuperator	96.52	2.56	2.83	38.76	74.68	113.44	10.55	65.82
turbine	94.97	2.54	2.72	61.23	18.04	79.27	7.09	22.77
CO_2 compressor (2)	55	2.72	5.82	39.69	15.71	55.40	113.97	28.34
CO_2 compressor (1)	67.31	2.72	4.75	33.51	18.00	51.51	74.63	34.92
intercooler (2)		2.78		28.49	9.78	38.27		22.84
intercooler (4)		9.53		32.73	0.72	33.45		2.10
CO_2 pump (2)	98.33	2.72	4.61	0.8	32.16	32.96	69.49	97.53
CO_2 compressor (3)	81.2	2.72	6	5.08	21.43	26.51	120.59	80.82
air compressor	91.02	2.72	3.25	10.31	11.17	21.48	19.49	51.93
intercooler (1)		2.66		13.98	3.14	17.12		16.85
O_2 compressor (1)	91.99	2.72	4.14	2.57	12.59	15.16	52.21	83.12
mixer (2)	15.8	2.8	8.14	14.48	0	14.48	190.71	0.00
condenser		2.54		10.01	2.63	12.64		18.78
intercooler (5)		8.14		11.39	0.68	12.07		5.37
O_2 compressor (2)	89.65	2.72	4.24	1.83	7.03	8.86	55.88	79.16
CO_2 pump (1)	70.56	2.72	5.75	3.13	5.24	8.37	111.40	62.62
intercooler (3)		2.8		1.72	2.56	4.28		53.38
natural gas compressor	87.21	2.72	4.03	1.24	2.86	4.10	48.16	69.57
mixer (1)	80.72	2.54	2.86	3.09	0	3.09	12.60	0.00
separator	100	2.8	2.8	0	0	0	0	
total ($\dot{E}_L$ = 36.31 MW)	50.05	1.13	3.50	284.73	359.76	641.49	209.73	52.48

DOI: 10.1021/acs.energyfuels.9b01348
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■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.energyfuels.9b01348.

Selected thermodynamic properties, exergoeconomic values (PDF)

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

Fontina Petrakopoulou would like to thank the Spanish Ministry of Science, Innovation and Universities and the Universidad Carlos III de Madrid (Ramón y Cajal Programme, RYC-2016-20971).

■ ABBREVIATIONS

ASU = air separation unit
CCS = carbon capture and storage
FCI = fixed capital investment
GHG = greenhouse gas
IPCC = Intergovernmental Panel on Climate Change
LCOE = levelized cost of electricity
LHV = low heating value
O&M = operation and maintenance
sCO_2 = supercritical carbon dioxide
TRR = total revenue requirement

Symbols

c = specific cost
$\dot{C}$ = exergy cost rate
$\dot{E}$ = exergy rate
ε = exergetic efficiency
f = exergoeconomic factor
i_c = real cost of opportunity
n = plant economic life
OH = operating hours
r = relative cost difference
W_{net} = net electric power
y = exergy ratio (over the total fuel exergy)
y^* = exergy ratio (over the total exergy destruction)
$\dot{Z}$ = investment-related cost rate

Subscripts

D = destruction
F = fuel
k = component k
L (in exergy) = loss
L (in TRR) = levelized
P = product
PV = present value
total = overall plant

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DOI: 10.1021/acs.energyfuels.9b01348
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