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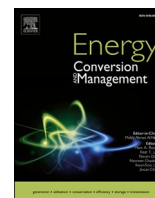
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Novel carbon-negative methane production via integrating anaerobic digestion and pyrolysis of organic fraction of municipal solid waste

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ABSTRACT

The use of bioenergy with carbon capture and storage (BECCS) is vital to reaching the desired climate goals. This study proposed a novel process combining anaerobic digestion, pyrolysis, catalytic reforming and methanation (APRM) to produce biomethane and to capture carbon emission from the organic fraction of municipal solid waste (OFMSW). The evaluation of the process was conducted by using modelling software and techno-economic analysis. The process modelling and evaluation result showed that 151.4 kg CH₄ and 355.64 kg stored carbon emission can be produced from 1 ton dry matter of OFMSW with an energy efficiency of 0.40. 6.74 MJ electricity was required to capture 1 kg of CO₂ via the proposed process. The energy balance of the pyrolysis reaction was investigated. The sensitivities of the pyrolysis temperatures, dewatering technologies and conversion of catalytic reforming on the process performance were analyzed. The result also indicated a positive net profit when using the APRM process to treat the OFMSW based on the calculation of operating expenses and revenue, when the CO₂ negativity can be sold as commodity.

1. Introduction

The increasing CO₂ emission has become one of the essential conundrums of the world. Over 80% of the energy consumption is contributed by fossil fuel globally, which corresponds to >90% of the CO₂ emission from human activities. The atmospheric CO₂ level has increased from 280 ppm in the pre-industrial age to 410 ppm in 2018 [1]. The intergovernmental panel on climate change (IPCC) has reported that without carbon capture and storage (CCS) technologies, the costs to keep atmospheric CO₂ levels below 450 ppm would be doubled by 2100. Furthermore, the possibility of keeping a global temperature increase below 2 °C would be significantly reduced without CCS [2]. Bioenergy with carbon capture and storage (BECCS) has been recognized as a critical negative emission technology, playing a crucial role in reaching the global climate goal [3].

Management of MSW has become an essential global concern focused by the scientific community in the past decades. The increasing urbanization accelerates the generation of municipal solid waste (MSW).

It is predicted that approximate 2.2 billion tonnes per year of MSW will be generated by 2025 [4]. Globally, MSW includes 46% organic waste, 17% paper, 10% plastic, 5% glass, 4% metal and 18 % other types [4]. The organic fraction of municipal solid waste (OFMSW), which contributes the most to the MSW, usually consists of the yard, slaughterhouse, and household residues. The OFMSW negatively affect the environment and public health if it is inappropriately managed.

The organic pollutants and microbial pathogens in the OFMSW contaminate the soil and water sources in the nearby region [5]. It has been suggested that anaerobic digestion (AD) is the most promising way for energy and materials recycling from OFMSW compared to incineration and landfilling [5,6]. An AD process can produce CH₄ riched biogas from the organic stream. The liquid and solid residue of AD called digestate are used as fertilizers. In recent years, the application of digestate as fertilizer has been limited due to its high nitrates content. The Nitrates Directive released by the EU (91/676/EEC) has revealed that the eutrophic water existing in the EU mainly results from the overload of nitrates pollution. Therefore, in order to reduce the water

Abbreviations: AD, Anaerobic digestion; APRM, Process combining anaerobic digestion, pyrolysis, catalytic reforming and methanation; BECCS, Bioenergy with carbon capture and storage; CCS, Carbon capture and storage; DSC, Differential scanning calorimetry; GHG, Greenhouse gas; HTC, Hydrothermal carbonization; IPCC, Intergovernmental panel on climate change; MSW, Municipal solid waste; NC, Nonconventional; OFMSW, Organic fraction of municipal solid waste; PSA, Pressure swing separation; TCR, Thermal catalytic reforming.

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pollution caused by the nitrates abuse, this Directive encourages the EU member states to limit the application of inorganic N fertilizer to crops; limit the applications of organic manure; restrict the application of slurry, manure and sludge on sandy and shallow soils seasonally; record the cropping, livestock numbers and fertilizer application [7]. Indeed, the digestate is a nitrogen-rich source due to its significant content of protein and protein derivatives, which have the potential to result in the eutrophication of the local water system if it is used as fertilizer [8]. Therefore, a more sustainable disposal method should be considered for the management of digestate from OFMSW.

Digestate contains a large number of organics, which is rich in nutrient and chemical heat [9]. Previous study investigated the thermal conversion of digestate into hydrochar, bio-oil, biochar, syngas, growth medium for cultivation of invertebrates and fungal [5,9,10]. Pyrolysis is a promising technology to convert organic waste into valorized products such as biochar, biogas, and bio-oil. By enhancing the product diversity via pyrolysis, the chance of energy & material recovery from digestate increases. A previous study has researched the potential of using digestate of OFMSW as feedstock for the pyrolysis process [11]. However, the main challenge of using digestate as feedstock is the high moisture content (>80%), which requires a massive amount of energy to evaporate during the pyrolysis. The moisture content can be reduced to 60% by applying mechanical dewatering to the digestate [12]. However, a 60% moisture content is still much higher than that in the lignocellulosic biomass, which decreases the energy efficiency of pyrolysis of digestate. Mei et al. have proposed a process that couples the pyrolysis process with steam reforming [13]. The moisture from drying and pyrolysis of digestate usually needs further cleaning, because of its odors and potential organic pollutants. By coupling the pyrolysis with the catalytic steam reforming, the moisture of digestate can be employed as reactants for catalytic reforming reaction. They claimed that 41.26% is the most optimized moisture content for this process when theoretical heating energy is adopted [13]. Hornung et al. studied the thermal catalytic reforming (TCR) process, which combined pyrolysis and steam catalytic reforming. They tested digestate, MSW, and other biomass on their TCR bench-scale reactor. In their studies, the pyrolysis temperature ranged from 400 to 500 °C, and the reforming temperature ranges from 450 to 750 °C. They found that the gas yield increased from 27 to 44% by increasing the reforming temperature from 500 to 750 °C [14–17]. According to the result from the case of using a reforming temperature 750 °C, the reformed gas consisted of H₂, CO₂, CO, CH₄ and etc. Furthermore, only 6% of oil fraction remained after the condensation. Wu et al., Amutio et al. and Xiao et al. studied the catalytic steam reforming of pyrolytic vapor from biomass [18–21]. They applied Ni catalysts to the steam reforming carried out at 600 °C, and found that the oil yield can be reduced to 0 after a condensation of the reforming product. These results presented a 100% conversion of pyrolytic vapor into syngas during the catalytic steam reforming process. In order to increase the value of the reformed gas, a methanation process is usually employed. The methanation process is well-developed and is able to convert CO and CO₂ into CH₄ via a hydrogenation reaction. The TREMP™ methanation technology from Haldor Topsøe can convert syngas from biomass gasification into CH₄ with a 95–98% purity, which has been employed successfully in the GoBiGas 20 MW demonstration plant [22]. By coupling pyrolysis, catalytic steam reforming, and methanation, CH₄ can be produced from digestate. The CH₄ riched gas from methanation of reformed pyrolytic vapor can be integrated with the biogas produced from anaerobic digestion. Thereafter, the CH₄ as a single product corresponds to a single-segment strategy, which can increase the competition of this process in the market [23]. Besides, the side product in the gas product stream is mainly CO₂, which can be separated by applying gas separation and carbon capture technologies. Therefore, the integrated process has the potential to become a BECCS technology. Previous studies investigated the potential of combining the AD and pyrolysis technologies [24–28]. Salman et al. studied the simulation of using biochar produced from digestate to enhance the biomethane production

of AD and evaluate the energy efficiency of pyrolysis, gasification and combustion of the digestate [24,28]. Monlau et al. investigated the feasibility of using biochar produced from digestate as a soil amendment, and the electricity production from combined AD and pyrolysis process [26,27]. However, no study focused on the potential of carbon capture and storage during the process which combined AD and pyrolysis technologies.

In this study, for the first time, a novel BECCS process coupling AD, pyrolysis, catalytic reforming, and methanation (APRM) is proposed to produce biomethane from OFMSW in a carbon-negative way. The implementation of this carbon-negative biomethane production process can reduce the water pollution caused by inappropriate disposal of digestate; supplies energy to the communities nearby; store the carbon dioxide from decomposition of digestate in the long term. The mentioned advantages of this process contribute to reaching the sustainable development goals 6-Clean water and sanitation, 7-Affordable and clean energy, 11-Sustainable cities and communities and 13-Climate action [29].

The main objective of this work is to evaluate the benefits of the proposed APRM process. The specific objectives of this study are to simulate the APRM process by using the Aspen Plus software; calculate the energy requirements and carbon negativity achievements; estimate the heat of the pyrolysis based on input and output streams; evaluate the energy and environmental impact of the APRM process and compare the results to the conventional AD process; analyze the influence of pyrolysis temperature, dewatering technology and catalytic reforming conversion on the process performance; evaluate the feasibility of the process based on the techno-economic analysis.

2. Methods

2.1. Process description

The proposed APRM process is illustrated as shown in Fig. 1. The components in the process have been classified into Input, Process, and Output. All the heat required in this process is assumed to be supplied by electric heating from a renewable source to minimize the carbon emission of this process. The OFMSW is firstly shipped to the APRM plant, and then treated in an anaerobic digestion process. The resulting product from the AD is dewatered using a screw press. The removed water, which contains a high amount of nutrients, can be utilized as a liquid fertilizer. The solid residue is then heated in the heat exchanger, then thermally dried to reduce the moisture content. Thereafter, the dried digestate is introduced into the pyrolysis reactor. The biochar product is removed from the bottom of the reactor. The pyrolytic vapour is heated in a second heat exchanger before it ends up in the catalytic reforming reactor. The reforming gas is then cleaned and cooled using a water scrubber and steam from the dryer. The clean reforming gas is compressed into high pressure for pressure swing separation (PSA) in order to adjust the gas composition for an optimized ratio between H₂, CO, and CO₂ according to the TREMP™ methanation technology [22]. Then the gas is heated up to 200 °C and introduced into the methanation reactor. After methanation, the gas is mixed with the compressed biogas from AD then cooled to the proper temperature for the second PSA. Finally, CH₄ and compressed CO₂ gases are achieved after the PSA treatment.

2.2. Model development

In this study, a kinetic free equilibrium model was developed using ASPEN Plus V11. The proposed process model included the AD, mechanically dewatering, thermal drying, pyrolysis, tar cracking, catalytic reforming methanation processes, as shown in Fig. 2. The modelling was built on experimental data from our previous study focusing on pyrolysis of digestate of OFMSW [11]. The type of blocks is described in Table S1. The list of compounds used in this simulation model is presented in Table S2. Conventional and nonconventional materials were defined in

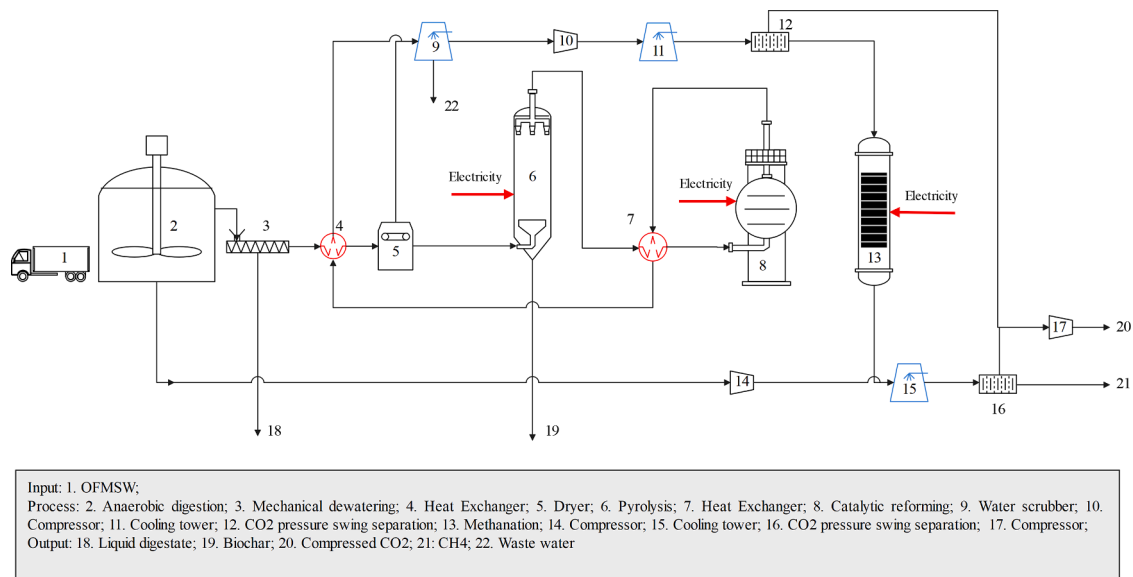


Fig. 1. Schematic APRM process.

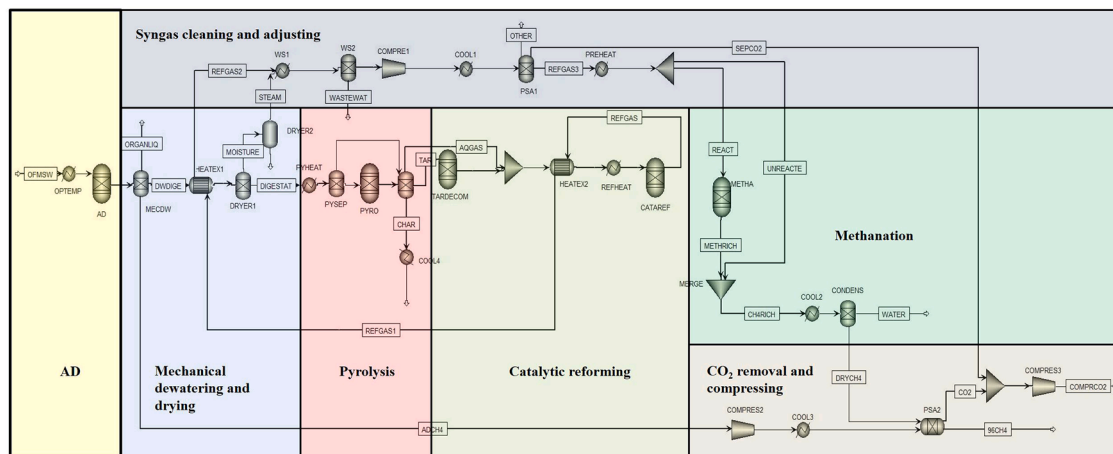


Fig. 2. Simulation flowsheet in ASPEN Plus.

this study. The simulation was performed in the following conditions and assumptions:

- The biomass feed input was 1 ton dry OFMSW with 3.2 ton water content.
- HCOALGEN and DCOALIGT were used to simulate the non-conventional materials. The necessary information for using the property models is present in Table S3.
- The PR-BM activity coefficient model method was chosen as the physical property method [30]
- The heat loss from reactors was assumed to be 10% [31].
- The minimum temperature approach between the hot and cold stream of the heat exchangers was set as 10 °C [32].
- The isentropic and mechanical efficiencies of compressors were set as 0.8 and 0.95, respectively.

2.2.1. Feedstock specification

The materials used for modeling in this study are the OFMSW and its digestate from the biogas plant in Skellefteå, Västerbotten, Sweden. The OFMSW consists of all types of organic solid waste from Skellefteå municipality, including household waste, municipal sewage sludge, and

industrial food residues. The proximate and ultimate composition of the feedstocks are shown in Table 1, which were determined by Eurofins AB, Lidköping, Sweden. The OFMSW and digestate were defined as nonconventional materials.

Table 1
 The proximate and ultimate analysis of OFMSW and digestate [11]

Proximate composition	Sample	
	OFMSW	Digestate
Moisture content (wt.%)	76.3	77.9
C-fix (% dw)	10.4	6.2
Volatile matter (% dw)	66.4	52.7
Calorific value of dry basis (MJ/kg)	18.05	12.92
Ash content (% dw)	23.2	41.1
Ultimate composition (% dw)		
C	42	29.7
H	5.4	2.8
N	5.57	5.37
O*	21.8	25.2
S	0.94	1.07
Cl	0.66	0.06

2.2.2. Anaerobic digestion

The AD of the OFMSW produced CH₄, CO₂, organic liquid, and digestate. In this study, the mass balance of the AD process was derived from the biogas plant in Skellefteå. According to the report from the plant, the mass of solid waste was reduced by 85% during AD. One tonne of the OFMSW can produce 200 Nm³ of CH₄ from AD at 52–53 °C, according to the information from the biogas plant [33]. The biogas usually contains 50–70 vol% CH₄. The rest of the biogas is mainly contributed by CO₂ [34]. In this study, the composition of biogas was defined as 60 vol% CH₄ and 40 vol% of CO₂. In the simulation of the AD process, the Stream *OFMSW* was firstly heated by the Heater *OPTEMP* to the preferred temperature of AD, then introduced into the AD reactor. The AD reactor was modeled by using an RYield block. The resulted product was then separated in the next block *MECDW* as shown in Fig. 2.

2.2.3. Mechanically dewatering and thermal drying

The water content in the digestate can be reduced by applying the mechanical dewatering process. In a previous study, different types of dewatering methods were discussed [16]. In this study, the screw press was chosen to dewater the digestate. The electricity consumption of the screw press was calculated outside of the ASPEN Plus software, which was defined as 1.1 kWh/ton digestate. The moisture content of dewatered digestate was determined to be 60%, according to the reference [16]. The separated liquid digestate abundant in nutrients was named *ORGANLIQ* in the model, which can be utilized as a liquid fertilizer [35]. The drying process of the digestate could be problematic because the water bonded with the matrix of the digestate requires a long time to remove. Zhu et al. studied the thermal drying efficiency of different sludge digestate at 100–200 °C [36]. In this study, a 150 °C of drying temperature was chosen for the thermal drying process. Expected moisture content after drying was defined as 50%. In the model, the dewatered digestate *DWDIGE* was introduced in the dryer, which was modeled by using a separator *DRYER1* and a Flash2 unit *DRYER2*. The *DRYER1* separated the excess water into the *DRYER2*, while left 50% of water in the digestate steam. The *DRYER2* was set at a 150 °C temperature and a 1 bar pressure.

2.2.4. Pyrolysis

In our previous experimental work [11], char, gas, aqueous fraction and tar were produced from the pyrolysis of digestate. A heater *PYHEAT*, a separator *PYSEP*, and an RYield reactor *PYRO* were used to simulate the pyrolysis process. The feedstock was first heated up in the *PYHEAT* heater. Then, the moisture was separated from the digestate by the *PYSEP* separator and remixed with pyrolysis product, facilitating the sensitivity analysis of dewatering technology. The dry digestate was then introduced into the *PYRO* reactor. In this model, The *PYRO* reactor was operated at 550 °C and using a 1 bar pressure. The product yield was based on the experimental data.

The components in the aqueous fraction were analyzed via GC/MS in the previous study [11]. The detected compounds were classified into 11 groups depending on the functional groups. The model compound was chosen to present each group in order to facilitate the model development and improve the convergence rate of the model. The chemical groups and model compounds are listed in Table S4. Tar fraction is abundant of heavy organics, which present as the solid state at room temperature. It becomes a liquid state when heated up to around 40 °C, according to our previous study [11]. In a previous study, the composition of tar from pyrolysis of digestate was analyzed [37]. The proximate and ultimate compositions of char product and gas products were present in our previous study and used in the current study [11]. In the modelling of pyrolysis, the char and tar fractions were determined as nonconventional materials. The product yield of pyrolysis was normalized and listed in Table 2.

2.2.5. Catalytic reforming

Aqueous, tar, and gas products were introduced into the catalytic

Table 2

The modified product yield of pyrolysis in percentage

Component	450 °C	550 °C	650 °C
Char	58.17	55.10	53.20
Tar	9.62	11.18	12.30
H ₂ O	18.85	17.90	17.04
Acetic acid	0.21	0.00	0.00
Cyclohexanol	0.00	0.03	0.00
Acetamide	0.06	0.00	0.00
Methyl-isopropenyl-ketone	0.20	0.12	0.74
Phenyl acetate	0.22	0.12	0.35
1,2,3,6-tetrahydrobenzaldehyde	0.15	0.06	0.01
N-undecane	0.24	0.69	0.24
Cyclopentanone	0.34	0.41	0.18
Benzonitrile	0.04	0.07	0.00
Pyridine	1.35	1.74	1.29
Phenol	0.28	0.23	0.12
Levoglucosan	0.19	0.00	0.15
Pyrazine	1.19	1.05	1.37
H ₂	0.08	0.21	0.36
CH ₄	0.42	0.94	1.30
CO	1.03	1.56	2.56
CO ₂	6.36	7.50	7.65
C ₂ H ₄	0.10	0.22	0.33
C ₂ H ₆	0.23	0.36	0.35
C ₂ H ₂	0.00	0.15	0.17
C ₃ H ₈	0.30	0.34	0.31
C ₃ H ₆	0.38	0.00	0.00
Total	100.00	100.00	100.00

reformer to form an H₂ riched gas. The RYield reactor *TARDECOM*, RGibbs reactor *CATREF*, heater *REFHEAT* are used to simulate this process [30]. As a nonconventional material, the reforming of tar fraction cannot be modelled by using the Gibbs free energy minimization procedure [38]. Therefore, the tar fraction was firstly separated from the pyrolytic vapour, cracked into the chemical substance of each element in the *TARDECOM* reactor, merged with other conventional compounds, heated, and finally introduced into the *CATAREF* reactor together with other products. The *CATAREF* was set as 800 °C and 1 bar pressure. Table 3 concluded the previous experimental work of catalytic

Table 3

Catalytic reforming of pyrolytic vapour from pyrolysis of biomass/wastes

Feedstocks	Configuration of pyrolysis/ Catalytic reforming	Catalyst	Conversion (%)	Ref.
Forest pine wood waste, particle size 1–2 mm	Pyrolysis: 500 °C in fluidized bed; Catalytic reforming: 600–700 °C in fixed bed	Ni supported on Al ₂ O ₃ , doped with Ca (Sud Chemie, G90LDP)	100 %	[18]
Meat and bone meal	Pyrolysis: 450–500 °C; Catalytic reforming: fixed bed 700–800 °C	Ni/γ-Al ₂ O ₃ doped with Ca, Mg, K; calcined dolomite	97.9–99.0 %	[39]
Wood sawdust	Pyrolysis: fixed bed 500 °C; Catalytic reforming: fixed bed 800 °C	Ni/CaAlO _x	95.0–99.0 %	[19]
Wood chips, Pig manure compost	Pyrolysis: fluidized bed 600 °C; Catalytic reforming: fixed bed 650 °C	Ni/Al ₂ O ₃ , Ni-brown coal char	> 99.0 %	[21]
Wood pellet	Pyrolysis: Screw reactor 500 °C; Catalytic reforming: fixed Bed 760 °C	Ni/Al ₂ O ₃	73.0 %	[20]
Olive tree cuttings	Pyrolysis: fixed bed 750 °C; Catalytic reforming: fixed Bed 900 °C	Biochar + Ni/Al ₂ O ₃ -CeO ₂	66.2 %	[40,41]

reforming of pyrolytic vapour from pyrolysis of biomass/wastes. Among all the studies, the pig manure compost and the meat and bone meal has a similar chemical composition with the digestate used in this study [21,39]. The conversion of the catalytic reforming of these two studies reached up to 97.9–99.0 %. In this study, the Ni catalysts was assumed to be used, and the conversion of the feedstocks into syngas was assumed to be 100% in order to facilitate the simulation. The variation of the conversion of catalytic reforming was further studied in the sensitivity analysis.

2.2.6. Syngas cleaning and adjusting

Several heat exchangers, water scrubbers, and gas compressors were used in this model. The sensible heat of syngas produced from catalytic steam reforming (800 °C) was recovered to heat the pyrolytic vapour and dewatered digestate by using two heat exchanger units *HEATEX1* and *HEATEX2*. After the syngas have been cooled by the heat exchangers, it was mixed with the steam from *DRYER2*, cleaned, and then cooled by a water scrubber *WS2*. The water content in the syngas and the steam from *DRYER2* was condensed and separated as *WASTEWAT* stream. Before introducing the syngas into the methanation reactor *METHA*, the gas composition needs to be adjusted according to the TREMP™ methanation technology, where the molar ratio of (H₂-CO₂)/(CO + CO₂) should reach 3, which requires a CO₂ removal of the dry syngas [22]. Also, a pressure swing separation (PSA) technology was chosen in this study to absorb the excess CO₂ gas. After the water scrubber treatment, the dry syngas was compressed to 16 bar in the gas compressor *COMPRES1*. Thereafter, the compressed syngas was cooled to the PSA's working temperature, which was set as 40 °C. Thereafter, the CO₂ molar ratio in the syngas was adjusted in the PSA separator.

2.2.7. Methanation

The methanation process was simulated by using an RGibbs block *METHA*. The input was preheated to 200 °C, according to the suggestion in reference [22]. The product was estimated by minimizing the Gibbs energy of the product. The syngas conversion followed the experimental data from TREMP™ methanation technology, which assumes a 95% conversion of CH₄ in the product [22]. In this study, the dry syngas stream was split into two streams representing 95 and 5% of the mass of the initial syngas; only the major stream was introduced into the *METHA* reactor.

2.2.8. CO₂ removal and compressing

The CH₄-rich gas from methanation was cooled down to condense the produced water. Then, the dry gas was mixed with the compressed biogas from AD and cleaned in the PSA to remove the CO₂ gas. The separated CO₂ from PSA was captured via compressing [42]. The energy consumption of PSA was defined as 114 kWh/ton CO₂ according to the literature [43].

2.2.9. The impact assessment

Two impact assessment procedures were defined in this study in order to evaluate the performance of the process, and to compare the result with those of the conventional AD process.

Process energy efficiency. The process energy efficiency η of the process is defined as shown in the following equation (1),

$$\eta = \frac{E_{\text{product}}}{E_{\text{process}} + E_{\text{feedstock}}} \times 100\% \quad (1)$$

while E_{product} represent the chemical heat of the produced CH₄, E_{process} is the electricity demand during the process, $E_{\text{feedstock}}$ is the chemical heat of the feedstock OFMSW.

Energy demand per capita of stored CO₂. Carbon negativity is represented by the compressed CO₂ and biochar in this study, which is converted

into CO₂ equivalents as CO₂eq. The total carbon negativity is represented by the CO₂ storage in kg. The energy demand per kg of CO₂ storage, E_{NC} , is an important indicator for evaluating the economic feasibility of using this process for BECCS, which is described using the following equation (2),

$$E_{\text{NC}} = \frac{E_{\text{process}}}{\text{NegativeCO}_2\text{eq}} \times 100\% \quad (2)$$

while the *Negative CO₂eq* is the amount of compressed CO₂ and the CO₂ equivalent been stored in biochar.

2.3. Sensitivity analysis

2.3.1. Pyrolysis temperature

The pyrolysis temperature is one of the key sensitivity parameters in this study. It is well known that pyrolysis temperature can influence both the composition and yield of pyrolytic products. Three pyrolysis temperatures of 450, 550, 650 °C were used in this study. In addition, the experimental results from previous research were used [11]. It should be noticed that char stability is one of the essential factors which affect the carbon stability of the biochar in the soil. Our previous study investigated the stability of carbon in biochar, by using the accelerated oxidation method [44]. According to this previous study, the recalcitrant carbon ratios in biochar from pyrolysis of 450, 550, 650 °C were defined as 0.26, 0.73, 0.85, respectively. The amount of recalcitrant carbon represents the carbon that can be stored for a long time. This study calculated the negative CO₂eq of biochar by assuming that all the recalcitrant carbon is converted to CO₂ gas.

2.3.2. Dewatering technology

Different dewatering technologies highly affects the dewatering efficiency and the moisture content of the dewatered digestate. Table 4 describes three conventional technologies for dewatering the digestate. In this study, different technologies were tested to analyze how sensitive the process performance is to the level of dewatering. For each dewatering technology, the highest electricity consumption and lowest moisture content were chosen for a sensitivity analysis.

3. Result and discussion

3.1. Model validations

The model of the AD process was validated by using the industrial data from the biogas plant Skellefteå biogasanläggning [33]. The model of pyrolysis process was validated by using the data from our experimental work, which used the OFMSW and digestate from the same biogas plant [11]. The model of catalytic reforming and PSA was validated by conducting the literature review of the catalytic reforming of pyrolytic vapour. The methanation process was validated by using the industrial data from the GoBiGas project [45]. The main limitations of such models are listed as follows: i. The composition of the OFMSW and digestate could varies from place to place, which can affect the feasibility of this process. ii. The pyrolysis experiment was conducted on bench scale fixed bed reactor. The product yield could be different from it in a continuous process. iii. The catalytic reforming of the pyrolytic

Table 4
The different dewatering technology and their efficiency [12]

	Mositure content after dewatering (wt %)	Electricity consumption (kWh/ton)	Dry matter content in the separated liquid (wt%)
Centrifuge	70–82	1.80–7.00	<0.5
Screw press	60–75	0.24–1.10	<0.5
Belt press	75–79	0.08–0.12	<0.5

vapour is an emerging technology. More research needs to be done on this technology.

3.2. Mass and energy balance

The Sankey diagrams of mass and energy balance of the APRM process are presented in Figs. 3 and 4. After AD, over 80% of the mass of the feedstock was converted into liquid digestate, which can be used as fertilizer. From the entire process, 151.4 kg CH₄ (with a purity of 96 vol %), 304.5 kg compressed CO₂, 80.8 kg biochar, and 184.5 kg wastewater were obtained. The APRM process increased the biogas production by 10% compared to when using the conventional AD process.

According to Fig. 4, it can be observed that the biogas produced from AD contains 40% of the energy from the feedstock. Also, 2398.53 MJ of electricity power was required to sustain this process. Two heat exchangers recovered 291.4 MJ of heat from the reforming gas, reducing energy consumption by around 10%. The chemical heat contained in the CH₄ product was increased by 12.2% when using the APRM process compared to the conventional AD process. For the APRM process, the process energy efficiency η was 0.40, and the E_{NC} was 6.74 MJ/kg CO₂eq.

It was indicated in many studies that pyrolysis of digestate is an exothermic reaction [46–49]. Therefore, the energy demand in pyrolysis reactor is defined as the heat required for heating up the reactant to the pyrolysis temperature, while the heat of pyrolysis is not taken into account. An rough estimation of the pyrolysis reaction heat is present as Table S6 in the Supplementary file. Furthermore, the heat loss from drying (>150C), methanation (>200C), and compressors before PSA (>400C) have the potential to be recovered.

3.3. Comparison between APRM and conventional CH₄ production processes

In order to evaluate the performance of the APRM process, the comparison between APRM and other methane production technologies (AD and gasification) was discussed. As shown in Table 5, the process energy efficiency of the APRM process is higher than it of the AD process, but lower than the gasification process. According to Fig. 4, the major consumption of electricity is contributed by drying, pyrolysis, reforming, and PSA treatment. Higher process energy efficiency could be reached by applying more efficient water removal and CO₂ separation technologies. Furthermore, only the APRM process has the potential to store carbon emission with an E_{NC} of 6.74 MJ/kg negative CO₂eq. In addition, the APRM process can reach nearly a 100% recycling rate of OFMSW.

3.4. Sensitivity analysis

3.4.1. Pyrolysis temperature

The pyrolysis temperature is an essential parameter for the pyrolysis process. It affects the composition of the pyrolysis vapor, yield of each product, and the heat required during the process [37]. In this study, three pyrolysis temperatures were chosen to evaluate the influence of the pyrolysis temperature on the performance of the APRM process. The product yield from the experiment was modified via a rigorous calculation based on mass and elemental balance. The detailed product distribution of the pyrolysis reactor is shown in Table 2. The effect of the pyrolysis temperature on the key indicators is presented in Table 6 and Fig. 5. The electricity consumption of each process, the CH₄ production, and amount of compressed CO₂ show a positive correlation with the pyrolysis temperature. This is because a higher pyrolysis temperature increases the yield of the pyrolytic vapor. Hence, more energy is required to heat this vapor. The reforming and methanation processes would consume more energy at higher temperatures compared to at lower temperatures, resulting in a higher total electricity consumption. It is difficult to determine which pyrolysis temperature is preferable for energy production as well as the environment. Hence, we have introduced two indicators, namely the process energy efficiency and energy demand per kg of negative CO₂eq. As shown in Fig. 5, the 550 °C case shows the highest process energy efficiency of 0.40, while demanding energy of 6.74 MJ to store 1 kg negative CO₂eq. The 450 °C case shows the lowest process energy efficiency of 0.39 and requires the highest energy of 7.07 MJ per kg negative CO₂eq, among the three APRM process cases.

3.4.2. Dewatering technology

In this sensitivity analysis, three different dewatering technologies combined with a 550 °C as pyrolysis temperature were chosen. The dewatering technology decides the moisture content of the digestate, which strongly affects the process energy efficiency due to the significant power demand of the drying process. The screw press, centrifuge, and belt press represent 1.1, 7, 0.12 kWh/tonne digestate power demand for dewatering and to reach 60, 70, 75 % of moisture contents after dewatering, respectively. The electricity consumption of the mechanical dewatering and thermal drying of different dewatering technology is presented in Table 7. It can be seen that the screw press could be the most energy-efficient technology. Fig. 6 shows that the decisive parameter for each indicators is the moisture content after dewatering, which positively correlates to the E_{NC} and is negatively correlated to the η . Therefore, one of the critical optimizations of this APRM process is to find an economically feasible way to increase the dewatering rate. One of the candidate technologies could be hydrothermal carbonization

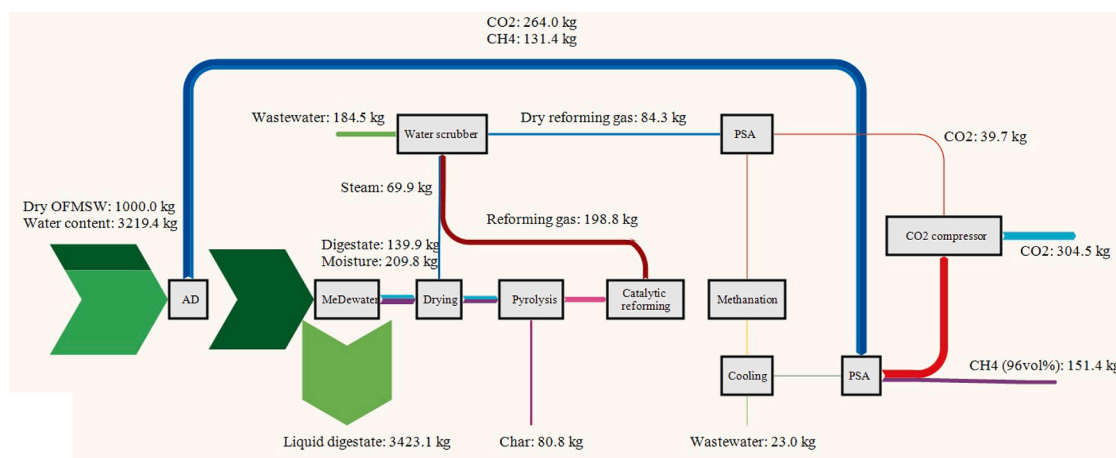


Fig. 3. Mass balance of the APRM process using a pyrolysis temperature of 550 °C and a screw press as the dewatering technology.

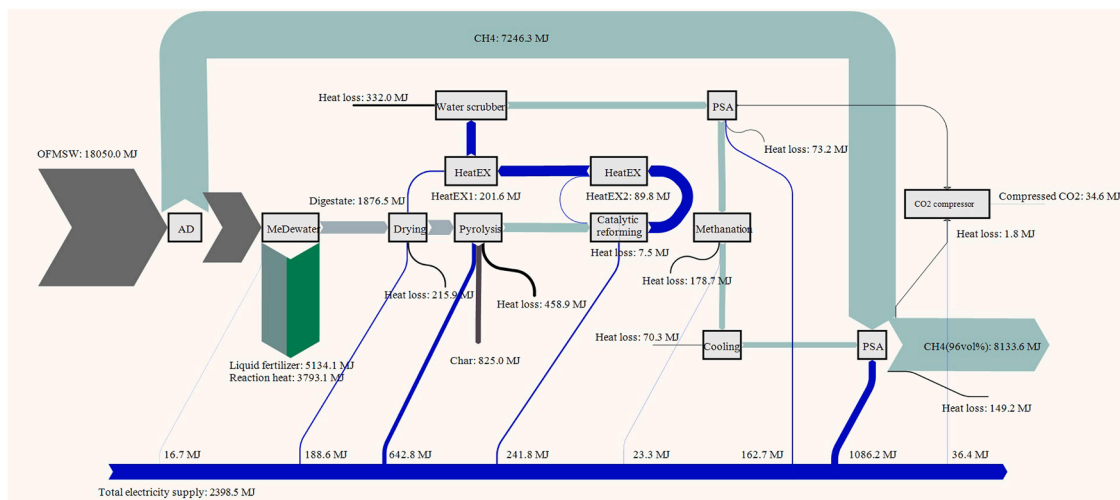


Fig. 4. Energy balance of the APRM process with pyrolysis temperature of 550 °C and a screw press as the dewatering technology.

Table 5

A comparison between the APRM and AD processes

	Total energy input/ MJ	CH ₄ production /MJ	Process energy efficiency	Waste reduction
APRM	20448.53	8133.63	0.40	100 %
AD [33]	18050.00	7227.00	0.40	85 %
Gasification: GoBiGas demonstration plant [45]	–	–	0.65	–

Table 6

Sensitivity analysis of pyrolysis temperature with screw press as dewatering technology

	450C	550C	650C
Electricity consumption/ MJ	676.36	766.24	806.34
Mechanical dewatering	16.71	16.71	16.71
Drying	188.59	188.59	188.59
Pyrolysis	573.08	642.80	716.75
Catalytic reforming	171.45	241.83	277.17
Methanation	18.21	23.27	24.19
PSA and Compressing	1266.14	1285.33	1288.90
CH ₄ production from digestate/ MJ	695.68	906.63	937.07
Total CH ₄ production/ MJ	7922.67	8133.63	8164.07
Compressed CO ₂ / kg	300.07	304.61	305.45
Negative CO ₂ eq of biochar/ kg	68.86	69.92	62.74

(HTC) process. It is claimed that the HTC process combined mechanical dewatering can save 70% energy during reduction of the moisture content of digestate [37,50].

3.4.3. Catalytic reforming efficiency

Another crucial parameter is the catalytic reforming efficiency. The catalytic reforming of the pyrolytic vapor is an emerging technology. The information on the selection of the catalyst and reforming conversion is limited. According to the literature review on the catalytic reforming of pyrolytic vapour present in Chapter 2.2.5, the conversion of the pyrolytic vapour varies largely. Therefore, a sensitivity analysis on the conversion is essential. In this study, the range of the conversion has been determined from 60 to 100%, depending on the catalyst performance. The result of the sensitivity analysis is shown in Fig. 7. It revealed η increases as the increase of the conversion of catalytic reforming, while E_{NC} shows reversed the trend.

3.5. Techno-economic assessment

The techno-economic assessment of the proposed process coupling with the commercial AD process was conducted through an operating expense (OPEX) calculation based on prices in Sweden. 550 °C as pyrolysis temperature, screw press for dewatering and a 100% conversion of catalytic reforming are employed for the OPEX calculation. The mass flow of the proposed process was defined based on the digestate productivity of Skellefteå biogasanläggning. The capacity and conditions of reactors are listed in Table S5. In this OPEX calculation, the OPEX and revenue of AD are not included since the individual AD is a profitable process. The number of labourers is assumed to be the same as the AD plant. Therefore the personal cost is defined as 0. In Table 8, the assumptions for OPEX calculation is listed. An average of 0.02% of the total catalyst is assumed to be replaced every hour to make up for the irreversible deactivation. The CO₂eq captured and stored by compressed CO₂ and biochar could be a potential commodity depending on future policies. The price of the negative CO₂eq was defined as the Swedish carbon tax-1200 SEK/ ton CO₂ emission. Table 9 present the main process parameters which were used for the OPEX calculation. The result of the annual OPEX is present in Table 10. The annual OPEX result shows that the proposed process is not profitable if it is independent from AD, with a loss of -0.055 SEK per kg dry OFMSW. This number can reach 0.371 SEK income per kg dry OFMSW when the negative CO₂eq can be sold as a commodity.

3.6. Discussion and future work

This proposed APRM process convert digestate waste into bio-methane and negative CO₂eq, which contributes to the UN's sustainability goals. In the IPCC AR6 report, the BECCS is described as the dominant CO₂ removal technology in the climate stabilization scenarios [58]. This affordable APRM process has the potential to play an important role in the BECCS field. In Sweden, the widely applied waste sorting technology enables the separation of OFMSW from MSW then disposed of through the AD process [33,59]. A considerable amount of digestate is available in Sweden. For example, in other developed countries, Germany, 35% of MSW is used for energy generation, 51% is used for recycling, and 14% is treated by composting [60]. However, the management of OFMSW varies from developed countries to developing countries. In China, >10% of the world's MSW is produced and treated by landfill (52%), incineration (45%) and composting (3%) [61]. Most OFMSW was not sorted out from the MSW, then disposed of via landfill and incineration. To implement the proposed APRM process for OFMSW treatment, a developed waste sorting system and biogas plant are the

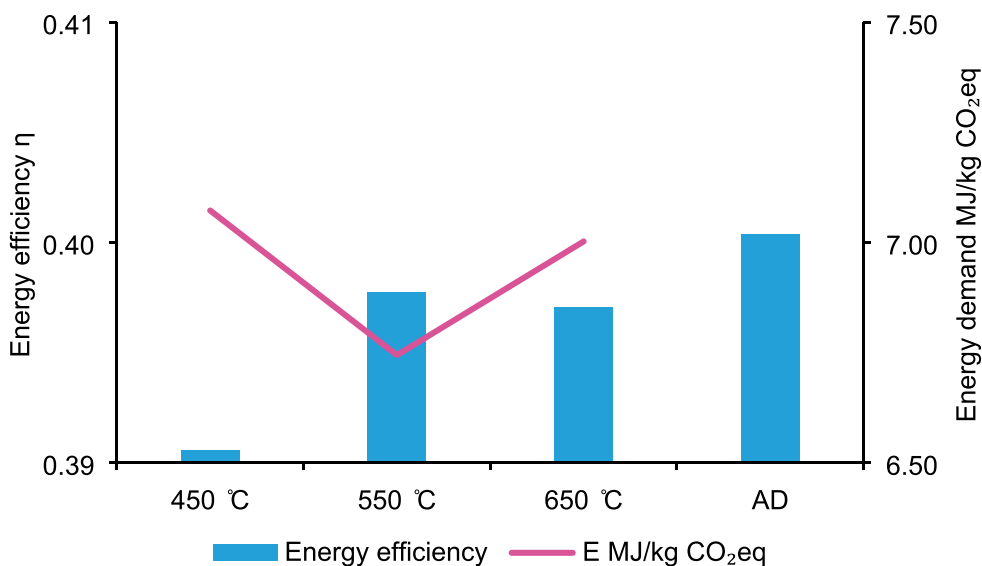


Fig. 5. The sensitivity analysis of pyrolysis temperature with screw press as dewatering technology and 100% conversion of catalytic reforming.

Table 7

The electricity consumption of mechanical dewatering and thermal drying of different dewatering technology with pyrolysis temperature of 550 °C

Electricity consumption/ MJ	Screw press	Centrifuge	Belt press
Mechanical dewatering	16.71	106.33	1.82
Thermal drying	188.59	502.91	754.36
Total	205.30	609.24	756.18

prerequisites. Furthermore, a life cycle analysis and a capital expenditures calculation are recommended for further validation of the feasibility of this process.

4. Conclusion

A steady-state equilibrium model was built to simulate the proposed process combining anaerobic digestion, pyrolysis, catalytic reforming, methanation, and carbon storage. 151.4 kg CH₄ (96 vol%), 355.64 kg

negative CO₂ equivalent storage is produced from the APRM process by consuming 1000 kg of dry matter organic fraction of municipal solid waste and 2398.53 MJ electricity. The model result and literature review shows that heat released from the pyrolysis of digestate can make up the energy demand of the pyrolysis reactor. 550 °C of pyrolysis temperature, screw press is the optimized parameter for this process in aspects of process energy efficiency and the energy demand for storage of 1 kg CO₂eq. The conversion of catalytic reforming shows a positive correlation with the process performance. The operating expenses and revenue calculation indicated a positive net profit of 0.371 SEK per kg dry organic fraction of municipal solid waste, if the CO₂ negativity can be sold as commodity.

CRediT authorship contribution statement

Shule Wang: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Yuming Wen:**

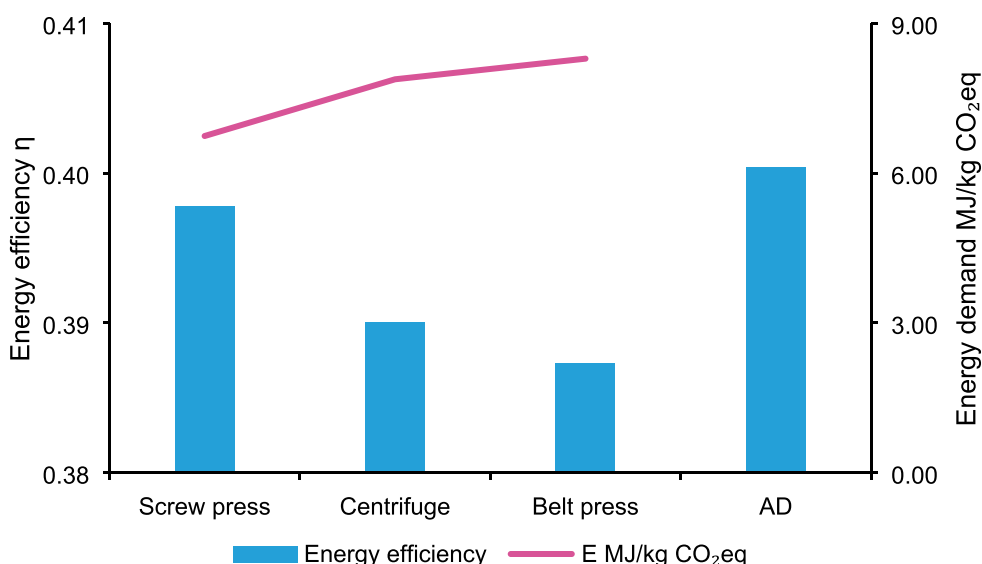


Fig. 6. The sensitivity analysis of dewatering technology at a base case of 550 °C of pyrolysis temperature and 100% conversion of catalytic reforming.

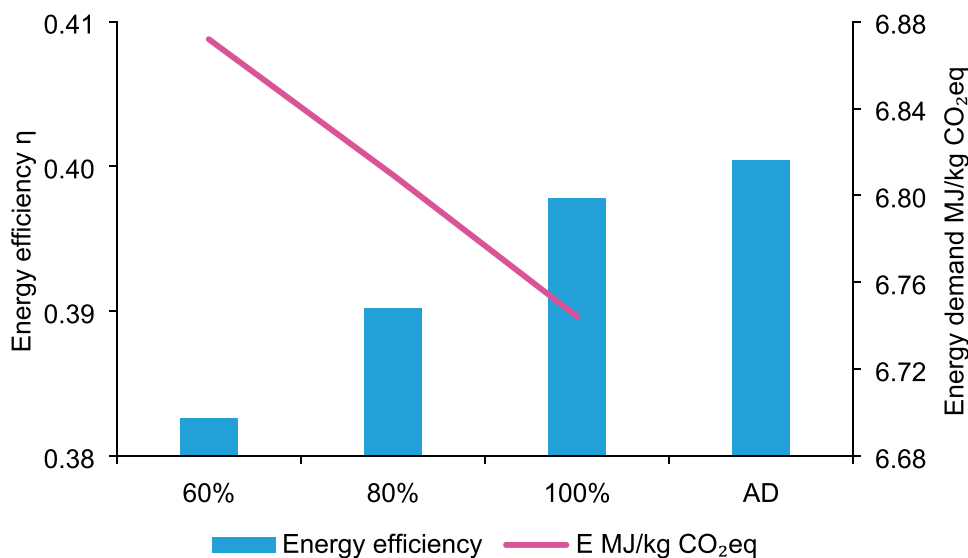


Fig. 7. The sensitivity analysis of catalytic reforming conversion at a base case of 550 °C of pyrolysis temperature and screw press dewatering.

Table 8

The assumptions of the prices for the OPEX calculation

Assumption and prices	Value	Ref.
Duration of operation (h/year)	8000	
Feedstock (SEK/kg)	0	
Electricity (SEK/kWh)	0.45	[51]
Biomethane (SEK/kg)	17.21	[52]
Carbon negativity (SEK/kg)	12.00	[53]
Reformer catalyst (SEK/kg)	60.00	[54]
Methanation catalyst (SEK/kg)	60.00	[54]
Solid disposal (SEK/kg)	3.9	[55]
Catalyst bulk density (kg/m ³)	1000	[54]
Gas hour space velocity for reforming and methanation catalyst (h ⁻¹)	4454	[56]
Replace of the irrisible deactivated catalyst reforming and methanation catalyst (make-up) (h ⁻¹)	0.02%	[57]

Table 9

The summary of the main parameters for OPEX calculation

Paramters	Values	Paramters	Values
Consumption			
OFMSW in dry basis (kg/h)	362.38	Catalytic reforming Electricity (kWh/h)	24.34
Mechanical dewatering Electricity (kWh/h)	1.68	Catalytic reforming Mak-up catalyst (kg/h)	0.004
Drying Electricity (kWh/h)	18.98	Methanation Electricity (kWh/h)	2.35
Pyrolysis Electricity (kWh/h)	64.70	Methanation Mak-up catalyst (kg/h)	0.002
Solid disposal (kg/h)	0.006	PSA and compression (kWh/h)	129.38
Product			
Biomethane produced from digestate (kg/h)	5.17	CO ₂ eq (kg/h)	128.88

Conceptualization, Validation, Resources, Data curation, Writing – review & editing, Visualization. **Ziyi Shi:** Software, Validation, Writing – review & editing. **Ilman Nuran Zaini:** Methodology, Formal analysis, Resources, Data curation, Visualization. **Pär Göran Jönsson:** Writing – review & editing. **Weihong Yang:** Conceptualization, Writing – review & editing.

Table 10

The annual OPEX of APRM process

Parameters	Values (MSEK/year)	Parameters	Values (MSEK/year)
Cost			
Mechanical dewatering Electricity	0.006	Methanation Electricity	0.008
Drying Electricity	0.068	Methanation Mak-up catalyst	0.001
Pyrolysis Electricity	0.233	Solid disposal	0.00
Catalytic reforming Electricity	0.088	PSA and compression	0.47
Catalytic reforming Mak-up catalyst	0.004		
Product			
Biomethane	0.711	Negative CO ₂ eq	1.237
Total OPEX	0.872	Total revenue	0.711
Total revenue with negative CO ₂ eq	1.948	Gross production cost (SEK/kg- dry OFMSW)	0.301
Loss/Gain based on OPEX (SEK/kg- dry OFMSW)	-0.055	Loss/Gain based on OPEX with negative CO ₂ eq (SEK/kg- dry OFMSW)	0.371

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.enconman.2021.115042>.

References

- [1] Lindsey R. Climate Change: Atmospheric Carbon Dioxide. Climate.gov. N. Climate.gov. online. 2020 <https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide>.
- [2] Babin A, Vaneckhaute C, Iliuta MC. Potential and challenges of bioenergy with carbon capture and storage as a carbon-negative energy source: A review. *Biomass Bioenergy* 2021;146:105968. <https://doi.org/10.1016/j.biombioe.2021.105968>.
- [3] Fajardy M, Mac Dowell N. The energy return on investment of BECCS: is BECCS a threat to energy security? *Energy Environ Sci* 2018;11:1581–94.
- [4] Tyagi VK, Fdez-Güelfo LA, Zhou Y, Álvarez-Gallego CJ, García LIR, Ng WJ. Anaerobic co-digestion of organic fraction of municipal solid waste (OFMSW): Progress and challenges. *Renew Sustain Energy Rev* 2018;93:380–99.
- [5] Peng W, Lü F, Hao L, Zhang H, Shao L, He P. Digestate management for high-solid anaerobic digestion of organic wastes: A review. *Bioresour Technol* 2020;297:122485. <https://doi.org/10.1016/j.biortech.2019.122485>.
- [6] Zamri MFMA, Hasmady S, Akhbar A, Ideris F, Shamsuddin AH, Mofijur M, et al. A comprehensive review on anaerobic digestion of organic fraction of municipal solid waste. *Renew Sustain Energy Rev* 2021;137:110637.
- [7] E. Commission. The Nitrates Directive. Environment. online. <https://ec.europa.eu/environment/water/water-nitrates/>.
- [8] Zhang T, Wu X, Shaheen SM, Zhao Q, Liu X, Rinklebe J, et al. Ammonium nitrogen recovery from digestate by hydrothermal pretreatment followed by activated hydrochar sorption. *Chem Eng J* 2020;379:122254.
- [9] Barbanera M, Pelosi C, Taddei AR, Cotana F. Optimization of bio-oil production from solid digestate by microwave-assisted liquefaction. *Energy Convers Manage* 2018;171:1263–72.
- [10] Hung C-Y, Tsai W-T, Chen J-W, Lin Y-Q, Chang Y-M. Characterization of biochar prepared from biogas digestate. *Waste Manage* 2017;66:53–60.
- [11] Wen Y, Shi Z, Wang S, Mu W, Jönsson PG, Yang W. Pyrolysis of raw and anaerobically digested organic fractions of municipal solid waste: Kinetics, thermodynamics, and product characterization. *Chem Eng J* 2021;415.
- [12] A. Karunanithi. System analysis of de-watering process for treating biogas digestate. 2014.
- [13] Mei Z, Chen D, Zhang J, Yin L, Huang Z, Xin Q. Sewage sludge pyrolysis coupled with self-supplied steam reforming for high quality syngas production and the influence of initial moisture content. *Waste Manage* 2020;106:77–87.
- [14] Neumann J, Binder S, Apfelbacher A, Gasson JR, Ramírez García P, Hornung A. Production and characterization of a new quality pyrolysis oil, char and syngas from digestate – Introducing the thermo-catalytic reforming process. *J Anal Appl Pyrol* 2015;113:137–42.
- [15] Sattar A, Leeke GA, Hornung A, Wood J. Steam gasification of rapeseed, wood, sewage sludge and miscanthus biochars for the production of a hydrogen-rich syngas. *Biomass Bioenergy* 2014;69:276–86.
- [16] Ouadi M, Jaeger N, Greenhalf C, Santos J, Conti R, Hornung A. Thermo-Catalytic Reforming of municipal solid waste. *Waste Manage* 2017;68:198–206.
- [17] Neumann J, Meyer J, Ouadi M, Apfelbacher A, Binder S, Hornung A. The conversion of anaerobic digestion waste into biofuels via a novel Thermo-Catalytic Reforming process. *Waste Manage* 2016;47:141–8.
- [18] Arregi A, Lopez G, Amutio M, Barbarias I, Bilbao J, Olazar M. Hydrogen production from biomass by continuous fast pyrolysis and in-line steam reforming. *RSC Adv* 2016;6:25975–85.
- [19] Chen F, Wu C, Dong L, Vassallo A, Williams PT, Huang J. Characteristics and catalytic properties of Ni/CaAlOx catalyst for hydrogen-enriched syngas production from pyrolysis-steam reforming of biomass sawdust. *Appl Catal B* 2016;183:168–75.
- [20] Efiika CE, Wu C, Williams PT. Syngas production from pyrolysis-catalytic steam reforming of waste biomass in a continuous screw kiln reactor. *J Anal Appl Pyrol* 2012;95:87–94.
- [21] Xiao X, Meng X, Le DD, Takarada T. Two-stage steam gasification of waste biomass in fluidized bed at low temperature: Parametric investigations and performance optimization. *Bioresour Technol* 2011;102:1975–81.
- [22] From coal to clean energy. National Energy Technology Laboratory. U.S.D.o. energy. online. 2011. <https://www.netl.doe.gov/sites/default/files/netl-file-from-coal-to-clean-energy-march-april-2011.pdf>.
- [23] Target Market Selection. NetMBA. 2010 <http://www.netmba.com/marketing/market/target/>.
- [24] Salman CA, Schwede S, Thorin E, Yan J. Enhancing biomethane production by integrating pyrolysis and anaerobic digestion processes. *Appl Energy* 2017;204:1074–83.
- [25] Hübner T, Mumme J. Integration of pyrolysis and anaerobic digestion – Use of aqueous liquor from digestate pyrolysis for biogas production. *Bioresour Technol* 2015;183:86–92.
- [26] Monlau F, Francavilla M, Sambusiti C, Antoniou N, Solhy A, Libutti A, et al. Toward a functional integration of anaerobic digestion and pyrolysis for a sustainable resource management. Comparison between solid-digestate and its derived pyrochar as soil amendment. *Appl Energy* 2016;169:652–62.
- [27] Monlau F, Sambusiti C, Antoniou N, Barakat A, Zabaniotou A. A new concept for enhancing energy recovery from agricultural residues by coupling anaerobic digestion and pyrolysis process. *Appl Energy* 2015;148:32–8.
- [28] Salman CA, Schwede S, Thorin E, Li H, Yan J. Identification of thermochemical pathways for the energy and nutrient recovery from digested sludge in wastewater treatment plants. *Energy Procedia* 2019;158:1317–22.
- [29] UN. Take Action for the Sustainable Development Goals. United Nations. online.2021 <https://www.un.org/sustainabledevelopment/sustainable-development-goals/>.
- [30] Kanatli TK, Ayas N. Simulating the steam reforming of sunflower meal in Aspen Plus. *Int J Hydrogen Energy* 2021;46(57):29076–87.
- [31] D. Gunarathne, C. Cuvilas, J. Li, Y. Weihong, W. Blasiak. Biomass Pretreatment for Large Percentage Biomass Co-Firing. 12th International Conference on Boiler Technology (ICBT 2014), Szczyrk, Poland, 2014.
- [32] Nurdiawati A, Zaini IN, Amin M, Sasongko D, Aziz M. Microalgae-based coproduction of ammonia and power employing chemical looping process. *Chem Eng Res Des* 2019;146:311–23.
- [33] Här produceras världens renaste drivmedel. Skellefteå Municipality. B. Skellefteå. Online. 2019. <https://skelleftea.se/invanare/startside/bo-trafik-och-miljo/avfall-och-atervinning/skelleftea-biogas-anlaggning>.
- [34] S. Tanigawa. Fact Sheet | Biogas: Converting Waste to Energy. in: J. Stolark, (Ed.). Environmental and Energy Study Institute, online, 2017.
- [35] Tampio E, Martinen S, Rintala J. Liquid fertilizer products from anaerobic digestion of food waste: mass, nutrient and energy balance of four digestate liquid treatment systems. *J Cleaner Prod* 2016;125:22–32.
- [36] Zhu F, Zhang Z, Jiang H, Zhao L. The Study of Sewage Sludge Thermo-Drying Efficiency. *Procedia Environ Sci* 2012;16:363–7.
- [37] Wang S, Persson H, Yang W, Jönsson PG. Pyrolysis study of hydrothermal carbonization-treated digested sewage sludge using a Py-GC/MS and a bench-scale pyrolyzer. *Fuel* 2020;262:116335. <https://doi.org/10.1016/j.fuel.2019.116335>.
- [38] Kumar A, Nouredдини H, Demirel Y, Jones DD, Hanna MA. Simulation of Corn Stover and Distillers Grains Gasification with Aspen Plus. *Trans ASABE* 2009;52:1989–95.
- [39] Lónyi F, Vályon J, Someș E, Hancsók J. Steam reforming of bio-oil from pyrolysis of MBM over particulate and monolith supported Ni/γ-Al₂O₃ catalysts. *Fuel* 2013;112:23–30.
- [40] Adrados A, Lopez-Urionabarrenechea A, Solar J, Requies J, De Marco I, Cambra JF. Upgrading of pyrolysis vapours from biomass carbonization. *J Anal Appl Pyrol* 2013;103:293–9.
- [41] Adrados A, Lopez-Urionabarrenechea A, Acha E, Solar J, Caballero BM, de Marco I. Hydrogen rich reducing gases generation in the production of charcoal from woody biomass carbonization. *Energy Convers Manage* 2017;148:352–9.
- [42] Ali U, Font-Palma C, Akram M, Agbonghae EO, Ingham DB, Pourkashanian M. Comparative potential of natural gas, coal and biomass fired power plant with post-combustion CO₂ capture and compression. *Int J Greenhouse Gas Control* 2017;63:184–93.
- [43] Shigaki N, Mogi Y, Haraoka T, Sumi I. Reduction of Electric Power Consumption in CO₂-PSA with Zeolite 13X Adsorbent. *Energies*. 2018;11(4):900. <https://doi.org/10.3390/en11040900>.
- [44] B. Chen. Pyrolytic biochar stability assessed by chemical accelerating aging method. TRITA-ITM-EX2020. p. 35.
- [45] Thunman H, Seemann M. The GoBiGas plant. In: Materazzi M, Foscolo PU, editors. *Substitute Natural Gas from Waste*. Academic Press; 2019. p. 455–74.
- [46] Han F, Yun S, Zhang C, Xu H, Wang Z. Steel slag as accelerant in anaerobic digestion for nonhazardous treatment and digestate fertilizer utilization. *Bioresour Technol* 2019;282:331–8.
- [47] Zhang C, Yun S, Li X, Wang Z, Xu H, Du T. Low-cost composited accelerants for anaerobic digestion of dairy manure: Focusing on methane yield, digestate utilization and energy evaluation. *Bioresour Technol* 2018;263:517–24.
- [48] Serrano A, Wyn H, Dupont L, Villa-Gomez DK, Yermán L. Self-sustaining treatment as a novel alternative for the stabilization of anaerobic digestate. *J Environ Manage* 2020;264:110544.
- [49] Huang X, Yun S, Zhu J, Du T, Zhang C, Li X. Mesophilic anaerobic co-digestion of aloe peel waste with dairy manure in the batch digester: Focusing on mixing ratios and digestate stability. *Bioresour Technol* 2016;218:62–8.
- [50] Wang S, Wen Y, Hammarström H, Jönsson PG, Yang W. Pyrolysis behaviour, kinetics and thermodynamic data of hydrothermal carbonization-Treated pulp and paper mill sludge. *Renewable Energy* 2021;177:1282–92.
- [51] Electricity prices and electricity contracts. Statistics Sweden. Online.2021 <https://www.scb.se/en/finding-statistics/statistics-by-subject-area/energy/price-trends-in-the-energy-sector/electricity-prices-and-electricity-contracts/>.
- [52] Tanka biogas. Skellefteå kommun. Online.2021 <https://skelleftea.se/invanare/startside/bo-trafik-och-miljo/avfall-och-atervinning/skelleftea-biogas-anlaggning/tanka-biogas>.
- [53] Sweden carbon tax. IEA International Energy Agency. Online.2021 <https://www.iea.org/policies/12725-sweden-carbon-tax>.
- [54] Hot recommend nickel methanation catalyst catalytic reforming price. Alibaba. Online.2021 <https://www.alibaba.com/product-detail/Hot-recommend-nickel-methanation-catalyst-catalytic-60707184457.html?spm=a2700.7724857.normal.offer.d.title.79064105zkZF>.
- [55] SwedishWaste Management 2018. A. Sverige. Online. 2018. https://www.avfallsverige.se/fileadmin/user_upload/Publikationer/Avfallshantering_2018_EN.pdf.
- [56] Rönisch S, Köchermann J, Schneider J, Matthischke S. Global Reaction Kinetics of CO and CO₂ Methanation for Dynamic Process Modeling. *Chem Eng Technol* 2016;39:208–18.

- [57] S.M. Jones, P.; Snowden-Swan, L.; Susanne, K.J.; Pimphan, M.; Asanga, P.; Eric, T.; Abhijit, D.; Jacob, J. Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels: Fast Pyrolysis and Hydrotreating Bio-Oil Pathway. U.S.D.o.E.B.T. Office. Online. 2013. <https://www.nrel.gov/docs/fy14osti/61178.pdf>.
- [58] Sixth Assessment Report Chapter 5. T.I.P.o.C. Change. Online. 2020. https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter_05.pdf.
- [59] Biogas. Tekniska Verken. Online.2021 <https://www.tekniskaverken.se/om-oss/verksamheten/biogas/>.
- [60] Pujara Y, Pathak P, Sharma A, Govani J. Review on Indian Municipal Solid Waste Management practices for reduction of environmental impacts to achieve sustainable development goals. J Environ Manage 2019;248:109238.
- [61] Ding Y, Zhao J, Liu J-W, Zhou J, Cheng L, Zhao J, et al. A review of China's municipal solid waste (MSW) and comparison with international regions: Management and technologies in treatment and resource utilization. J Cleaner Prod 2021;293:126144.