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Techno-economic analysis of a decentralized wastewater treatment plant operating in closed-loop. A Finnish case study

Kirill Murashko*, Markku Nikku, Ekaterina Sermyagina, Johanna Julia Vauterin, Timo Hyppänen, Esa Vakkilainen, Juha Pyrhönen

Lappeenranta University of Technology, LUT School of Engineering Science, Skinnarilankatu 34, 53850 Lappeenranta, Finland

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ABSTRACT

The study analyzes a potential to improve the local waste and wastewater management in a Finnish community. The Lappeenranta wastewater treatment plant (WWTP) is used as a case study. Two different technological setups are considered for improving the wastewater treatment plant. These are used to construct four alternative wastewater reclamation scenarios. The mass and energy balances for the considered scenarios are developed and used as input for the profitability evaluation. The utilization of the sewage sludge from the WWTP and municipal solid waste fraction that cannot be recycled for the generation of heat and electricity at the CHP plant is investigated with the aim to improve the economic performance of the wastewater treatment facility. The studied scenarios are initially compared based on their investment and operational costs. The cost of water treatment increases significantly in the case of the investigated tertiary treatment systems: higher amounts of chemicals and electricity are needed to improve the water quality. At the same time, the study indicates that the profitability of a WWTP integrated with a CHP plant can be reasonably high in a wide range of likely price scenarios for alternative wastewater purification systems. The results of the analysis showed a significant potential for the investigated wastewater reclamation systems to improve the efficiency of solid waste and wastewater management in the community.

1. Introduction

Urban wastewater is a mixture of wastewater from domestic and industrial sources and in many cases also from rainwater run-offs. Discharge of urban wastewater into natural water basins leads to high levels of nutrient pollution causing eutrophication [1]. Conventional wastewater treatment plants (WWTP), which usually include chemical, physical and biological treatment processes, cannot fully prevent nutrient pollution. As a result, the levels of nitrogen and phosphorus compounds originating from WWTP discharge in many rivers and lakes in the European Union (EU) are relatively high [2]. In addition to the nutrient pollution, there are increasing health concerns about the harmful effects of micro plastics, pesticides, hormones, drugs, antibiotics, fire retardants, and heavy metals finding their way into the fresh water supply. These man-made environmental challenges urgently require systemic and sustainable solutions.

Wastewater reclamation and reuse is one of the most promising solutions for decreasing the pollution run-offs into rivers and lakes [2]. The effluents of a conventional WWTP can be treated further and reused, for example for irrigation or for various industrial purposes. Under certain conditions, water reuse may have a lower environmental impact than utilization of other alternatives of fresh water supply such as water transfer or desalination [3]. In addition, it can enable the recovery of nutrients, resulting in a reduction of raw materials required for fertilizer production [4]. Despite the possible advantages of the wastewater reclamation and reuse, it is not common in the EU, mainly due to the low economical attractiveness of reuse solutions and a lack of common EU environmental standards [2]. In 2015, the European Commission presented an action plan for the circular economy to promote the water reuse [5]. One of the proposed actions was to set minimum quality requirements for the use of reclaimed water in agricultural irrigation to reduce the need for over-precautionary approaches and unnecessary treatment costs. In addition, in 2016 the European Commission approved guidelines for the harmonization of water reuse practices across the EU [6]. Despite this progress, the economic attractiveness of wastewater reclamation and reuse is still an open question.

The issue of cost of water reclamation is especially important in

* Corresponding author.
E-mail address: kirill.murashko@lut.fi (K. Murashko).

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Finland, where despite advanced WWTP systems, effluent discharges have caused significant nutrient pollution in many lakes and the Baltic Sea. For example, in 2010 the accumulated level of nutrient pollution in lake Haapajärvi in the Lappeenranta region was unacceptably high and temporary drying of the whole lake had to be implemented in order to improve its ecological situation [7]. Currently in Finland, due to the wide availability and low cost of clean surface and ground water, water is consumed without long-term consideration of the consequences of the so-far limited implementation of wastewater reclamation and reuse, leading to continued effluent discharges into waterways and lakes. Such a situation leads to gradual pollution of potential surface water resources. Moreover, the contaminants from municipal and industrial waste sources can be transferred via rivers to the Baltic Sea which is almost totally surrounded by agricultural land and presents a vulnerable ecosystem which is highly endangered by continued pollution. Wastewater reclamation and reuse is not only a solution to the problem of limiting the contamination of fresh water resources, but it also offers a new reusable fresh water supply. Therefore, it is extremely important to study the profitability of investing in enhanced treatment of wastewater, on a global and local scale.

In this work, a concept for de-centralized waste management is analyzed. The aim of the study is to assess the potential of the concept to improve the economic feasibility of wastewater reclamation in Finland. The region of South Karelia is considered as a case study. To improve the quality of the treated wastewater at the Lappeenranta WWTP, two tertiary treatment systems, which consist of a ultrafiltration (UF) membranes, a reverse osmosis (RO) membranes filtration and an ultraviolet (UV) disinfection, are considered. These tertiary treatment technologies are selected as they are commonly implemented for the production of reclaimed water from wastewater effluent [8]. At present, membrane technologies have been broadly applied for deep treatment of different types of wastewaters [9–11]. The combination of UF membranes and ultrasound for cleaning the municipal wastewaters was experimentally investigated by Borea et al [12]. Krahnstöver et al. [13] demonstrated the separation efficiency of UF membranes in a pilot-scale wastewater reclamation system. RO membrane, technology is a fully mature technology for the desalination of seawater [14,15], and RO membranes have been used effectively for removing salts and organic compounds from industrial and municipal wastewaters [16]. Gündoğdu et al. [17] showed that by integrating membrane bioreactor (MBR) with nanofiltration and RO processes it is possible to produce water, which well satisfies the quality standard requirements for use in agricultural irrigation and as process water. Therefore, reverse osmosis technologies are installed and used in wastewater reclamation plants, generally, to act as a final stage treatment process [18]. Various combinations of membrane filtration technologies – membrane bioreactor with reverse osmosis and ultrafiltration unit with reverse osmosis have been tested in a pilot study in [19]. The pilot study showed that both systems demonstrate excellent performance for the treatment of wastewater stream. However, to the best knowledge of the authors, the majority of these studies only look at one or a couple of treatment methods but they do not provide the comprehensive comparison between possible configurations. Moreover, there is lack of studies identifying the determinants of economic efficiency improvement of a WWTP when modern tertiary treatment technologies are used. Therefore, in this article the integration of the wastewater sludge and the municipal solid waste (MSW) co-incineration within the wastewater treatment process is evaluated from the perspective of improving the economic feasibility of a WWTP that is equipped with modern tertiary treatment technologies. Based on the selected tertiary treatment systems four different scenarios are considered to analyze the suggested de-centralized waste management concept.

2. Material and methods

2.1. Current wastewater treatment system and processes

The study uses the waste and wastewater management data of the Lappeenranta WWTP example case. The latest complete annual data is available from the year 2016, which is used in this work, if not mentioned otherwise. Lappeenranta is the capital of the South Karelia region which is situated on the shores of Lake Saimaa and has a population density of 24.6 inhabitants/km^2, corresponding to the average Finnish population density [20]. There are 132,000 inhabitants in the South-Karelian area, of which 73,000 live in the city of Lappeenranta. The average amount of wastewater generated in Lappeenranta is 16,000 m^3/day, and most of the wastewater is produced by households [21]. The Lappeenranta WWTP is the largest WWTP in the South Karelia region [22]. The WWTP applies chemical and biological means to treat the wastewater. The majority of the phosphorous is removed from the wastewater by applying chemicals such as ferrous sulphate (PIX-105), and the average efficiency of phosphorus removal by this procedure ranges up to about 96% [21]. Calcium hydroxide is used to maintain an adequate level of alkalinity. The annual consumption of ferrous sulphate and calcium hydroxide are 791 t and 555 t, respectively. Nitrogen is mostly removed by using biological treatment methods with an average removal efficiency of 61% [21]. Moreover, sodium hypochlorite (15%) is used for the disinfection of the wastewater after biological treatment. The consumption of this chemical is 8 tons per year. The sludge produced from wastewater treatment has a total solids (TS) concentration of 3.5% and is dewatered with centrifuges up to 21 %TS by using polymer Zetag 8165 which is consumed at an average rate of 8.8 t/a [21]. Finally, the sludge is transported over a distance of 20 km to the Kukkuroinmäki landfill plant (Fig. 1) for composting with other biomasses. Lappeenranta WWTP produces about 9600 t/a of 21 %TS sewage sludge. The current cost of the

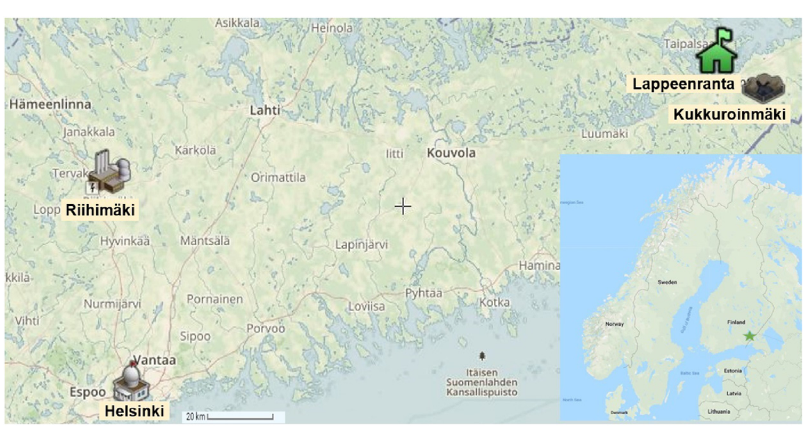

Fig. 1. Location of the waste treatment facilities involved in this study.