INTRODUCTION

Biomass and waste usually have a high moisture content that can be up to 50% for biomass and even higher for municipal solid wastes (MSW). To improve the energy efficiency of biomass/waste-fueled combined heat and power (CHP) plants, flue gas condensers (FGCs) are commonly employed, resulting in a large amount of condensed water. For example, in Sweden, the annual amount of generated condensate from FGC is estimated to be nearly 400 Mton. The condensed water gets contaminated with the organic and inorganic compounds in the flue gas (FG), such as acidic gases (SO$_2$ and HCl), NH$_3$, and heavy metals. Therefore, it needs to be treated before it can be discharged into the environment. In addition to the polluted water, a substantial amount of freshwater is also taken from rivers or lakes for cooling purpose and also as make-up water for steam cycles and the district heating. This adds more burden on the environment in terms of water and energy use.
Currently, stricter regulations require further reduction of negative impacts on the environment due to released pollutants like organic compounds, acids and heavy metals, polluted water, and solids. According to the European Commission, the large incineration power plants are expected to reduce emission through water, such as organic compounds dissolved in the discharge water.\textsuperscript{10,11} Furthermore, the EU Water Framework Directive demands the reduction of freshwater withdrawal and increased water recycle with internal reuse in order to reduce the disturbance to the natural water.\textsuperscript{12} For new biomass-based CHP plants, integrating a flue gas quench (FGQ) before FGC is gaining attention. In the FGQ, water is introduced to wash the FG and the water-soluble pollutants are removed from the FG.\textsuperscript{13-16} As a result, the FG leaving the FGQ becomes cleaner that improves the water quality from the FGC. Since the FGQ employs wastewater from the FGC during the water scrubbing, a large amount of water can evaporate and leave with the FG. The FGC can then effectively reduce the amount of wastewater that needs be further treated and, consequently, save a considerable amount of energy in the wastewater treatment plant (WWTP).

Our previous study on the FGQ has briefly reviewed the research works available in the literature about the development and performance of the FGQ.\textsuperscript{17} A mathematical model was developed to study the operation of FGQ. The current study is a continuation of our research work on the FGQ, and the primary objective is to establish knowledge about the potential environmental benefits when integrating the FGQ in biomass/waste-fueled CHP plants. The potential benefits are evaluated from the perspectives of (i) removal of pollutants from FG, (ii) reduction in energy demand of wastewater treatment, and (iii) reduction in external freshwater use. A detailed analysis based on mass balance is performed to investigate the distribution and transfer of pollutants from the FG to water. The combined role of the FGQ in the FG cleaning and wastewater treatment is also studied. The key knowledge gaps bridged by this study are:

- What are the potential reductions in pollutants emission (removal of pollutants) through wastewater that will be discharged from CHP plants?
- What is the potential reduction in external freshwater use from the integration of FGQ?
- What are the potential energy savings from wastewater treatment plant due to reductions in the amount of wastewater?
- Which factors can clearly affect the load reduction in the WWTP and coupled energy savings?

\section{SYSTEM DESCRIPTION AND METHODOLOGY}

\subsection{Reference CHP plant and FGQ}

In current study, a typical biomass-based CHP plant with the thermal capacity of 170 MW is taken as a reference. Figure 1 shows the schematic diagram of the flue gas cleaning process.\textsuperscript{19} The NOx is removed when the FG passes through the primary de-NOx and the secondary de-NOx based on the selective noncatalytic reduction (SNCR). Most of the dust in the FG is filtered out by the bag house filter (BHF). Sulfur, halides, and alkali dissolved in water are removed using the wet scrubber. Typically, the wet scrubber is suitable for the cold downstream application.\textsuperscript{23} In the FGC, moisture is condensed from the FG to recover heat. Since the FG still contains a large amount of pollutants, the condensate from the FGC also contains high levels of pollutants, such as SOx, HCl, NH3, HF, dioxin, furans, and heavy metals.\textsuperscript{20} Such a stream requires treatment that consumes additional energy.\textsuperscript{21,22} In order to reduce the amount of wastewater that needs treatment, the FGQ is proposed to be added before the FGC that can use the wastewater from the FGC.\textsuperscript{4,24}

In order to analyze the variations of pollutants in the flue gas and the process water under different operating conditions of the CHP plant, three cases have been developed and studied. A brief explanation of studied cases is presented:

- Case 1: with FGC but without FGQ (Streams 1-5)

This case corresponds to the conventional CHP plant. After BHF, the FG is introduced to the FGC to recover heat (Stream 1). The FG is released to the atmosphere through the stack (Stream 2). The FGC not only improves the boiler efficiency by recovering the sensible and latent heat of the FG, but also reduces the emissions of pollutants such as dissolved salts, aerosols pollutants that can be discharged into the atmosphere without the FGC.\textsuperscript{25} The condensate from the FGC is discharged to the wastewater treatment unit (Stream 3) that produces clean water (Stream 5). The remaining water that contains high concentration pollutants is discharged into the WWTP (Stream 4).

- Case 2: with FGQ and FGC (Streams 6-14)

In this case, the FGQ is integrated before the FGC as shown in Figure 1. The FG first passes through the FGQ before going into the FGC. It is important to note that the condensate can be distributed into two streams: one stream
is distributed to the FGQ (Stream 9) and the other stream is distributed to the WWT (Stream 10). After the wastewater treatment, Stream 11 is also introduced to the FGQ. Streams 9 and 11 are used for FG scrubbing. Due to continuous operation of the FGQ, a substantial amount of pollutants from the WWT and the FG are accumulated in the quench water. In order to control the concentration of contaminants below the safe level, a part of the pollutant-rich wastewater is rejected to the boiler.

– Case 3: with FGQ but without FGC (Streams 15–18)

In summer, due to the reduced heat demand, the FGC is not in operation. In such a scenario, there is no condensate produced from the FGC. To run the FGQ, external water is needed instead for the FG scrubbing.

2.2 Mass balances of pollutants in flue gas and process water

A model based on mass balance is developed in order to analyze the pollutant distribution and the transfer from FG to the process water.

Case 1: with FGC but without FGQ

For FGC:

\[ m_1 - m_2 = m_3 \]  \hspace{1cm} (1)

\[ m_1 C_{1,i} - m_2 C_{2,i} + \Delta m_{\text{FGQ},i} = 0 \]  \hspace{1cm} (2)

\[ m_3 C_{3,i} + \Delta m_{3,i} = 0 \]  \hspace{1cm} (3)

FIGURE 1 Schematic diagram of flue gas cleaning process
For WWT:

\[ m_3 = m_4 + m_5 \]  
\[ m_3 C_{i,j} - m_4 C_{4,j} - \Delta m_{WWTP,j} = 0 \]  
\[ m_5 C_{i,j} + \Delta m_{5,j} = 0 \]

where \( m_1 \) and \( m_2 \) represent the mass flow rate of the FG at the inlet and outlet of the FGC (kg/s); \( m_3, m_4, \) and \( m_5 \) are the mass flow rate of condensate, wastewater discharged to the WWTP, and clean water (kg/s); \( C_{1} \) and \( C_{2} \) are contaminant concentrations in FG of inlet and outlet FGC (mg/Nm\(^3\)); \( C_{3}, C_{4}, \) and \( C_{5} \) are contaminant concentrations in the condensate, wastewater, and clean water (mg/L); \( \Delta m_{FGC} \) and \( \Delta m_{WWTP} \) are the mass flow rate of contaminant in the condensate and wastewater (mg/s); and \( i \) represents the different contaminants.

Case 2: with FGQ and FGC

For FGC:

\[ m_8 = m_9 + m_{10} \]  
\[ m_6 - m_7 + dm = 0 \]  
\[ m_9 C_{6,j} - m_7 C_{7,j} + \Delta m_{FGQ,j} = 0 \]  
\[ m_9 + m_{11} - m_{12} = dm \]  
\[ m_9 C_{9,j} + m_{11} C_{11,j} - m_{12} C_{12,j} = \Delta m_{FGQ,j} \]

where \( m \) represents the mass flow rate of the FG (stream 6, 7) and water (Stream 8-12) (kg/s); \( C \) is contaminant concentration in FG and water (mg/Nm\(^3\) or mg/L); similarly, \( dm \) is water evaporation in FGQ (kg/s); and \( \Delta m_{FGQ,j} \) is the amount of contaminants captured by quench water from FG (mg/s). For the model of mass balance of FGC and WWT, it is identical with the Case 1.

Case 3: with FGQ but without FGC

For FGQ:

\[ m_{15} - m_{16} + dm = 0 \]  
\[ m_{15} C_{15,j} - m_{16} C_{15,j} + \Delta m_{FGQ,j} = 0 \]  
\[ m_{17} - m_{18} - dm = 0 \]  
\[ m_{17} C_{17,j} - m_{18} C_{18,j} + \Delta m_{FGQ,j} = 0 \]

\[ \Delta m_i = \lambda_i m_{j,i} C_{j,i} \]  

where \( m_{15} \) and \( m_{16} \) represent the mass flow rate of FG of inlet and outlet FGQ (kg/s); and \( m_{17} \) and \( m_{18} \) are the mass flow rate of external water and rejection water to the boiler from FGQ (kg/s), respectively.

The contaminants removed from FG can be calculated by Equation (16):

| TABLE 1 | Content of major pollutants in external water |
|-----------------|-------------------------------|-----------------|-----------------|
| Contaminant (mg/L) | NH\(_4\)-N | Cl | S |
| External water | 0.08 | 16 | 14.3 |

| TABLE 2 | Content of major pollutants in flue gas (1/6) |
|-----------------|-----------------|-----------------|-----------------|
| Contaminant (mg/Nm\(^3\)) | NH\(_3\) | HCl | SO\(_2\) |
| FG after BHF | 7.6 | 8.3 | 43 |

where \( \Delta m_i \) is the amount of contaminants captured by water (mg/s); \( C_{j,i} \) represents the different contaminant concentrations in different streams (mg/L); \( m_{j,i} \) represents the mass flow rate of FG or water in different steams (kg/s); and \( \lambda_i \) is the coefficient of pollutant removal from FG or water.

2.3 | Inputs and assumptions

In current study, three main contaminants, i.e. NH\(_3\), SO\(_2\), and HCl, are considered. It is assumed that 90% of NH\(_3\), SO\(_2\), and HCl can be removed from the FG by water scrubbing.\(^{18,26–28}\) In order to reduce the pollutant concentrations, it is assumed that the removal rate of NH\(_4\)-N, HCl, and SO\(_2\) are 99.7%, 80%, and 96%.\(^{29–31}\) The contents of such contaminants in external water and FG (Stream 1 and Stream 6) are listed in Table 1;\(^{20}\) and Table 2.\(^{32}\) According to our previous work,\(^{17}\) the profiles in various streams are shown in Table 3.

3 | RESULTS AND DISCUSSIONS

3.1 | Results on mass balance

Based on the mass balance model and the measurement data in Tables 1-3, the pollutant concentrations are calculated in various streams under different operation conditions.

Case 1: with FGC but without FGQ

Figures 2 and 3 show the pollutant concentration in the FG and the process water. In case 1, a significant amount
of contaminant is reduced in the FGC. Due to the fact that a considerable amount of pollutants is transferred from the FG to the condensate, the concentrations of NH₄-N, Cl, and S in Stream 3 are high, which are 99, 108, and 554 mg/L. The WWT unit needs to remove such pollutants, where the concentrations of NH₄-N, Cl, and S are limited to 0.33, 24, and 25 mg/L. Figure 3 shows that the concentrations of NH₄-N, Cl, and S in the process water are up to 976, 857, and 5266 mg/L, respectively, and the process water is then discharged to the WWTP.

### Table 3

| Stream | 1/6/15 | 2  | 3  | 4  | 5  | 7/16 | 8  |
|--------|--------|----|----|----|----|------|----|
| T (K)  | 436    | 320| 320| 318| 318| 338  | 320|
| Flow rate (kg/s) | 93.7  | 85.3| 8.4| 0.9| 7.6 | 96   | 10 |
| T (K)  | 320    | 320| 318| 12/18| 13 | 14   | 17 |
| Flow rate (kg/s) | 1.3   | 9.2| 0.9| 0.2| 8.2 | 85.3 | 2.2|

**Case 2: with FGQ and FGC**

For Case 2, the pollutant concentrations in the FG and the process water are shown in Figures 4 and 5. After the FGQ and the FGC, the concentrations of NH₃, HCl, and SO₂ need to be as low as 0.08, 0.083, and 0.43 mg/Nm³, respectively. For the process water, due to two stages of scrubbing, the pollution concentrations in condensate (Stream 8) are lower than Case 1 (Stream 3), which are 8, 9, and 45 mg/L for NH₄-N, Cl, and S. Stream 9 and Stream 10 have identical pollutant
concentrations with Stream 8. Compared with Case 1, the pollutant concentrations of wastewater are decreased by 92% after the WWT unit. The concentrations of NH$_4$-N, Cl, and S in Stream 11 are 79, 69, and 425 mg/L. After the condensate and discharged water from WWT are injected to the FGQ to scrub FG, the pollutant concentrations of NH$_4$-N, Cl, and S in FGQ water are up to 5084, 5473, and 28 399 mg/L.

In the FGQ, a large amount of water is evaporated due to the high temperature of the FG. In consequence, more condensate is produced in the FGC. Although a part of condensate water is sent to FGQ, the flow rate of Stream 10 in this case is still higher than Stream 3 in Case 1. Therefore, more clean water is produced in Case 2, with concentrations of NH$_4$-N, Cl, and S at 0.03, 1.9, and 2 mg/L.

**Case 3:** with FGQ but without FGC

Typically, the FGC is not in operation during the summer and the water needed by the FGQ is taken externally due to the nonavailability of the condensate. The concentrations of NH$_3$, HCl, and SO$_2$ of FG after the FGQ (Stream 16) are estimated to be 0.76, 0.83, and 4.25 mg/Nm$^3$, and the concentrations of NH$_4$-N, Cl, and S of rejection water (Stream 18) are 4624, 5250, and 26 074 mg/L (see Figure 6). The released FG shows higher pollutant concentrations in Case 1 and Case 3 than in Case 2. For water, the pollutant concentrations of rejection water to boiler in Case 3 are lower than in Case 2, reducing by 9.05%, 4.06%, and 8.2%, respectively, for NH$_4$-N, Cl, and S. This will lead to more pollutants that are sent into the atmosphere.

### 3.2 Potential savings in WWTP

The comparison between Case 1 and Case 2 shows a significant reduction in the amount of wastewater that needs to be treated at the WWTP in Case 2. For the reference plant, CHP without FGQ discharges about 73 tonnes per day of wastewater (with 976 mg/L of NH$_4$-N, 857 mg/L of Cl, and 5266 mg/L of S) to the WWTP, whereas, when FGQ is integrated, nearly an identical amount of wastewater from internal WWT unit is used as injection water to FGQ and the rejection water from FGQ is further introduced to the boiler. Moreover, the concentrations of contaminants are also substantially lower when FGQ is integrated, that is, the injection water to FGQ contains about 79 mg/L of NH$_4$-N, 69 mg/L of Cl, and 425 mg/L of S.

In addition, the stream data from the FGQ highlight lower contents of contaminants in the wastewater that need to be treated by the internal WWT unit due to the FGQ integration, i.e. 8 mg/L of NH$_4$-N, 9 mg/L of Cl, and 45 mg/L of S in comparison with 99 mg/L of NH$_4$-N, 108 mg/L of Cl, and 554 mg/L of S in the case without the FGQ integration.

### 3.3 Potential reduction in freshwater use

The condensate after treatment can be used internally. Without the FGQ, the amount of wastewater for the internal WWT is about 727 tonnes per day and 654 tonnes per day of clean water is produced. In comparison, with the FGQ, the amount of wastewater is about 791 tonnes per day that produces 711 tonnes per day of clean water. This implies that nearly 57 tonnes per day of more clean water are available for internal use, resulting in less burden on the external freshwater use.

### 3.4 Energy savings in the WWTP

The potential reduction in the amount of wastewater to be treated by the WWTP results in considerable energy savings. The average energy consumption at Scandinavian
wastewater treatment plants is quantified as an average of 0.49 kWh/m³ with a standard deviation of 0.197, and the density of wastewater is between 998 and 1001 kg/m³. The comparative analysis between systems with and without FGQ shows a potential reduction of 73 tons of wastewater per day to the WWTP that may result in potential annual energy savings of about 13.1 MWh based on the reference CHP plant capacity.

### 3.5 Sensitivity analysis

In this section, a brief sensitivity analysis is performed for Case 1 and Case 2 to analyze the variation of potential load reduction on WWTP, potential reduction in the freshwater use, and energy savings in WWTP due to the fluctuation of pollutants concentrations in the FG. Case 3 is not included in the sensitivity analysis as no water is discharged.

#### TABLE 4 Sensitivity analysis for the concentrations of NH₃, HCl, and SO₂ in different streams in Case 1

(a) The concentration of NH₃ in different streams

| NH₃/NH₄-N (mg/Nm³/mg/L) | Range (%) | 2       | 3       | 4       | 5       |
|-------------------------|-----------|---------|---------|---------|---------|
| 20                      | 0.996     | 108     | 1064    | 0.36    |
| 15                      | 0.95      | 106     | 1044    | 0.35    |
| 10                      | 0.91      | 104     | 1022    | 0.35    |
| 5                       | 0.87      | 101     | 999     | 0.34    |
| 0                       | 0.83      | 99      | 976     | 0.33    |
| -5                      | 0.79      | 96      | 951     | 0.32    |
| -10                     | 0.75      | 94      | 924     | 0.31    |
| -15                     | 0.71      | 91      | 897     | 0.30    |
| -20                     | 0.67      | 88      | 867     | 0.29    |

(b) The concentration of HCl in different streams

| HCl/Cl (mg/Nm³/mg/L) | Range (%) | 2       | 3       | 4       | 5       |
|----------------------|-----------|---------|---------|---------|---------|
| 20                   | 0.91      | 118     | 934     | 26.2    |
| 15                   | 0.87      | 115.6   | 916     | 25.7    |
| 10                   | 0.83      | 113.2   | 897     | 25.2    |
| 5                    | 0.8       | 110.7   | 877     | 24.6    |
| 0                    | 0.76      | 108.2   | 857     | 24.1    |
| -5                   | 0.72      | 105.3   | 834     | 23.4    |
| -10                  | 0.68      | 102.4   | 811     | 22.8    |
| -15                  | 0.65      | 99.3    | 787     | 22.1    |
| -20                  | 0.61      | 96.1    | 761     | 21.4    |

(c) The concentration of SO₂ in different streams

| SO₂/S (mg/Nm³/mg/L) | Range (%) | 2       | 3       | 4       | 5       |
|---------------------|-----------|---------|---------|---------|---------|
| 20                  | 5.1       | 604     | 5741    | 26.9    |
| 15                  | 4.9       | 592     | 5630    | 26.4    |
| 10                  | 4.7       | 580     | 5513    | 25.8    |
| 5                   | 4.5       | 567     | 5391    | 25.2    |
| 0                   | 4.3       | 554     | 5266    | 24.7    |
| -5                  | 4.0       | 539     | 5128    | 24.0    |
| -10                 | 3.8       | 525     | 4986    | 23.3    |
| -15                 | 3.6       | 509     | 4836    | 22.6    |
| -20                 | 3.4       | 492     | 4678    | 21.9    |
3.5.1 Variations of pollutant concentrations in FG before FGQ

To analyze the variations of pollutant concentrations in the FG before the FGQ, the average values of pollutant concentrations are used. To better understand the impacts of pollutant concentrations in the FG on different streams, it is assumed that the pollutant concentrations before the FGQ can vary by ±20% of their average value, as shown in Figure 7. For the above three pollutant concentrations, the results are obtained by calculation.

Case 1: with FGC but without FGQ

The pollutant concentrations in Streams 2-5 are changed after varying the pollutant concentrations in the FG before the FGC, as shown in Table 4(a), (b), and (c). It can be

### Table 5 Sensitivity analysis for the concentrations of NH₃, HCl, and SO₂ in different streams in Case 2

(a) The concentration of NH₃ in different streams

| Range (%) | 7 | 8/9/10 | 11 | 12 | 13 | 14 |
|-----------|---|--------|----|----|----|----|
| 20        | 0.996 | 9.5    | 76 | 6566 | 2.12 | 0.0996 |
| 15        | 0.96 | 9.3    | 74 | 6292 | 2.09 | 0.095 |
| 10        | 0.91 | 9.2    | 72 | 6019 | 2.04 | 0.091 |
| 5         | 0.87 | 9.0    | 71 | 5746 | 1.99 | 0.087 |
| 0         | 0.83 | 8.7    | 69 | 5473 | 1.94 | 0.083 |
| −5        | 0.79 | 8.5    | 67 | 5199 | 1.89 | 0.079 |
| −10       | 0.75 | 8.3    | 66 | 4926 | 1.84 | 0.075 |
| −15       | 0.71 | 8.0    | 64 | 4653 | 1.79 | 0.071 |
| −20       | 0.66 | 7.8    | 61 | 4379 | 1.73 | 0.066 |

(b) The concentration of HCl in different streams

| Range (%) | 7 | 8/9/10 | 11 | 12 | 13 | 14 |
|-----------|---|--------|----|----|----|----|
| 20        | 0.91 | 8.7    | 86 | 6101 | 0.029 | 0.091 |
| 15        | 0.87 | 8.5    | 84 | 5847 | 0.0285 | 0.087 |
| 10        | 0.83 | 8.4    | 83 | 5593 | 0.0279 | 0.083 |
| 5         | 0.78 | 8.2    | 81 | 5339 | 0.0273 | 0.078 |
| 0         | 0.76 | 8.0    | 79 | 5084 | 0.0267 | 0.076 |
| −5        | 0.72 | 7.8    | 77 | 4830 | 0.026 | 0.072 |
| −10       | 0.68 | 7.6    | 75 | 4576 | 0.0252 | 0.068 |
| −15       | 0.65 | 7.3    | 72 | 4322 | 0.0245 | 0.065 |
| −20       | 0.61 | 7.1    | 70 | 4068 | 0.0237 | 0.061 |

(c) The concentration of SO₂ in different streams

| Range (%) | 7 | 8/9/10 | 11 | 12 | 13 | 14 |
|-----------|---|--------|----|----|----|----|
| 20        | 5.1 | 48.8   | 464 | 34 078 | 2.17 | 0.51 |
| 15        | 4.9 | 47.9   | 455 | 32 658 | 2.13 | 0.49 |
| 10        | 4.7 | 46.9   | 446 | 31 239 | 2.09 | 0.47 |
| 5         | 4.5 | 45.8   | 436 | 29 819 | 2.04 | 0.45 |
| 0         | 4.3 | 44.7   | 425 | 28 399 | 1.99 | 0.43 |
| −5        | 4.0 | 43.6   | 414 | 26 980 | 1.94 | 0.40 |
| −10       | 3.8 | 42.4   | 403 | 25 560 | 1.89 | 0.38 |
| −15       | 3.6 | 41.1   | 391 | 24 140 | 1.83 | 0.36 |
| −20       | 3.4 | 39.8   | 378 | 22 721 | 1.77 | 0.34 |
seen that the pollutant concentrations are up to the maximum value and minimum value after the concentrations increased and decreased by 20%, respectively, in each stream. Especially, the variations of the pollutant concentrations are more obvious after WWTP (Stream 4) that the concentrations of NH₃, HCl, and SO₂ are 1028, 1171, and 6319 mg/L and 685, 781, and 4213 mg/L, respectively, for maximum value and minimum value.

**Case 2: with FGQ and FGC**

The pollutant concentrations in Streams 7/8/9/10, and 11-14 are changed after varying the pollutant concentrations in FG before FGQ, as shown in Table 5(a), (b) and (c). The trends of variation of pollutant concentrations are same as Case 1. But in case 2, the more obvious variation of the pollutant concentrations occurred in Stream 12 (from FGQ to the boiler). The maximum value and minimum value of concentrations of NH₃, HCl, and SO₂ are 6101, 6567, and 34 079 mg/L and 4068, 4378, and 22 720 mg/L.

### 3.5.2 Variations of potential load reduction on the WWTP

Figure 8 shows the impacts of variation of pollutant concentrations on potential load reduction of the WWTP. The flow rate of different streams is changed after the pollutant concentrations increased or decreased. This results in increasing or decreasing in potential load reduction of the WWTP. Figure 8 shows that the potential load reduction increases with the increase of pollutant concentrations. With variations in the pollutant concentrations (± 20%), there is a significant impact on the potential load reduction of the WWTP, that is, load reduction varies between 66 tonnes/d and 81 tonnes/d and decreased or increased by 11%. This variation will further have direct implications on the energy consumption and energy savings in the WWTP.

### 3.5.3 Variations of potential reduction in freshwater use

Figure 9 shows the impacts of variation of pollutant concentrations on potential reduction in freshwater use. It shows that the potential reduction in freshwater use increases with the increase of pollutant concentrations. This is due to that the flow rate of condensate water increases with the pollutant concentrations. The maximum and minimum of potential reductions in freshwater use are 73 and 41 tonnes per day, respectively, decreased or increased by 28%.
3.5.4 Variations of energy savings in WWTP

Figure 10 shows the impacts of variation of pollutant concentrations on energy saving in WWTP. It also shows that the energy saving in WWTP increases with the increase of pollutant concentrations. It indicates that the produced injection water increases with increase of pollutant concentrations. When FGQ is integrated into the CHP system, the injection water is introduced into FGQ that can reduce the energy consumption of the WWTP. The maximum and minimum of energy savings in WWTP are 11.8 and 14.5 MWh per year, respectively.

4 CONCLUSIONS

In this study, a detailed analysis is presented to understand the role of flue gas quench (FGQ) in the wastewater treatment and the FG cleaning for a biomass fueled CHP plant. The impacts on the distributions of pollutants, the energy demand of the WWTP, and the withdrawal of external freshwater have been investigated. Based on the reference CHP plant, the answers to the identified key research questions are given:

(i) The system with FGQ has less amount of wastewater to be treated (about 73 tonnes/d) together with less pollutant contents in the wastewater (in terms of NH₄-N, Cl, and S) compared to the system without FGQ.
(ii) There is relatively more clean water (about 57 tonnes/d) available for internal use within FGQ system resulting in less burden on the external freshwater use.
(iii) The CHP plant with FGQ may result in a potential annual energy saving of about 13.1 MWh in WWTP due to less wastewater and pollutant load.
(iv) The sensitivity analysis shows that the variations of pollutant concentrations have a significant impact on load reduction in MWWTP and coupled energy savings.

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NOMENCLATURE

Abbreviations
- C: Contaminant concentrations in FG or water, mg/Nm³ or mg/L; dm: Flow rate of water evaporation in FGQ, kg/s; m: Flow rate of FG or water, kg/s; ΔmFGC: Mass of contaminants captured by condensate from FG, kg/s; ΔmWWTP: Mass of contaminants removed by WWTP from condensate, kg/s.
- Symbols
  - λ: Coefficient of pollutant removal from flue gas
  - i: Different contaminants: NH₄-N, Cl, and S
  - j: Different steams

Acronyms
- BHF: Bag house filter
- CHP: Combined heat and power
- EU: European union
- FG: Flue gas
- FGQ: Flue gas quench
- MWWTP: Municipal wastewater treatment plant
- WWTP: Wastewater treatment plant

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