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A Novel Integrated System Driven by Allam Cycle for the Simultaneous Energy, Water, and Waste Management

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Energy and water are indispensable to human activities and economic growth, especially with increasing energy and water security concerns in the coming years. In addition, with fast urbanization, how to deal with huge amounts of urban sewage becomes critical to achieve a sustainable future. Simultaneous management of energy, water, and waste could potentially increase the techno-economic-environmental performance of the integrated system. Recently, an oxy-combustion power cycle (the Allam cycle) has attracted increasing attention because of its near-zero emissions and high thermal efficiency, while supercritical CO_2 (sCO_2) extraction is a promising technology for wastewater treatment. The presented work proposes a novel Allam cycle-driven system integrated with a Multi-Effect Desalination unit (MED) in order to provide power and fresh water. The sCO_2 produced in the Allam cycle is used in a Sewage Treatment Plant (STP), and this can decrease the operating costs of the STP. Energy and exergy analysis is carried out for the proposed system using the Engineering Equation Solver (EES) and MATLAB. Finally, in order to evaluate the effect that the decision variables have on each of the objectives, a comprehensive parametric study is conducted. The analysis indicates that the inlet temperature and pressure of the gas turbine and the number of effects in the MED are the main factors influencing the objective functions.

1. Introduction

Energy–Carbon–Water (ECW) are inextricably linked in both energy units and residential consumption. The water shortages caused by climate change will affect 40 percent of the world's population by 2030. A significant portion of the energy used in the water sector comes from fossil fuels, leading to carbon dioxide emissions (Alirahmi et al., 2022). It is estimated that 4 % of all global electricity consumption is consumed by the water sector, of which 25 % is spent on wastewater treatment (IEA, 2020) and it is a serious health crisis for 4.5 billion people and the environment because 80 % of all wastewater is discharged untreated due to financial and resource constraints (Rani et al., 2022).

The majority of Wastewater Treatment Plants (WWTP) currently use flotation, coagulation, membrane technology, and biological treatment technologies. Each method has its own advantages and disadvantages. The primary method used in sewage treatment facilities is conventional floating wastewater treatment (Korhonen et al., 2011). Nevertheless, this method requires a long residence time, a large floating tank, as well as additional chemicals, which may contribute to secondary pollution of the environment. A new supercritical carbon dioxide (sCO_2) extraction technology was proposed recently to meet the water quality standard. This technology could be applied both to separate oil from water and to reduce the chemical oxygen demand value in industrial wastewater (Jan and Wang, 2020).

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Since sCO_2 has high solubility, high density like a liquid, low viscosity, low surface tension, and high diffusivity like a gas, it is expected to have both gas and liquid characteristics (Fomin et al., 2015). Carbon Capture and Utilization (CCU) can be integrated into the existing sewage infrastructure during treatment without using additional land or transport. Integrating wastewater treatment and CCU may transform energy-intensive, carbon-emitting WWTPs into integrated Water Resource Recovery Facilities (WRRFs) that recover nutrients, energy, water, and other valuable carbon products with economic, environmental, and social benefits. In this context, there is a possibility that CCU could play an important role in the global wastewater treatment market. A novel energy system for wastewater extraction based on CO_2 captured from LNG was presented by Tan et al. (2022). According to Jan and Wang (2020), supercritical CO_2 is an effective method for extracting organic matter from wastewater.

A promising CCU technology is the Oxy-Fuel Combustion (OFC) cycle. In the OFC cycle, oxygen is used instead of air for combustion, resulting in a flue gas primarily composed of CO_2 and water vapor. Recently, the Allam cycle is developed as a type of OFC cycle (Allam et al., 2013). With efficiencies up to 59 %, the Allam cycle is significantly more efficient than traditional gas-fired power plants. The Allam cycle is a near-zero emission cycle due to its semi-closed loop structure, which means captured carbon dioxide can be used to create a synthetic fuel such as methane instead of releasing it into the atmosphere.

In a parallel scenario, modern energy systems increasingly rely on renewable energy sources, such as solar and wind (Shabani and Kalantar, 2021). In spite of this, the availability of these sources is not always assured, due to factors such as wind speed and cloud coverage (Mahdizadeh Shalmaei and Asghari Gorji, 2022). As a solution to these challenges, Power-to-X (PtX) technology as a large-scale energy storage system offers an innovative solution. PtX is an energy conversion process that uses renewable energy sources, such as wind and solar, to produce energy carriers such as hydrogen, methane, and synthetic fuels (Park et al., 2021). This process provides an alternative to traditional energy sources, such as oil and gas, and enables us to transition to a more sustainable energy future. During the PtX process, oxygen is a byproduct that is rarely used in most applications and is often released into the atmosphere or piped into tanks for later use. The efficient use of oxygen can be the key to improve the economic performance of the PtX process.

The purpose of this study is to propose a novel Integrated Energy System (IES) that uses oxygen as the oxidant stream for OFC in order to improve efficiency. Although energy systems and desalination units have been studied extensively, studies on the wastewater industry have been sparse. Since wastewater is produced wherever humans are active, this study aims to introduce a new IES based on the Allam cycle with an integrated wastewater system.

2. System description

A key aspect of this work is the optimal method for using CO_2. To accomplish this, the main parts of the system are examined as CO_2 capture and utilization. PtX and the WWTP unit have been placed to utilize CO_2, and the Allam cycle has been used to produce pure CO_2 and electricity. Additionally, the Multi-Effect Distillation-Thermal Vapor Compression (MED-TVC) unit uses the excess heat generated by the Allam cycle to produce fresh water.

2.1 CO_2 capture

High pressure supercritical CO_2 is used in the Allam cycle as a working fluid in the oxy-combustion process for electricity generation. In the Allam cycle, electricity and heat are produced, while pure CO_2 is produced as the only emission. The almost pure, high-pressure oxygen (State 6, see Figure 1) is mixed in the Allam cycle with the preheated, recycled CO_2 flow (State 27). Following this, in the combustion chamber, when the fuel enters (State 14), the combustion gases (State 15) are released at pressure of 200 to 400 bar and temperatures of 700 to 1,250 °C. The hot combustion gases are then expanded through a turbine with pressure ratio of 5 to 15 (State 16). Next, the flue gases enter a heat exchanger with a temperature of 700-800 °C, which allows the effective recovery of the available heat by preheating the recycling streams. A Heat Recovery Steam Generator (HRSG) is placed at the outlet of the recuperator (State 17) to supply the heat needed by the MED-TVC unit, and then the combustion gases (State 18) enter the condenser and are cooled (State 19) to a temperature close to the ambient temperature. Water is separated from the stream (State 21), and the remaining stream is pure CO_2 (State 20).

2.2 CO_2 utilization

- PtX

The PtX system produces methane through the Sabatier reaction via two main processes; 1) electrolysis, which splits water into O_2 (State 4) and H_2 (State 2) with extra electricity from renewable energy, and 2) the Sabatier reaction, which converts H_2 (State 3) and CO_2 (State 7) into Synthetic Natural Gas (SNG) (State 12) and water

(State 11). In this way, the PtX is able to convert renewable energy into fuel, without emissions. SNG is used as the fuel in the production of electricity in Allam cycle.
The produced waste heat in the methanation unit can be recycled in a heat exchanger network and used for supplying the system heating requirement and improving the total efficiency of the power plant.

- WWTP

The WWTP unit uses sCO_2 for extraction. sCO_2 from the Allam cycle (State 23) is injected to the extraction unit, which is filled with wastewater, and after the extraction, the purified water is separated for further processing. Then the mixture (State 33) of sewage impurities and sCO_2 is isothermally depressurized in the separation unit, and the supercritical CO_2 is converted to CO_2 with a pressure slightly higher than the triple point pressure (State 34).

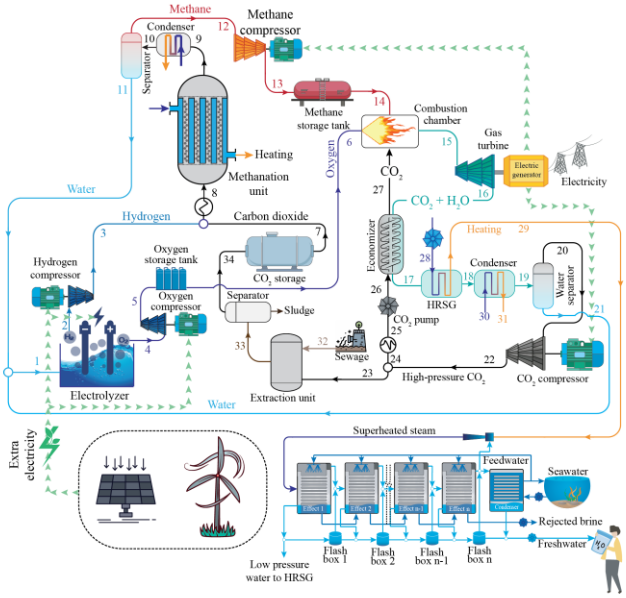

Figure 1: Schematic of the proposed system

3. Modeling

The proposed integrated system in Figure 1 is evaluated based on thermodynamic energy and exergy analysis. MATLAB is used to model the MED-TVC unit and EES is used as a computational tool for the rest of the system components. All system components are evaluated separately by applying thermodynamic equations including energy balance, mass balance, and exergy balance. The present study is based on a case study of Denmark, where it is assumed that the methane produced by the methanation unit will be equivalent to 1 % of Denmark's current natural gas consumption and equal to 45 t/day. Additionally, several inputs are considered for the modeling process: Electrolyzer and Methanation reactor operates at ambient pressure and 80 °C and 300 °C.
When renewable energy production exceeds the load demand of the grid, excess electricity can drive water electrolysis process (to produce H_2 and O_2) along with a methanation unit (to produce CH_4 and H_2O). Hydrogen production through PEM electrolysis has become increasingly popular in recent years due to its low maintenance costs and favourable environmental properties. The chemical reactions in PEM are as follows (Rejeb et al., 2022):

$$\mathrm{H_2O + energy \rightarrow H_2 + \frac{1}{2}O_2} \tag{1}$$

$$\text{Cathode: } \mathrm{2H^+ + 2e^+ \rightarrow H_2} \tag{2}$$

$$\text{Anode: } \mathrm{H_2O \rightarrow 2H^+ + \frac{1}{2}O_2 + 2e^+} \tag{3}$$

Additionally, the Gibbs energy minimization method is used to calculate the equilibrium composition of CO_2 hydrogenation. CO_2 is converted to methane by the following reaction:

$$\text{Sabatier reaction: } \mathrm{4H_2 + CO_2 \rightarrow CH_4 + 2H_2O} \tag{4}$$

There are several side reactions that may occur during the hydrogenation of CO_2 (Beyrami et al., 2022):

$$\text{Methanation reaction: } 3H_2 + CO \rightarrow CH_4 + H_2O \quad (5)$$

$$\text{Water gas shift reaction: } H_2O + CO \rightarrow CO_2 + H_2 \quad (6)$$

$$\text{Carbon monoxide reduction: } H_2 + CO \rightarrow C + H_2O \quad (7)$$

$$\text{Carbon dioxide reduction: } 2H_2 + CO_2 \rightarrow C + 2H_2O \quad (8)$$

Then, combustion products and reactants of the Allam cycle are given as (Sleiti and Al-Ammari, 2021):

$$CH_4 + CO_2 + 2O_2 \rightarrow 2CO_2 + 2H_2O \quad (9)$$

Finally for exergy analysis physical, chemical, potential, and kinetic are the main components of exergy. Exergy efficiency refers to how much of the exergy input into a system is converted into useful exergy. It is defined as the ratio of output exergy to input exergy. In the present study due to the presence of chemical reactions, the concept of chemical exergy is essential. For an ideal gas mixture, the molar chemical exergy is calculated using the following equation:

$$\overline{ex}_{ch} = \sum_k x_k \overline{ex}_{ch}^k + RT_0 \sum_k x_k ln(x_k) \quad (10)$$

where x_k and $\overline{ex}_{ch}^k$ are the molar fraction and standard chemical exergy of the *k*th component.

4. Results and discussion

One of the most important parameters is the Allam cycle Gas Turbine Inlet Temperature (GTIT). For the sensitivity analysis, the GTIT varies between 850 and 1,250 °C. As Figure 2 shows, the exergy efficiency of the system and the output power of the Allam cycle increase with the increase in the GTIT. However, due to the limitations of the gas turbine, a higher GTIT is not possible. Also, by increasing this parameter, the outlet temperature of the gas turbine is increased, resulting in higher fresh water mass flow rate.

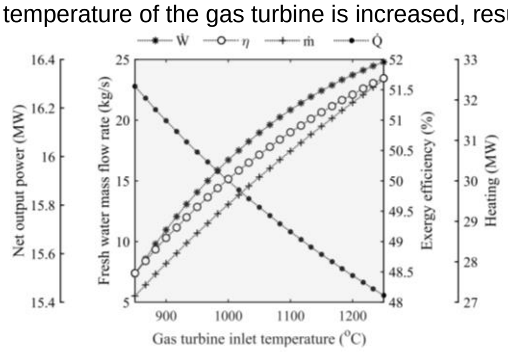

Figure 2: Impact of inlet temperature of the turbine on the system's performance

The Gas Turbine Inlet and Outlet Pressure (GTIP and GTOP) have a great effect on the performance of the MED-TVC and Allam cycle. As shown in Figure 3, with an increase of GTIP, the amount of fresh water decreases initially until P = 325 bar and then increases with increasing GTIP.

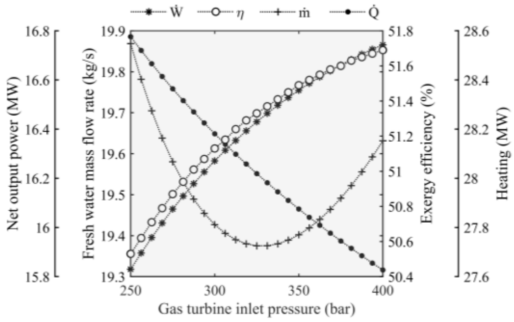

Figure 3: Impact of inlet pressure of the turbine on the system's performance

The effect of GTOP on the system's performance is shown in Figure 4. By increasing the GTOP, more energy reaches the desalination unit, which leads to an increase in the mass flow rate of fresh water, however, net power output and heat decrease. while exergy efficiency increases at first, and then decreases.

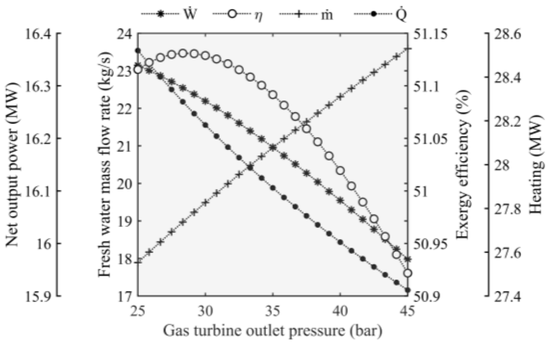

Figure 4: Impact of output pressure of the turbine on the system's performance

Finally, Figure 5 shows the effect of the number of effects of the MED-TVC unit on the fresh water flow rate. The number of effects in the desalination unit does not have a significant effect on the rest of the subsystems, because this unit is separate from the rest of the units and changes in this unit do not affect the rest of the units. According to Figure 5, by increasing the number of effects from 4 to 8, the flow rate of fresh water increases from 11.4 kg/s to 21.62 kg/s (for GTIP = 250 bar and GTOP = 45).

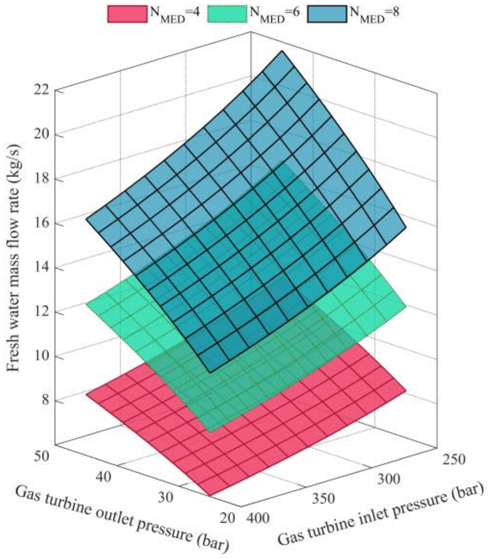

Figure 5: Impact of number of MED-TVC effects on the fresh water mass flowrate

5. Conclusions

The findings of this work show that the Allam cycle has significant potential in assisting the negative emission approaches and preserving the aqueous environment and general health. In general, integrating Power-to-X (PtX), wastewater treatment, and Carbon Capture and Utilization (CCU) can provide opportunities for major CO_2-emitting industries, such as cement factories, power plants, and refineries. Power plants can reuse the Water Resource Recovery Facilities (WRRF)-treated wastewater.

In this study, a new integrated system has been investigated for wastewater treatment and producing electricity, heating, and fresh water. The proposed system consists of a PtX unit, Allam cycle, MED-TVC unit and a WWTP unit. A CO_2-recycling Allam cycle has been used to remove NOx, and the CO_2 that is generated by the Allam cycle has been used to treat wastewater. Several parametric studies have been conducted to investigate the effect of various inputs on system performance. The following are some concluding remarks from the research:

- By increasing the gas turbine inlet temperature from 850 to 1,250 °C, the efficiency of the system and net power output are increased.
- The mass flow rate of produced fresh water decreases with the increasing inlet pressure of the gas turbine to reach a minimum point and then increase.
- While with the increase in the outlet pressure of the gas turbine, the net outputs of heating and power decreased from 28.5 MW to 27.43 MW and 51.11 % to 20.92 %.
- From exergy efficiency point of view, sensitive analysis of the gas turbine outlet pressure show that the optimum pressure is around 27 bar.

Aligning with the objective of this study, future research might focus on improving efficiency and utilizing other auxiliary technologies to increase functionality. A comparative study about the use of different types of desalination units and main power sources can be conducted by considering the economic, exergoeconomic, and life cycle assessment to achieve better performance.

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