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Scenarios for carbon capture integration in a waste-to-energy plant

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ABSTRACT

In this work, the performance of an amine-based post-combustion carbon capture system using MEA (monoethanolamine) integrated to a Waste-to-Energy (WtE) plant is studied. WtE plants are affected by fluctuations at different time-scales, due to changes in waste properties as well as variations in district heat demand. A dynamic model of the combined plant is used to study the effect of flue gas fluctuations on capture plant operation, and the effect of integrating the capture plant into the WtE plant.

When the two plants are considered separately, the heat requirement of the capture plant corresponds to 27% of the nominal thermal capacity of the WtE plant. When integrating the two plants, steam extraction from the boiler drum to provide the heat necessary to the capture plant reduces the power and district heat production of the WtE plant by 30% and 6% respectively, while extraction from the turbine causes a reduction of 8% and 12%. By modifying the condensers' temperature, it is possible to maintain 96% of the original district heat production. By performing carbon capture only when excess heat is available, it is possible to capture 47% of the CO_2 emitted by the WtE plant, while reducing the power production by only 5%.

1. Introduction

Carbon capture and storage (CCS) has been identified as an important part of the solution to reach the 2050 goal to cut greenhouse gas (GHG) emissions and mitigate climate change [1,2].

Waste management contributes to GHG emissions but its impact will vary widely with the treatment methods applied (or lack thereof) [3]. The Waste Hierarchy established by the EU has the purpose to regulate waste management in order to reduce its impact [4]. Waste-to-Energy (WtE) should be applied to those Municipal Solid Waste (MSW) fractions that cannot be reused or recycled, in order to (1) reduce their volume and destroy contaminants, (2) recover useful energy, and (3) reduce emissions to the environment as compared to landfill [5].

European WtE plants incinerate waste that is approximately 50% biogenic (i.e. originated from renewable biomass). Therefore, energy from WtE plants has a lower carbon intensity than that produced through fossil fuel-based power plant [6]. When combined with carbon capture technologies, WtE would therefore enable for energy production with negative CO_2 emissions, and thus help mitigating climate change. It has indeed been estimated that the treatment of MSW in WtE-CCS plants would allow for the removal from the atmosphere of 2.8 billion tons of CO_2 per year [7].

While at different stages of development, CCS technologies for application in combustion processes can be categorized into pre-combustion technologies, oxy-fuel combustion, chemical looping combustion and post-combustion technologies [8]. In pre-combustion processes, the fuel is pre-treated to generate a syngas, from where CO_2 is separated before the syngas is combusted [9]. In oxy-fuel combustion, a mixture of oxygen and CO_2 is used instead of air as the oxidising agent, so that the resulting flue gas mainly consists of CO_2 and water, which can be easily separated from the stream [10]. The flue gas is typically recirculated to allow for temperature control. Also in the case of chemical looping combustion, oxygen is used as the oxidizer. However, in this case, the oxygen is provided by a metal oxide and the process takes place in two steps in separate reactors [11]. In post-combustion capture solutions, CO_2 is removed from the flue gas after combustion. For this reason, they are the most straightforward options for retrofitting existing plants [8].

Few works can be found in the literature where WtE plants has been considered in combination with CCS solutions. The retrofitting of a generic WtE plant with a calcium looping cycle for removal of CO_2 from the flue gas was study through a techno-economic

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analysis [12]. Results are compared with a benchmark absorption capture plant. Life-cycle analysis and techno-economic analysis were carried out for a grate incineration plant without and with CO_2 capture technologies, including monoethanolamine (MEA) absorption, pressure/vacuum swing adsorption, and oxy-fuel combustion [13]. A process for the gassification of MSW to produce syngas was studied in combination with a chemical looping solution for CO_2 capture [14]. Three post-combustion solutions (MEA absorption, advanced amine absorption and membrane separation) have been analysed in terms of design and costs for the application to a general WtE plant [15]. However, none of the works above considered the behavior of actual WtE plant, which are typically subjected to both fluctuations in fuel properties and energy delivery. The experimental work of Fagerlund et al. [16] tested the potential of amine absorption for CCS in an operating WtE plant. The operation of the pilot capture plant highlighted remaining challenges such as energy integration and the effects of WtE process fluctuation on capture.

In this work, we consider the implementation of post-combustion carbon capture using amine absorption in a real WtE plant. Amine absorption is an established technology for separation of CO_2 from gas mixtures. Amine absorption found its first full scale application on offshore plants [17] and was later adopted as a post-combustion capture solution. The first full scale post combustion application was in a coal-fired power plant where CO_2 was captured from the flue gas [18]. Among amine solvents, MEA (monoethanolamine) is the most exploited for post-combustion CO_2 separation, since it is particularly suitable for low CO_2 partial pressure applications [19].

However, some characteristics of WtE plants might be challenging for the integration of carbon capture technologies. Indeed, MSW is a highly inhomogeneous mixture, with chemical and physical properties that vary continuously in an unpredictable way. This causes continuous fluctuations in CO_2 concentration in the flue gas as well as in the flue gas amount. Such fluctuations affect the operation of the absorption plant and the heat necessary for the solvent regeneration process, which in return can affect the WtE plant energy production.

The thermal power generated by the WtE plant is utilized to produce both power and district heat in proportions that fluctuate over the year to follow the district heat demand. Since MSW needs to be process shortly after being delivered to the plant due to limited storage capacity (and continuous delivery), the thermal production of the plant is approximately constant over the year. In the warmer months of the year, the heat that is not utilized by the district heating network is dissipated to the surroundings.

The heat produced by the WtE plant can also potentially be used to cover the heat demands of the absorption carbon capture plant. The integration of CCS absorption systems in coal-fired power plants is well established [20], while only few absorption plants integrated to WtE plants exist [21]. A WtE plant is subject to inevitable fluctuations, which make necessary to consider dynamic operation when analyzing such a system. Many studies can be found in the literature that describe and study the dynamics of absorption systems [22] and its integration to different kinds of plants, such as steel mills [23], natural gas- [24] and coal-fired power plants [25]. The possibility to operate energy systems in a flexible way acquires more and more importance as the penetration of intermittent renewable energy sources increases [26].

The aim of this work is to assess how different scenarios for operation of the absorption plant impact the heat and power delivery of the WtE plant. While previous works do not consider the dynamic operation of the WtE plant, this analysis addresses this important feature. The Returkraft WtE plant in Kristiansand, Norway, is used as case study. Historical data from a full year of operation are used to determine fluctuations in both flue gas properties and district heat requirement. The capture plant is designed based on the analysis of the operational data from the considered WtE plant. A dynamic model of the absorption plant is developed and integrated into a previously developed model of the WtE plant [27] in order to investigate different scenarios for operation of the combined processes.

The studied system and the mathematical model used to describe it are presented in Section 2. After describing the selected scenarios in Section 3, results are presented and discussed in Section 4. Finally, conclusions are summarized in Section 5.

2. Methods

The present work investigates scenarios for operation of an absorption system for carbon capture integrated to a WtE plant. The Returkraft WtE plant in Kristiansand, Norway, is used as a case study. While the study is specific to a real WtE plant, its characteristics are typical for many Europe WtE plants and its results will be relevant to many grate-fired CHP (Combined Heat and Power) WtE plants.

2.1. WtE plant

Fig. 1 shows a schematic overview of the considered WtE plant. The plant started operation in 2010 and it incinerates 130 000 t of household and industrial solid waste every year (in proportion approximately 60–40%) to produce heat and power. The plant has a nominal thermal power capacity of 54 MW and produces approximately 90 GWh electricity and 120 GWh district heat per year.

Waste is incinerated in the combustion chamber producing a high temperature flue gas, whose thermal energy is recovered through a series of heat exchangers. The heat recovered from the flue gas is collected in a drum that contains saturated water and vapor.

Steam is extracted from the boiler drum and is further heated in the superheater section of the boiler. The superheated steam is sent to a steam turbine, where it expands to produce electricity. The expanded steam leaves the turbine at two pressure levels. The steam from the low pressure stage of the turbine enters a low pressure (LP) condenser where the cold water from the district heating network is pre-heated. The steam from the high pressure turbine stage is sent to the high pressure condenser, where the district heating water preheated in the LP condenser is further heated and sent back to the district heating network. During the summer months the water flow circulating in the district heating network is not enough to absorb the condensation heat of the steam sent to the condensers. Therefore, an additional water flow is added to the district heating (DH) water flow before this is sent to the condensers. An equal amount of water flow is then separated from the DH water flow and sent to a cooler, where the extra heat is dispersed in the surroundings.

As a combustion product, the plant produces also approximately 25 Nm_3/s of flue gas with an average CO_2 concentration of 10 vol% (wet basis). This corresponds to approximately 150 000 t CO_2 emissions per year. After heat recovery, the flue gas undergoes a series of cleaning treatments, which are necessary to bring pollutant concentrations below national and international regulation emission limits. After the cleaning system, the flue gas has a temperature of approximately 140 °C and a pressure close to the atmospheric one.

Since the plant needs to process MSW continuously, the plant is generally operated at full load as much as possible. Exceptions are start-up and shut-down procedures that take place due to maintenance and emergency stops. Process set points are also

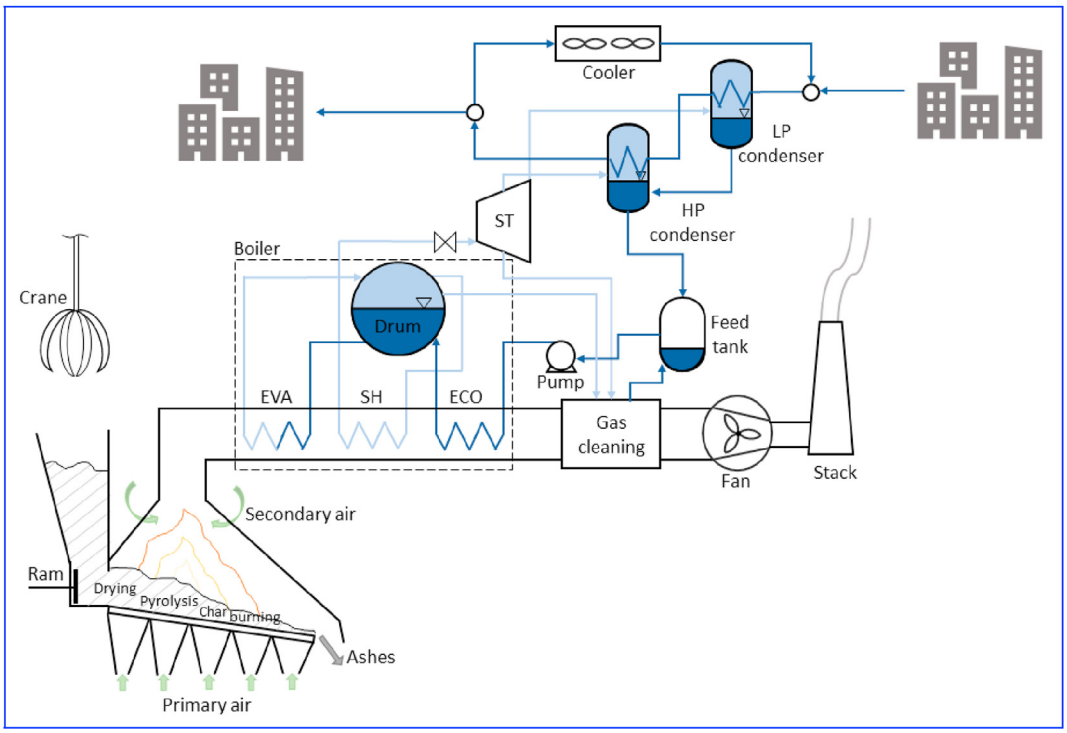

Fig. 1. A schematic illustration of Returkraft WtE plant (Kristiansand, Norway). Steam streams are light blue, while dark blue indicates water streams. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

sometimes adjusted to cope with waste batches that have significantly different properties than average.

However, due to the high heterogeneity of MSW, process conditions varies continuously during operation, in spite of the action of the control system. Flue gas flow and its CO_2 content can both vary up to ± 10%. Moreover, due to variation in the district heat demand, the delivered heat ranges from 35 MW in winter to 3.6 MW in summer, and the delivery temperature varies between 90 °C and 115 °C. The electricity production is approximately 20% higher in summer than in winter. Since the WtE plant has contractual obligations regarding heat delivery to the DH network, plant operation is heat driven.

2.2. Amine absorption plant

The absorption plant uses 30 wt% aqueous MEA. Fig. 2 shows a schematic representation of the plant. The flue gas from the WtE plant needs to be cooled down to approximately 40 °C before it can enter the absorption column. In the adsorption column, the amine solution absorbs CO_2 from the flue gas, which leaves the absorber at the top of the column. The processed flue gas is heated up to ca 120 °C by recovering heat from the incoming flue gas, before being sent to the stack. The CO_2-rich amine solution is sent to a stripper, which is connected to a reboiler and to a overhead condenser. In the stripper, the CO_2-rich amine is separated into a lean solution, which is recirculated to the absorber, while a CO_2 gas stream that is separated at the condenser. While the absorption process is exothermic, the regeneration process requires a large amount of heat, which is provided in the reboiler by a steam flow.

The carbon capture system is designed for the average amount of flue gas of 25 Nm_3/s and a CO_2 concentration of 9.8 vol%. The desired nominal capture efficiency is 85%.

2.3. The dynamic models

The dynamic model of the WtE plant was developed and validated in a previous work of ours [27]. The model was developed using Simulink, which is a MATLAB-based environment for modelling and simulation of dynamic systems [28]. A detailed description of the WtE plant model can be found in Ref. [27], where the model was validated using process data from the same WtE plant considered in this work. To easily integrate both models, the model for the capture plant was developed using the same software as the WtE plant model. The dynamic model of the absorption plant was developed following the approach presented by Flø et al. [29], who developed a general dynamic model for post combustion absorption process and validated it using process data from operation of a pilot plant.

The dynamics of each of the process components in the absorption plant shown in Fig. 2 was described by a set of differential equations. The absorber, stripper and heat exchangers were modelled as one-dimensional systems, discretized in the direction of the moving fluid as a series of control volumes. The condenser, reboiler and buffer tank were modelled as block diagrams.

A generic column model was used for modeling of the absorber and the stripper [29]. In each control volume, a gas and a liquid phase are present. The mass balance of the i-th component in the gas phase g in the control volume n can be written as:

$$\frac{dM_i^{n,g}}{dt} = F_{i,in}^{n,g} - F_{i,out}^{n,g} - F_i^{n,g-l} \quad (1)$$

where the subscript i indicates the different components in the gas phase. Moreover, $M_i^{n,g}$, $F_{i,in}^{n,g}$, and $F_{i,out}^{n,g}$ are the mass, the inlet mass flow and the outlet mass flow of the i-th gas component. Finally, $F_i^{n,g-l}$ is the flow rate of the component i from the gas to the liquid phase.

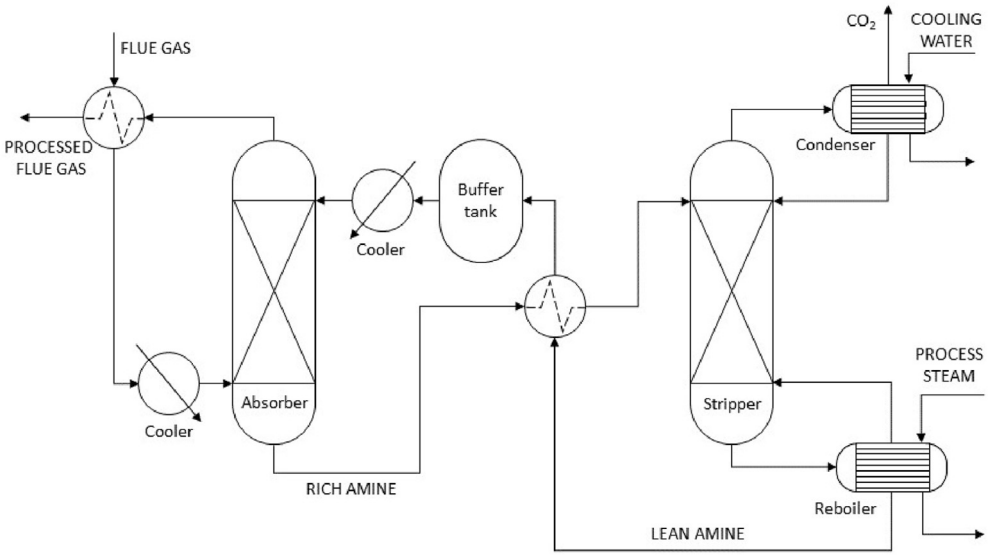

Fig. 2. A schematic illustration of the absorption plant.

Similarly, the mass balance on the liquid side was written as:

$$\frac{dM_i^{n,l}}{dt} = F_{i,in}^{n,l} - F_{i,out}^{n,l} + F_i^{n,g-l} \tag{2}$$

where the superscript l is used to indicate the liquid phase.

The energy balances for the gas and liquid phases were written as:

$$C^{n,g}\frac{dT^{n,g}}{dt} = F_{in}^{n,g}c_p^g\left(T^{n-1,g} - T^{n,g}\right) - Q^{n,g-l} - \sum_i F_i^{n,g-l}\Delta H_i^{g-l} \tag{3}$$

$$C^{n,l}\frac{dT^{n,l}}{dt} = F_{in}^{n,l}c_p^l\left(T^{n-1,l} - T^{n,l}\right) + Q^{n,g-l} \tag{4}$$

where $C^{n,g}$ and $C^{n,l}$ were the total heat capacity of the gas and the liquid phase, $F_{in}^{n,g}$ and $F_{in}^{n,l}$ were the total gas and liquid mass flow entering the control volume, $T^{n,g}$ and $T^{n,l}$ were the temperature of the gas and liquid phase, c_p^g and c_p^l were the specific heat capacities of gas and liquid phase, $Q^{n,g-l}$ was the sensible heat exchanged between the gas and liquid phase, and ΔH_i was the latent heat associated with the transfer of component i from the gas to the liquid phase.

Heat and mass transfer between the gas and liquid phase was modelled through a rate based approach as:

$$F_i^{g-l} = K_i\left(p_i^g - p_i^{eq}\right) \tag{5}$$

$$Q^{g-l} = H\left(T^g - T^l\right) \tag{6}$$

where p_i^g p_i^{eq} were the partial and equilibrium pressure of the component i in the gas phase. K_i and H were the overall mass and heat transfer coefficient, calculated as described by Flø et al. [29].

The condenser and reboiler were modelled as flash tanks, where the gas and liquid phase were assumed to be in equilibrium and both completely mixed. The mass and energy balances for the gas and liquid phases were:

$$\frac{dM_i^g}{dt} = F_{i,in}^g - F_{i,out}^g - F_i^{g-l} \tag{7}$$

$$\frac{dM_i^l}{dt} = F_{i,in}^l - F_{i,out}^l + F_i^{g-l} \tag{8}$$

$$C^g\frac{dT^g}{dt} = F_{in}^g h_{in}^g - F_{out}^g h_{out}^g - Q^{g-l} - \sum_i F_i^{g-l}\Delta H_i^{g-l} \tag{9}$$

$$C^l\frac{dT^l}{dt} = F_{in}^l h_{in}^l - F_{out}^l h_{out}^l + Q^{n,g-l} \tag{10}$$

where h was the specific enthalpy of the considered phase.

The buffer tank was modelled as a continuously stirred tank. The amine solution in the buffer tank was considered to only be in liquid form, and to be perfectly mixed. The mass and energy balances were:

$$\frac{dM_i^l}{dt} = F_{i,in}^l - F_{i,out}^l \tag{11}$$

$$C^l\frac{dT^l}{dt} = F_{in}^l h_{in}^l - F_{out}^l h_{out}^l \tag{12}$$

2.4. Interactions between the WtE plant and the amine absorption plant

The WtE plant and the amine absorption plant interact mainly through two process flows, which will be the main focus of the analysis in this work:

- **Flue gas flow**: the flue gas that leaves the existing gas cleaning system of the WtE plant is sent to the absorption plant for removal of CO_2. The flue gas has a temperature of approximately 140 °C and an average composition of 10% vol CO_2, 8% vol O_2 and 21% vol H_2O (N_2 represents most of the remaining fraction). The relatively high oxygen content in the flue gas is due to (1) the

fact that MSW combustion takes place with excess air, to ensure complete combustion of this heterogeneous material (the combustion air is controlled to achieve 6% O_2 in the raw flue gas), and (2) air infiltration along the flue gas path from the combustion chamber to the stack. The flue gas water content is also high, due to (1) high moisture content of the MSW (15–30%), and (2) washing of the flue gas in the gas cleaning system. Once the gas has been processed in the absorption plant, it is sent back to the WtE plant, where it is released into the atmosphere through the stack. In order to comply with local regulations, the flue gas sent to the stack needs to have a temperature higher than 120 °C.

- **Heat for absorbent regeneration**: the amine regeneration process in the absorption plant reboiler is energy intensive and requires a large amount of heat to maintain the temperature of the solvent at approximately 120 °C. This heat can be provided by a portion of the steam produced by the WtE plant.

The operation of the capture plant also requires cooling water as well as electric power for running pumps and fans. While the sum of the energy requirements of these components is not negligible, its analysis is not included in the present work, since it is small in comparison to the energy requirements of similar components in the WtE plant.

Table 1 presents the WtE plant data most relevant for the integration of the capture plant. Table 2 lists the main process parameters of the absorption plant (see Table 2).

3. Investigated cases

To better investigate how the capture plant can be integrated with the WtE plant, several scenarios were considered:

- **CASE 0:** the flue gas from the WtE plant cleaning system is sent to the capture plant. The heat necessary for amine regeneration in the reboiler is provided by an external source. Therefore, the operation of the capture plant does not affect the operation of the WtE plant and its heat and power delivery (base case).
- **CASE 1a:** the heat necessary for the amine regeneration process is provided by steam extracted from the WtE plant boiler. The other WtE plant process parameters are kept constant. Steam extraction from the boiler will have an impact on both heat and power delivery of the WtE plant.
- **CASE 1b:** the heat necessary for the amine regeneration process is provided by steam extracted from the turbine. The other WtE plant process parameters are kept constant. Similar to Case 1a, there will be an impact on both heat and power delivery of the WtE plant.
- **CASE 2:** the heat necessary for the amine regeneration process is provided by steam extracted from the boiler drum. The heat delivery to the district heating network is kept as equal as possible to the base case by modifying some key process parameters such as condensers' temperature. This will cause a further impact on the power delivery of the WtE plant.
- **CASE 3a and 3b:** the capture plant is operated only when excess heat is available at the WtE plant. Steam extraction from the boiler drum and the turbine will have a different impact on the CO_2 capture efficiency of the CCS plant, as well as on the power production of the WtE plant.

It should be noticed that while in the other cases 85% capture will be achieved over the year, in Case 3 the overall capture efficiency will be lower. Fig. 3 summarizes the investigated cases.

Table 1
Main WtE plant parameters and nominal data.

Parameter	Value	Unit
Thermal power capacity	55	MW
Drum pressure	54	bar_a
Turbine nominal power	14	MW
HP condenser nominal pressure	0.785	bar_a
LP condenser nominal pressure	0.394	bar_a
Turbine steam extraction nominal pressure	3.8	bar_a
Turbine steam extraction nominal flow	2	kg/s
Temperature of heat delivered to DH network	90–115	°C

Table 2
Main nominal process parameters for the absorption plant.

Parameter	Value	Unit
Absorber temperature	40	°C
Reboiler temperature	120	°C
Condenser temperature	95	°C
Stripper pressure	2	bar_a
Lean loading	0.28	kmol/kmol
Rich loading	0.49	kmol/kmol
capture efficiency	85	%
Absorber liquid/gas ratio	3	kg/kg

4. Results and discussion

4.1. WtE plant data

Process data were collected every 5 min for a full year of operation of the WtE plant. Fig. 4 shows the flue gas flow leaving the WtE plant (Fig. 4a) and its CO_2 content (Fig. 4b) throughout the year 2018. The outliers in June were due to a temporary complete shutdown of the plant for scheduled maintenance. Other minor outliers were due to partial shutdown and cooling in connection with operational problems.

Fluctuations take place at different time scales: both in the instantaneous values of the considered process variables (black lines) and in their 7-day moving average (grey lines). After removal of the outliers, 29% of the remaining flue gas measurements deviated more than ± 5% of the corresponding 7-day moving average, while 6% deviated more than ± 10%. The 7-day average values vary from −11% to +14% of the average flue gas value.

The combined fluctuations of flue gas flow and CO_2 concentration gave a CO_2 flow that varied between 2 Nm_3/s and 3 Nm_3/s.

Fig. 5 shows how the heat delivered to the district heating network (black line) and the electric power produced (grey line) vary over the year. Most of the heat produced by the WtE plant is delivered to the DH network during the winter months. However, the demand for district heat is much lower during the summer months and up to 30 MW_{th} are dissipated into the surroundings using cooling fans (blue line). The lower delivery temperature during the summer months (90 °C) with respect to that of the winter months (up to 115 °C) allows for an higher power production in summer (12 MW_{el}) than in winter (9 MW_{el}). Part of the heat that is currently dissipated to the surroundings can be utilized by the CCS plant, causing minimal penalty to the energy production of the plant.

4.2. Case 0

In Case 0, the flue gas from the WtE plant is treated in a capture plant designed to sequestrate 85% of CO_2. Calculations are carried out for the full year 2018. The heat necessary for regeneration of the amine solution is assumed to be provided by an external source.

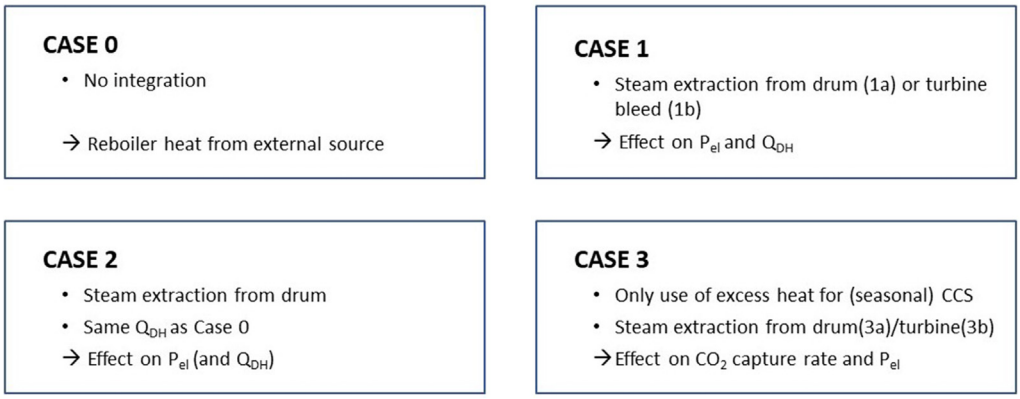

Fig. 3. WtE + carbon capture integration scenarios summary.

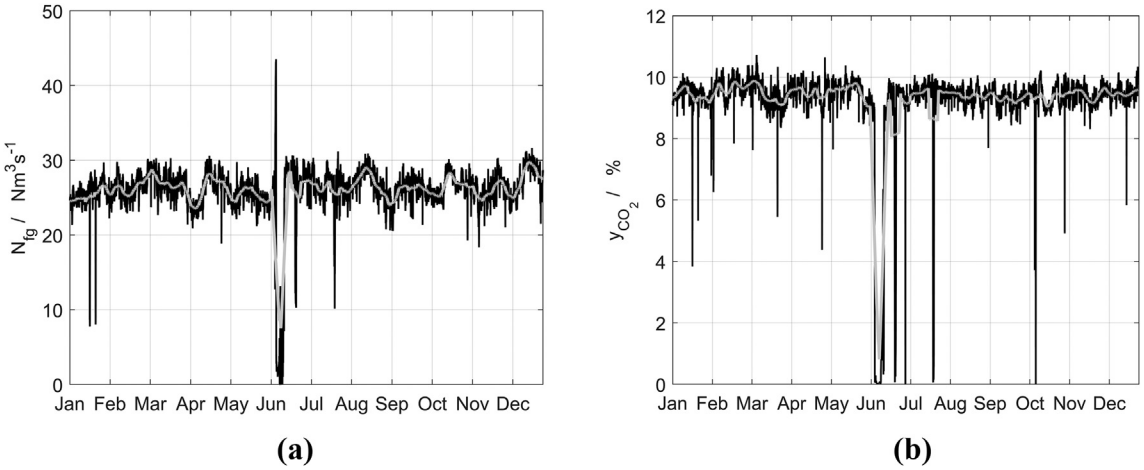

Fig. 4. Process data from the considered WtE plant in 2018, for (a) flue gas flow and (b) CO_2 concentration in the flue gas. The black lines represent process values reported every 5 min, while the grey line shows the 7-day moving average.

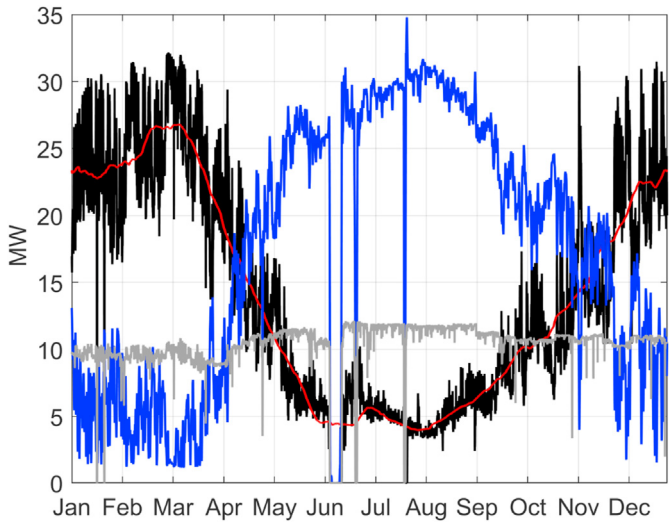

Fig. 5. Process data from the considered WtE plant in 2018, for the heat delivered to the district heating net, Q_{DH}, (black line), the electric power delivered to the grid, P_{el}, (grey line), and the heat dissipated to the surroundings, Q_{ex} (blue line). The red line represents the 30-day moving average of Q_{DH}. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

As shown by the scheme in Fig. 2, the flue gas from the WtE plant is cooled down from approximately 140 °C–40 °C, the operational temperature for CO_2 capture by amine. Due to the high initial moisture content in the flue gas, the cooling procedure caused condensation of some of the water. On average, 2.21 kg/s of water was condensed in the cooler. The flue gas left the cooler saturated for water, making it unnecessary to humidify the gas flow before it entered the absorber column [30].

Fig. 6a shows how the CO_2 capture efficiency changes over the year. Fluctuations in the capture efficiency were mainly due to fluctuations in the WtE flue gas flow and in its CO_2 content. Experimental works in the literature showed that the dynamic of the absorption plant is much slower than the frequency of fluctuations of the flue gas [30]. In the present work, the lean amine mass flow was controlled to keep the liquid/gas ratio in the absorber constant. The CO_2 capture efficiency was calculated as:

$$\varepsilon_{CO_2} = \frac{N_{fg}^{in} y_{CO_2}^{in} - N_{fg}^{out} y_{CO_2}^{out}}{N_{fg}^{in} y_{CO_2}^{in}} \cdot 100 \quad (13)$$

where the superscript and *out* indicate the values of the considered variables at the inlet and outlet of the capture plant at a given instant. The inlet flue gas flow changes continuously over time and the gas flue gas takes some time to flow through the capture plant. This caused a mismatch in the inlet and outlet values used in Eq.

(13), which was responsible for the ε_{CO_2} values larger than 100% that appear in Fig. 6a. The 20-min moving average (red line) gave a better indication of the actual capture efficiency. The average CO_2 capture efficiency did not change considerably during the year, and a total of 125 310 t of CO_2 was captured by the absorption plant. Fig. 6b shows the heat absorbed from the hot source in the reboiler for regeneration of the absorbent. While fluctuating from a minimum of 11 MW to a maximum of 17.3 MW, the absorption plant required an average of 14.7 MW_{th}. Such thermal duty represents approximately 27.2% of the nominal thermal capacity of the WtE plant.

4.3. Case 1a and 1b

In Case 1a and 1b, the capture plant is fully integrated into the WtE plant so that the heat necessary to the reboiler is provided by the WtE plant itself [31]. From Case 0, it was found that approximately 14.7 MW of heat should be delivered to the reboiler at a temperature higher than 120 °C. In the WtE plant, steam can be extracted both from boiler drum (Case 1a) and from intermediate stages of the turbine of the WtE plant (Case 1b).

The steam in the boiler drum is saturated steam at approximately 269 °C and 54 bar_a. Since MEA degrades at high temperatures, the solvent temperature in the reboiler should be limited to 120–122 °C [32]. To ensure the amine temperature stayed below these limits, in Case 1a the steam from the boiler was expanded and cooled down through water injections before entering the reboiler [33], to the temperature and pressure of 150 °C and 3.8 bar_a (superheated conditions). The steam is condensed into the reboiler and sent to the feed water tank. Alternatively, superheated steam can be extracted from an intermediate turbine stage at approximately 3.8 bar_a and 159 °C, and follow the same cooling procedure (Case 1b).

Fig. 7 shows the steam flow necessary to supply the reboiler in Case 1a (black line) and in Case 1b (grey line). Since the steam in the boiler had higher temperature and pressure, the steam extraction from the boiler drum was slightly smaller than that from the turbine. However, the extracted steam flows were quite similar in magnitude, with an average of 6.72 kg/s for extraction from the boiler drum and 6.77 kg/s for extraction from the turbine.

Table 3, shows how the heat delivery to the reboiler impacted power and district heat production. The extraction of steam from the boiler caused the power production to decrease by 30.3%. By taking advantage of the excess heat that in Case 0 was dispersed in the surroundings, the district heat production decreased by only 6.4%. Steam extraction from the boiler caused the steam flow through the superheater to decrease. However, due to the complex dynamic in the boiler, the decrease in steam flow was smaller than the steam extraction. This was due to two phenomena. First, a smaller steam flow in the superheater caused the temperature of the superheated steam along the heat exchanger to increase, increasing the water injections for temperature control in the attemperators [27] and, therefore, increasing the final steam flow leaving the superheater. Second, a lower steam flow reduced the heat exchanged in the superheater, which increased the heat exchanged in the evaporator and, therefore, the steam production in the evaporator. Since the overall steam flow leaving the superheater was smaller than in Case 0, the power and the heat production in the condenser decreased.

Extraction of steam from the turbine caused a reduction in power and district heat by 8.2% and 12.2% (Case 1b). In this case, the

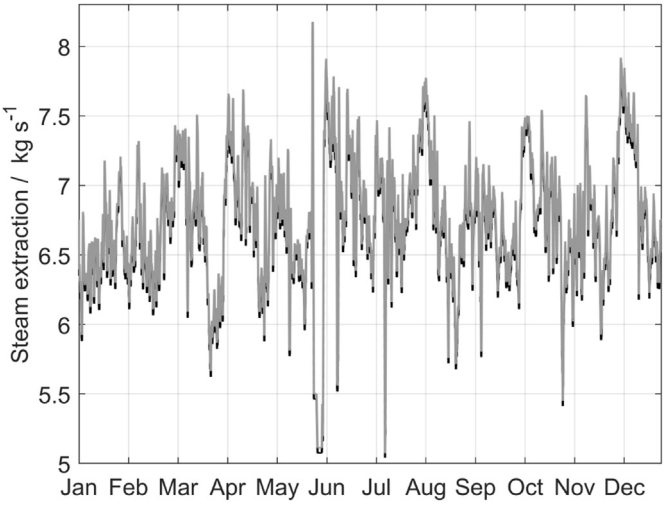

Fig. 7. Steam extracted from the boiler (black line) in Case 1a and from the turbine (grey line) in Case 1b to provide the amine regeneration heat to the capture plant. The two lines appear to almost coincide at the scale of the representation.

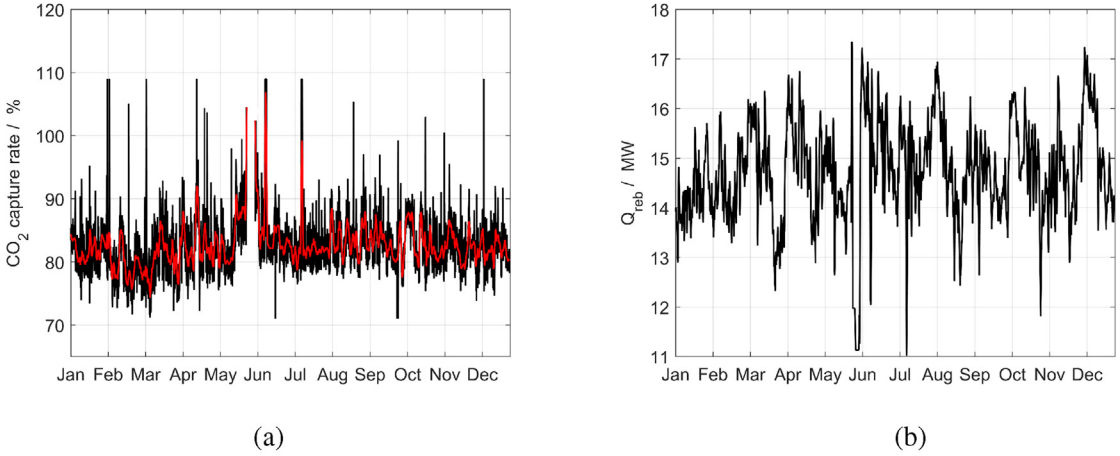

Fig. 6. Simulation results for Case 0 of the CO_2 capture plant treating the flue gas from the WtE plant in 2018, for (a) CO_2 capture efficiency and (b) regeneration duty. Black lines indicate instantaneous values, while the red line shows their 7-day moving average. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

boiler dynamics remained rather unchanged. Also in this case it was possible to utilize some of the previously unused heat. Since the steam extraction took place after it had partially expanded in the turbine, the power penalty was lower than in Case 1a.

While maintaining the main process parameters unchanged, Case 1a and Case 1b attained the same CO_2 capture efficiency penalizing the production of power and district heat in different ways. While Case 1a had a larger impact on power production, Case 1b penalized the district heat production more.

For both cases, the reduction in power production was approximately constant over the year. On the other hand, while there was no reduction in district heat production from middle April to middle October, in the winter months Q_{DH} was penalized by up to 28% in Case 1a and 45% in Case 1b.

4.4. Case 2

In Case 2, the heat necessary for amine regeneration in the reboiler was provided by the WtE plant, while trying to keep the heat delivery to the district heating network equal to the base case (Case 0). Similarly to Case 1a, the steam for regeneration was extracted from the boiler drum. In order to maintain the district heat production unchanged, the temperature in both the high pressure and low pressure condenser needed to be increased. Due to constraints on the temperature of the district heating net, the temperature in the high pressure condenser cannot be higher than 125 °C. Moreover, the two condensers should maintain a temperature difference of at least 20 °C. A higher temperature and, therefore, pressure in the condensers caused a further penalty in power production (Table 3). Because of the limitations on district heating temperature, it was not possible to keep the district heating production unchanged, and Q_{DH} was reduced by 4.3% with respect to the reference case. However, while district heat production was unchanged from beginning of April to the end of October, in the winter months Q_{DH} was penalized for short periods by up to 24%.

4.5. Case 3a and 3b

In Case 3, carbon capture was carried out only when excess (i.e. unused) WtE heat was available to regenerate the amine in the reboiler, so that the district heat production of the WtE plant would stay the same as in the reference case. Since the capture plant has long response times, the selected intervals of time were such that the capture plant could be operated in a rather continuous way. By extracting steam from the boiler drum (Case 3a), it was possible to operate the capture plant for a slightly longer period, from April 2 to October 24. The operation of the capture plant caused the power production in this period to decrease by approximately 30%, causing the overall power production in 2018 to decrease by 17.3%. An overall CO_2 capture efficiency of 47.1% was achieved.

When steam was extracted from the turbine (Case 3b), the period during which it was possible to continuously operate the capture plant with only use of excess heat was two days shorter (from April 3 to October 23). This caused the overall CO_2 capture efficiency to be slightly lower than when steam was extracted from the boiler drum (ε_{CO_2}=46.7%). The power production decreased by 4.9% with respect to the reference case. Case 3b had almost the same capture efficiency as Case 3a, but a significantly smaller decrease in power production.

5. Discussion

Looking at the bigger picture, the main features of the scenarios considered can be compared and summarized as such (Table 3):

- No WtE-CCS integration without detrimental energy penalty is possible in the scenarios studied, even when focusing on the use of excess heat (Case 3a and 3b). Case 3b has the lowest overall energy penalty of all cases but only offers seasonal CO_2 capture. The case with the most acceptable (rather than lowest) energy penalty and 85% capture efficiency (Case 1a and 1b and 2) will be a matter of trade-off for a given WtE plant, given its specific constraints and requirements (see also next section concerning energy delivery);
- Case 1b is by far the worst when it comes to heat delivery reduction (see also next section concerning energy delivery) while Case 1a and Case 2 are the ones leading to the lowest power production, but they all attain the desired capture efficiency;
- Given the average biogenic content of waste in Norway (60% on weight basis and 52% on energy basis [34], seasonal CO_2 capture (Case 3) with a CO_2 capture efficiency of approximately 47% would still mean that the Returkraft WtE plant would probably be carbon neutral or even slightly carbon negative depending on its specific MSW composition. However, the (social and political) acceptability of this scenario, basically leaving the capture plant unused for 5 months, is doubtful. The economic aspect will be dependent on the carbon capture framework the plant is operating under (CO_2 tax, incentives, etc.)

Apart from the respective merits and performance offered by the different scenarios investigated in terms of CO_2 capture and energy recovery (see overview in Table 3) when integrating CCS to WtE, two other aspects should be considered when discussing the various scenarios and possibilities for integration:

- Technical challenges and plant limitations when integrating the carbon capture process. The equipment and retrofitting required for the different configurations and the complexity of combined operation may differ. As an example, constraints exist on the amount of steam that can be extracted from the turbine.
- Energy delivery requirements. The question of CHP plants and their energy delivery obligations is an important consideration when determining the most appropriate configuration(s) for CCS integration. When it comes to heat delivery, most WtE plants in Norway are base load plants that must also process

Table 3
Comparison of the scenarios' results calculated for year 2018. Values in brackets indicate relative reduction with respect to the base case (Case 0) on a yearly basis.

	External heat	Power production	DH production	CO_2 capture efficiency
	GWh	GWh	GWh	%
CASE 0	125.8	91.7	124.9	83.9
CASE 1a	–	63.9 (−30.3%)	116.9 (−6.4%)	83.9 (−0%)
CASE 1b	–	84.1 (−8.2%)	109.6 (−12.2%)	83.9 (−0%)
CASE 2	–	63.5 (−30.8%)	119.5 (−4.3%)	83.9 (−0%)
CASE 3a	–	75.8 (−17.3%)	124.9 (−0%)	47.1 (−43.9%)
CASE 3b	–	87.3 (−4.9%)	124.9 (−0%)	46.7 (−44.4%)

MSW continuously. They will often be contractually obligated to deliver a predefined amount of heat to the district heat network and cannot allow for significant decreases in heat production during the winter months, making case 1b the less favourable. Power production does not usually pose the same challenge in Norway so production decrease will reduce incomes but will not cause problems with satisfying contract obligations. However, if carbon capture (especially negative CO_2 emissions) can be monetised, monetary penalty due to reduced power production will be mitigated if not irrelevant. Furthermore, if the WtE plant is adequately integrated with other heat centrals, more operational flexibility may be allowed to the WtE plant when it comes to heat delivery.

Prioritisation according to various parameters (CO_2 capture efficiency, incomes, investment costs, maintenance costs, operational complexity, operational flexibility, etc) will dictate the preferred integration configuration in a given case so there is no single, best case at this stage of CCS development. However, it is probable that WtE will have to implement CCS in the coming years in order to contribute to climate change mitigation. Before this can happen, several regulatory and economic challenges need to be solved.

Several aspects are not part of this study but can have an impact on the WtE-CCS integration, such as techno-economic aspects, environmental considerations related to the use of amines, and possible use(s) of CO_2. Moreover, the consideration of additional CO_2 treatment processes such as conditioning and liquefaction would provide additional possibilities for integration that will change the overall picture of power penalty.

6. Conclusions and future works

In this work, different scenarios for integration of a CO_2 capture plant in a WtE plant were investigated. The grate-fired WtE plant located in Kristiansand, Norway, producing both heat and power was used as a case study.

An amine-based absorption plant was designed to separate CO_2 from the flue gas emitted by the WtE plant during a reference year. When the two plants were considered separately, the heat requirement of the capture plant was found to correspond to 27.2% of the nominal thermal capacity of the WtE plant.

When the two plants were integrated, steam extraction from the boiler drum and steam extraction from the turbine impacted heat and power production in different ways. When steam was extracted from the boiler drum, the power and district heat production of the WtE plant reduced by 30.3% and 6.4% respectively. Extraction from the turbine caused a reduction of 8.2% and 12.2% in heat and power production, respectively.

By modifying the temperature in the condensers, it was possible to satisfy the heat requirement of the capture plant while maintaining the district heat production equal to 95.7% of that of the reference case. This caused a reduction in power production by 30.8%.

The district heating demand is much lower in the summer months than in the winter months. This caused large part of the heat produced by the WtE plant to be unused during the summer months. The unutilized heat can be used by the capture plant without causing any penalty to the district heating production. In such a case, the CO_2 capture efficiency reduced from 85% to 47%, as it only took place between April and October.

The different cases presented different advantages and drawbacks in terms of both performance and complexity. This showed that the preferred configuration could be adapted to the WtE plant specific requirements (in terms of power and heat delivery for example) and limitations.

Future works will focus on the analysis of alternatives CCS technologies such as membrane separation and oxy-fuel combustion, and on their possible application and integration in WtE plants.

Credit roles

Elisa Magnanelli: Conceptualization, Methodology, Software, Writing – original draft. Jostein Mosby: Data curation, Writing – review & editing. Michael Becidan: Conceptualization, Writing – review & editing.

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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Nomenclature

C: Heat capacity, JK^{-1}
cp: Specific heat capacity, $Jkg^{-1}K^{-1})]$
F: Mass flow, kg s^{-1}
H: Overall heat transfer coefficient, $Js^{-1}Pa^{-1}$
h: Specific enthalpy, J kg^{-1}
Ki: Overall mass transfer coefficient, kg $s^{-1}Pa^{-1}$
M: Mass, kg
N: Volumetric gas flow, Nm_3s^{-1}
P_{el}*:* Electric power, MW
Q: Heat, MW
R: Consumption rate, kg s^{-1}
T: Temperature, K
t: Time, s
y: Volume fraction,
ε_{CO2}*:* Outlet
g: gas phase
g-l: from the gas to the liquid phase
in: Inlet
l: liquid phase
n: n-*th* control volume
out: Outlet
CCS: Carbon Capture and Storage
CHP: Combined heat and power
ECO: Economizer
EU: European Union
EVA: Evaporator
GHG: Green House Gases
HP: High pressure
LP: Low pressure
MSW: Municipal Solid Waste
SH: Superheater
ST: Steam turbine
WtE: Waste-to-Energy
DH: District heating
ex: Excess heat
fg: Flue gas
i: i-*th* component in the gas phase
in: Inlet
out: Output