Life Cycle Assessment of Upgrade Options of a Municipal Sewage Treatment Plant for Energy Self-sufficient

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Abstract. The environmental impact of four municipal sewage treatment scenarios were investigated by life cycle assessment (LCA). The environmental impacts were assessed with four categories: acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), and human toxicity potential (HTP). Compared to the current operation scheme (Scenario 1), EP was significantly reduced but AP, GWP and HTP was increased in A\textsuperscript{2}O-MBR process (Scenario 2). Compared to the Scenario 2, Scenario 3 (water source heat pump) and Scenario 4 (sludge anaerobic digestion) processes for the energy self-sufficient alternatives achieved the greatest environmental improvement in all impact categories. These results suggested that the proposed energy self-sufficient scenarios may greatly reduce the environmental impact of energy consumption in the whole sewage treatment process.

1. Introduction
In recent years, the surface water pollution control has been achieved good result in China. According to the 2018 Report on the State of the Ecology and Environment in China, in major river basins in China, such as Yangtze River, Yellow River, Pearl River, Songhua River, Huaihe River, Haihe River and Liaohe River, the proportion of Grade I, Grade II and Grade III standards accounting for 74.3%, and the Grade V dropping to 6.9%[1]. In order to improve surface water quality, the wastewater discharge standard system has seen significant improvement over the past decades in China. According to the policy “Water Pollution Action Plan” and “13th Construction of Urban Sewage Treatment and Recycling Facilities Five-year Plan”, in sensitive areas or cities where the water quality does not meet the Grade IV standard for surface water, aimed at improving wastewater discharge standard to meet Class 1A standards[2]. Therefore, new driving forces in the research and development of new municipal wastewater treatment processes and the upgrade and reconstruction of existing processes in China at present. Nevertheless, wastewater treatment processes have substantial environmental impacts due to energy consumption, chemical usage, sludge generation and other gas emissions. Moreover some upgrading wastewater treatment processes not only increases operating costs, but also need more energy consumption and chemicals [3-5]. Therefore, from the sustainability and lifecycle perspectives, the goal of sewage treatment plants are not only to mitigate treated sewage discharge standard, but also to comprehensively consider the energy utilization, environmental impact, and operating costs[6].

At present, energy and resource recovery in the sewage treatment plant have been attracted more and more attention [7-9]. Wastewater or sewage can be regarded as a carrier of heat energy, using
waste heat from wastewater has great heat recovery potential\cite{10-11}. Water source heat pump technology can fully utilize the low-temperature waste heat form the sewage discharged. The daily energy cost of a heat pump hot water system is equivalent to that of a gas-fired boiler, about 2/3 of an oil-fired boiler, and 1/3 of an electric boiler\cite{12-13}. Alnahhala and Spremberg indicated that up to 30% of heat energy can be recovered from wastewater by using heat pumps\cite{14}. Most of the sludge of the sewage treatment plants are regarded as waste, but these "waste" are both a source of energy and a source of nutrients \cite{15-16}. Anaerobic digestion process can providing a part of electricity of wastewater treatment plant, thereby reducing the environmental impact of all considered categories\cite{17}.

Life cycle assessment (LCA) is an assessment tool for systematically evaluating the potential environmental impacts by quantifying various input and output data from the production of raw materials to the disposal of the waste generated (ISO 14040, 2006)\cite{18}. In addition, it facilitates the establishment of action plans for environmental improvements at all stages of production, use and disposal. A significant number of LCA studies have been published to evaluate the current situation and compare alternatives for wastewater and sludge treatment processes\cite{19}.

This study is based on the LCA method to compare the environmental impacts before and after the upgrade, to clarify the resource consumption, energy consumption and their impact on the environment. Under the existing sewage treatment process conditions, choose efficient energy recovery methods such as wastewater heat pump energy and sludge anaerobic digestion for energy recovery scenarios to reduce the current environmental pressure. In this model case, we propose the Shuangyang sewage treatment plant (S-STP) located at Jilin Province, China.

2. Method and scenarios description

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The principal goal of this LCA study was to analyze the environmental impacts of the current and upgrade operation in the S-STP and compare the environmental impacts and benefits from the products of the two proposed energy self-sufficient scenarios. The LCA results were characterized based on the functional unit (FU) of 1000 m$^3$ of influent sewage.

2.2. Scenarios description

The current situation and upgrade alternatives were proposed, as shown in Figure 1.

- **Scenario 1**: Before the upgrade, the sewage treatment process was the intermittent activated sludge process, the sewage treatment capacity was 25,000 tons / day, and the discharge standard was meet Class 1B.

- **Scenario 2**: After the upgrade, the sewage treatment process is A$^2$/O-MBR, the discharge standard is meet Class 1A. The daily treatment capacity is 25,000 tons. Build a new membrane grid room and MBR membrane pool room in the biochemical pool, and transform the existing CAST biochemical pool into an A$^2$/O biochemical pool; dismantle the current sludge adjustment tank; newly build sludge dewatering room and sludge tank.

- **Scenario 3**: On the basis of the Scenario 2 process, a water source heat pump is added in the sewage treatment stage for energy recovery.

- **Scenario 4**: On the basis of the Scenario 2 process, anaerobic digestion is added in the sludge treatment stage to recover energy.
2.3. Life cycle Inventory (LCI)

LCI involves the data collection and calculation procedures necessary to complete the inventory. The procedure for collecting the real operating data and the other subsystem data are summarized in table 1.

Table 1. Inventory data of four scenarios in S-STP.

| Item               | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 |
|--------------------|------------|------------|------------|------------|
|                    | Input      | Output     | Input      | Output     | Input      | Output     | Input      | Output     |
| Wastewater treatment |            |            |            |            |            |            |            |            |
| SS kg              | 275.71     | 20.87      | 204.99     | 11.99      | 204.99     | 11.99      | 204.99     | 11.99      |
| COD kg             | 506.09     | 55.57      | 375.99     | 35.20      | 375.99     | 35.20      | 375.99     | 35.20      |
| TP kg              | 6.19       | 1.22       | 3.29       | 0.39       | 3.29       | 0.39       | 3.29       | 0.39       |
| NH₄-N kg           | 39.51      | 5.89       | 32.81      | 2.61       | 32.81      | 2.61       | 32.81      | 2.61       |
| Electricity kWh    | 479.28     | 758.57     | 898.4      | 758.57     |            |            |            |            |
| Sludge kg          | 15973.80   | 12450.6    | 12450.6    | 12450.6    | 12450.6    | 12450.6    |            |            |
| Sludge treatment   |            |            |            |            |            |            |            |            |
| Electricity kWh    | 120        | 150        | 99.06      |            | 223.51     |            |            |            |
| PAM kg             | 0.24       | 0.44       | 0.44       |            | 0.44       |            |            |            |
| PAC kg             | 6.29       | 6.29       | 6.29       |            |            |            |            |            |
| Sludge cake kg     | 479.21     | 373.52     | 373.52     | 224        |            |            |            |            |
3. Results and discussion
The results of the Life cycle impact assessment (LCIA) derived in four categories at the four Scenarios of the S-STPs at Jilin, China are summarized below. In this research we used Gabi Software to calculate the LCIA result. Processes were divided three lines which were wastewater treatment, sludge treatment and sludge landfill. The first two processes were further subdivided into variables such as plant operation and electricity consumption, and chemical consumption.

3.1. Acidification potential (AP) for the Scenarios
For AP, Scenario 3 had the minimal impacts among them. As shown in Figure 2(a), the main contributions to AP were the electricity consumption of the wastewater and sludge treatment processes, which accounted for 56.2% and 26.2%, respectively. The A_2/O-MBR process in Scenario 2 requires a lot of aeration to provide the necessary oxygen and to purge the remaining material in the membrane, so more electricity is needed than Scenario 1. The major benefits appeared in Scenario 3, in which 60% more electricity was generated in water source heat bump than that in Scenario 2. AP was attributed to excess atmospheric emissions of gases such as H_2S, HCl, SO_2, and NOx through the electricity production process. The chemical consumption of sludge treatment, especially due to the SO_2 emission in the PAC production process, accounted for 3.7% of AP, respectively. Additionally, SO_2 and NOx were emitted through the landfill stage, which accounted for 2.1% in S-STP. Scenario 1, Scenario 2 and Scenario 4 showed very similar trends to those in Scenario 3, such that the electricity consumption of the wastewater treatment processes made the greatest contribution to AP at 81.3%, 80.10% and 75.2%, respectively.

3.2. Eutrophication Potential (EP) for the Scenarios
For EP, Scenario 3 and 4 performed best among them. As shown in Figure 2(b), the main impacts were attributed to discharge of the treated effluent (67.9%, 48.5%, 54.1% and 55.6% in Scenario 1, 2, 3 and 4, respectively). Phosphate in the effluent contributed more than 60% of EP. Another key point was the sludge landfill process, which accounted for 29.5% and 17.5% of the total EP in Scenario 3 and 4, respectively, due to the ammonia and phosphorus discharge to the soil through the landfill process.

3.3. Global Warming Potential (GWP) for the Scenarios
Figure 2(c) shows that GWP was the highest in Scenario 2 and 4, where the electricity consumption from the wastewater treatment line accounted for 54.8% and 52.6% of GWP. The main contributor in the wastewater treatment process was the direct emissions of N_2O (50%) and CH_4 (18%). The landfill processes contributed more than 27.5%, 17.8%, 25.5% and 14.6% of GWP, respectively.

3.4. Human Toxicity Potential (HTP) for the Scenarios
Scenario 2 and 4 showed significantly higher HTP than Scenario 1 and 3, as shown in Figure 2(d). The major contribution to HTP was electricity consumption of the sewage and sludge treatment processes, which accounted for 83.2% and 16.5% in Scenario 2 and 78.9% and 20.7% in Scenario 4, respectively. These HTP results were attributed to excess atmospheric emissions of dust, nickel and nitrogen oxides (NO) during the electricity generation of the required electricity.
4. Conclusion

Two upgrade alternatives for energy self-sufficient in the S-STP were proposed with water source heat pump and sludge anaerobic digestion. The four kinds of environmental impact were evaluated based on LCA in order to compare the current and upgrade alternatives. Based on the LCA of the four scenarios, the sewage treatment process had the greatest environmental impact, compared to the sludge treatment and sludge disposal processes. Among the impact categories, AP and HTP were mostly attributable to the electricity consumption in the aerobic reactor, and GWP to A²/O-MBR process. Among them the upgrade Scenario 3 showed the lowest environmental impacts. The environmental impacts were reduced by 44%, 30% and 46% in Scenario 3 compared to Scenario 2 in terms of AP, GWP and HTP, respectively.

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