Impact of a methane emission tax on circular economy scenarios in small wastewater treatment plants

Diego Teixeira Michalovicz1 · Patricia Bilotta2,3

Received: 7 October 2021 / Accepted: 26 March 2022 / Published online: 13 April 2022 © The Author(s), under exclusive licence to Springer Nature B.V. 2022

Abstract
This paper analyzes the impact of methane emissions taxation on the recovery of the investments required for implementing technologies that use biogas energy in small wastewater treatment plants (WWTPs) in Brazil. It is based on the hypothesis that the adoption of a national methane emission tax policy would encourage small WWTPs to become sustainable power plants. The procedure involved 173 anaerobic plants to analyze: (a) methane production; (b) available useful energy; (c) investments and avoided costs for implementing STHIL system (thermal drying sludge) and motor generator (electricity generation); (d) financial impact for two scenarios (C1: no emissions tax; C2: with tax). Positive environmental and financial results were observed for WWTPs, varying according to the period of time analyzed for both technologies. Investments must be made in cogeneration in anaerobic WWTPs for achieving satisfactory results. Taxation must not be viewed simply as a punitive instrument; on the contrary, it should be seen as a tool to encourage continuous process improvement. The circular economy may support the enlargement of the wastewater collection and treatment system, guaranteeing widespread sanitation conditions in urban areas. However, the actual implementation of a methane emission tax in Brazil still requires many rounds of discussion among sanitation companies, government, and civil society, to establish emission limits, and unit taxes, as well as to consolidate a carbon trade to follow through with this decision in the sanitation sector.

Keywords Energy sustainability · Industrial sustainability · Sustainable wastewater treatment plant · Waste-to-energy
1 Introduction

Due to the expansion of sewage infrastructure among municipalities, the sanitation sector is one of the largest industrial consumers of energy in the cities. Therefore, it is indispensable that economically viable and sustainable solutions be developed for meeting this sector’s growing energy demands (Dong et al., 2017). One such strategy that may be applied in anaerobic sewage treatment plants is to use biogas and biological sludge as sources of energy (Mittal et al., 2019).

The use of by-products from sewage treatment for generating energy also promotes environmental sustainability (Zivkovic & Ivezic, 2021), since it enables the valorization of waste and its reinsertion into the economy as an input, thus stimulating the circular economy. Another example of waste-to-energy is biogas production from vinasse (liquid residue from ethanol distillation) digestion. A study performed in 645 cities in the state of São Paulo (Brazil) revealed a potential to generate approximately 829 GWh year$^{-1}$ of renewable energy from industrial ethanol plants (Pereira et al., 2020). The concept of the circular economy describes a regenerative and more efficient system in which both the entry and waste of resources are minimized (Geissdoerfer et al., 2017; Gherghel et al., 2019). Accordingly, the principles of the circular economy have been adopted for achieving energy self-sufficiency in the operation of WWTPs by means of recovering the energy, either for subsequent feeding into the treatment system itself (Mo & Zhang, 2012; Oladejo et al., 2018; Song et al., 2019) or for use in the thermal drying and cleaning of sludge (Maragkaki et al., 2018; Mills et al., 2014).

Moreover, the use of biogas as a fuel to conduct the thermal drying of the sludge has been pointed out as a technique that can minimize operating costs while contributing to the reduction of the sludge volume and its cleaning using thermal processes such as the technology known as STHIL. In this technology, burning biogas produces heat that heats water, which in turn circulates in a pipe arranged in a serpentine pattern on a concrete floor beneath the drying bed (Gontijo et al, 2018; Possetti et al., 2012). Therefore, when the hot water meets with the sludge, heat exchange occurs, which results in moisture being removed by evaporation. This results in a radiant floor that heats, sanitizes, and dries the sludge deposited upon it. Other equipment necessary for the proper operation of the STHIL includes a radial compressor (for ensuring the biogas pressure gauge), a desulfurizer (to minimize the concentration of hydrogen sulfide and particulate matter), and a dehumidifier (Rosa et al., 2016).

In addition to its potential for energy recovery, the combustion of the biogas results in reduced greenhouse gas (GHG) emissions. Some authors have pointed out that it is possible to reduce GHG emissions in sewage treatment by up to 40% by using biogas in the thermal drying of biological sludge (Brown et al., 2010; Pili et al., 2015). A study conducted in the city of Curitiba, Brazil, involving a WWTP that serves 190,000 inhabitants showed that it is possible to reduce CO$_{2eq}$ emissions by 522.9 tons per month by using the biogas produced in 6 anaerobic fluidized bed reactors (Bilotta & Ross, 2016). The authors of another study, which analyzed 60 WWTPs located in Spain, observed an estimated reduction in emissions of approximately 10% when the by-products from the treatment of the sewage in these plants were used. This represents 44,413 tons of CO$_{2eq}$ avoided per year (Senante et al., 2014).

Some studies suggest that the best strategy for smaller plants is to use the direct combustion of the biogas as a heat source for the thermal drying of the sludge, since these WWTPs do not produce enough biogas to perform the conversion of thermal energy into other forms.
of energy (either mechanical or electrical). For medium and large stations, the production of electric energy from the biogas produced in the anaerobic system is feasible (MetCalf & Eddy, 2016; Taschelmayer & Bilotta, 2021). Anaerobic digestion is becoming increasingly popular as a means of producing renewable electric energy from waste while generating economic and environmental benefits (Appels et al., 2011; Beegle et al., 2018).

Santos et al. (2016b) analyzed the potential for producing electricity from biogas generated during the anaerobic treatment of domestic sewage in Brazil. According to the authors, 64% of the WWTPs in Brazil use anaerobic treatment, thus indicating a great potential for using biogas as the main source of energy for meeting the demands of these facilities and achieve energy sustainability for the sector. In Germany, more than 800 WWTPs already use biogas to produce energy, generating a total of 900 GWh year\(^{-1}\) of electricity and 1800 GWh year\(^{-1}\) of thermal energy. This is equivalent to almost 25% of the electricity consumed by all the WWTPs in the country.

The National Agency of Petroleum, Natural Gas and Biofuels (ANP) establishes rules to produce biogas in WWTPs and for its use in industrial plants (ANP, 2017) to promote the green transition to a low-carbon economy and support the National Determined Contribution (NDC) (Pin et al., 2020). The implementation of waste-to-energy technologies may support the investment that is needed to update infrastructure, equipment (biogas cleaning, storage, and utilization), and technical training by reducing future operating expenses (Sun et al., 2015; Taschelmayer & Bilotta, 2021).

In summary, studies published previously have considered various waste sources and methodologies for potential biogas generation (biomass), estimating the amount of energy available by exploring a wide variety of applications. However, there is a gap in the literature regarding the implementation of a green waste-to-energy transition in small WWTPs. For Brazil, this issue is very important because 80% of the Brazilian WWTPs are found in small towns (less than 20,000 inhabitants) (von Sperling, 2016) that produce small quantities of biogas (insufficient for some applications), and the investments in technology that would be required for energy recovery in many cases would be unfeasible.

In view of the above, the current study examines the hypothesis that the adoption of a national methane emissions tax policy would result in small WWTPs becoming sustainable power plants. The aim of this paper is therefore to analyze the impact of methane emissions taxation on the recovery of the investments necessary for implementing (a) thermal drying of sludge (STHIL technology) and (b) a motor generator (for generation of electricity) in 173 plants with flow a rate of up to 60 L s\(^{-1}\).

The taxing of methane emission is already practiced by several countries to reach their NDC and to mitigate climate change toward to a low-carbon economy (Canada, 2020; United Kingdom, 2012; Goulder et al., 2013; Thompson et al., 2013), but it is not yet a reality in Brazil. The novelty of this paper consists in the following aspects: (i) the collection of information necessary for policy makers to develop rules for methane emissions taxation in the sanitation sector (conditions, horizon, and values); (ii) the definition of governmental support necessary for updating technology and infrastructure (specific financing credit to priority destinations); (iii) the possibility of converting small WWTPs into sustainable energy sources on an urban scale; and (iv) description of the enormous potential of sewage treatment plants in Brazil for implementing the green transition (waste-to-energy).
2 Materials and methods

This study was conducted using secondary data from 173 small anaerobic WWTPs in the state of Paraná, Brazil, which operate using an anaerobic reactor (flow rate up to 60 L s⁻¹). The study was structured in four stages: (1) estimation of methane production; (2) determination of the amount of useful energy available; (3) identification of investments and avoided costs for the implementation of two technologies (STHIL system for thermal drying of sludge, and motor generator for electricity generation); (4) evaluation of the financial impact of the methane energy recovery in a carbon emission taxation scenario.

This methodology was used to predict the current potential installed for biogas recovery in 173 WWTPs and analyze the financial impact that a methane emission tax would have on the implementation of technologies for heat and energy applications.

2.1 Estimation of methane production

The average biogas and methane production was determined using the Probio software. This program calculates the standardized production of biogas (Nm³ d⁻¹) and methane (Nm³ d⁻¹), the CO₂eq emission rate, and the chemical energy available in the biogas (kWh d⁻¹) from the input data regarding the flow of COD (chemical oxygen demand) affluent in the WWTP and the population served (data provided by the state sanitation company) (Taschelmayer & Bilotta, 2021).

The Probio software allows one to simulate the following three scenarios for estimating the production of biogas and methane: (a) conservative (greater loss of methane and less effectiveness in removing COD); (b) excellent (greater biogas production, greater potential for COD removal and less loss of methane); (c) typical (intermediate values). The current work adopted the typical scenario, since it better represents the performance of the WWTPs that were analyzed (Taschelmayer & Bilotta, 2021). In this scenario, the software assumes an efficiency of 65% for the removal of COD during the anaerobic treatment and 75% methane in the biogas, providing as a result the amount of chemical energy corresponding to the flow of the biogas produced.

2.2 Amount of available useful energy

The following two technological alternatives for using the biogas were analyzed: (a) thermal drying of the sludge until maximum total solids (TS) content with the available energy using the STHIL technology (all the WWTPs in the study already have a drying bed); and (b) generation of electric energy by means of a motor generator using the excess biogas produced (if any). The theoretical performance corresponding to each technology was then applied.

An efficiency of 80% was adopted for the conversion of chemical energy from biogas into thermal energy, since this rate is commonly used in technologies that employ direct combustion (Rosa et al., 2016). For the motor generator (an internal combustion engine), a 30% efficiency in the conversion of chemical energy into electrical energy was assumed (Rosa et al., 2016; Santos et al., 2016).
2.3 Investments and avoided costs in implementing the technologies

Quotes for equipment and components recommended by Possetti et al. (2012) for the configuration of a STHIL with a higher cost/efficiency ratio were used. The system was designed for all the WWTPs included in this study. The investment estimates used for the generator were those reported by Carvalho (2016), which include the methane-powered internal combustion engine, gas flow meter, compressor, moisture drainage tank, desulfurizer, and activated carbon filter for the reality. The quotes for this equipment were provided by the manufacturers. Both studies were performed in Brazil, and thus, they describe the Brazilian reality in terms of technologies available.

2.4 Carbon taxation scenario

Two scenarios affecting the financial impact of implementing the STHIL technology and generator were considered: C1) without methane emissions tax (the current situation in Brazil); C2) with methane emissions tax (as is currently the case in several countries). The following unit values were used for estimating the avoided cost in each of the two scenarios: R$ 0.60 kWh$^{-1}$ of electricity (COPEL, 2020), R$ 150.00 kg$^{-1}$ of transported sludge (Mulinari et al., 2017), and R$ 59.50 ton$^{-1}$ of avoided methane emissions (Table 1).

The American Environmental Agency has set the value for methane emitted in the sanitation sector at US$ 55.00 ton$^{-1}$ (EPA, 2017). In Brazil, no fee has been set for the emission of GHGs from WWTPs; therefore, the authors decided to adopt 25% of the value used in the USA, considering the exchange rate between the two currencies during the first quarter of 2020 (R$ 4.08 / US$ 1.00), before the effects of the pandemic, and the difference in the gross domestic product between the two countries. In the scenario with an emissions tax, only methane was considered since it is the main GHG emitted in anaerobic reactors and accounted for by the Brazilian GHG Protocol Program in scope 1 (Filippini, 2018).

The financial impact was analyzed by calculating the return on the investment for various periods of operation (1, 2, 3, 4, 5, and 10 years) after the incorporation of STHIL technologies and motor generator for both scenario 1 (no methane emissions tax) and scenario 2 (with methane emissions tax).

### Table 1 Conditions analyzed in each of the 2 scenarios

| Scenarios                        | Equations/variables |
|----------------------------------|---------------------|
| (C1) Without methane tax         | CE1 = (T + E) - I   |
|                                  | CE1: Balance in the scenario without tax (R$ year$^{-1}$) T: Cost avoided for sludge transportation (R$ year$^{-1}$) E: Avoided electricity cost (R$ year$^{-1}$) I: Investment in the STHIL system and motor-generator (R$ year$^{-1}$) |
| (C2) With methane tax            | CE2 = (T + E) - I + Ce |
|                                  | CE2: Balance in the scenario with tax (R$ year$^{-1}$) T: Cost avoided for sludge transportation (R$ year$^{-1}$) E: Avoided electricity cost (R$ year$^{-1}$) I: Investment in the STHIL system and motor-generator (R$ year$^{-1}$) Ce: Cost avoided due to non-emission of CH$_4$ (R$ year$^{-1}$) |
2 (with methane emissions tax). The following criteria were applied: (a) positive financial return on investment (net present value positive or NPV > 0); (b) no positive financial feedback on investment for the period evaluated (net present value negative or NPV < 0). The NVP financial indicator was chosen since it allows for the establishment of a cash flow (input and output values) and an estimation at present of future operational costs over 1, 2, 3, 4, 5, and 10 years. Discounted payback time (DPBT) and minimum attractive rate of return (MARR) were also used as financial indicators (Adamo et al., 2021; Lauer et al., 2018). MARR was 3.75% (basic rate for fees in the Brazilian economy—Selic tax) (BCB, 2020).

3 Results and discussion

3.1 Characterization and performance

Of the 173 small WWTPs currently in operation in the state of Paraná, Brazil, that were initially covered in the study, 15 were discarded since they do not have the drying bed infrastructure already installed for the implementation of the STHIL system (flow rates between 6 and 31 L s\(^{-1}\)). Table 2 presents the results of the analysis of the remaining 159 WWTPs studied. The data were grouped into 6 categories according to the affluent flow of each plant.

The following results were obtained: 49.7% of the 159 WWTP have a flow rate below 9.9 L s\(^{-1}\), and 6.3% have a flow rate above 50 L s\(^{-1}\); 70.8% of the useful thermal energy from the methane gas is concentrated in the WWTPs with flow rates of up to 39.9 L s\(^{-1}\); 6.36% of the WWTPs fall into the category having the highest flow rate (above 50 L s\(^{-1}\)), but they represent 19.2% of the total available thermal energy; 48.1% of the sludge production occurs in the WWTPs whose flow rates are below 19.9 L s\(^{-1}\); the WWTPs with the highest flow rates (greater than 50 L s\(^{-1}\)) produce 9.6% of the total sludge; 46.3% of the methane is emitted by WWTPs with flow rates between 10 and 19.9 L s\(^{-1}\) and above 50 L s\(^{-1}\); 22% of the WWTP use sludge for agriculture, 30.6% for landfills, and no data regarding sludge use are available for the 47.4%.

All the WWTPs analyzed produce biogas in sufficient quantities to meet the thermal energy demand of the STHIL dryer and increase the TS content in the sludge by up to approximately 80%. It was also observed that only 2 WWTPs (whose flow is greater than 50 L s\(^{-1}\)) have the potential for producing excess biogas and generating electricity (2,767.7 kWh d\(^{-1}\)).

The implementation of a circular economy is a way in to promote sustainability by means of a green transition (D’Adamo et al., 2021). This concept recommends that raw materials be substituted by wastes, thereby extending product life (Webster, 2015) and contributing to the introduction of triple bottom line principles (Loviscek, 2021) in various sectors. The circular economy is a regenerative system in which inputs, waste of resources, gas emissions, and energy leaks are minimized (Geissdoerfer et al., 2016); sustainable societies must be based on the efficient use of these by-products (Pearlmutter et al., 2020). Many cities have implemented measures to promote the circular economy (Chrispim et al., 2021); however, these measures generally do not integrate the various aspects involved (organic solid waste, sludge, water, energy) (Paiho et al., 2021). For this reason, a link must be established between energy, water, and waste systems to make progress toward the goal of achieving sustainable cities (Wang et al., 2018).
Table 2  Performance of the WWTPs analyzed in the study

| Flow class | Total |
|------------|-------|
| Number of WWTP | 159 |
| Population range (inhabitants) | 1,678,876 |
| Total sludge production (ton year⁻¹) | 4,030 |
| Range of CH₄ production (Nm³d⁻¹) | 17,230 |
| Total CH₄ production (Nm³d⁻¹) | 112,538 |
| Total CH₄ emission (ton year⁻¹) | 171,255 |
| Chemical energy available (kWh d⁻¹) | 116,555,116 |
| Range of useful thermal energy available (kcal d⁻¹) | 8,868,850 |
| Range of thermal energy demand (kcal d⁻¹) | 116,555 |
| Useful thermal energy available (10³ kcal d⁻¹) | 100.0 |
| Useful thermal energy available (%) | 2,767.7 *** |
| Useful electric available (kWh d⁻¹) | 2,767.7 *** |

*80% of yield for the STHIL system. ** 30% of yield for the motor generator (ROSA et al., 2016; SANTOS et al., 2016). *** Only 2 WWTPs
Biomethane is another a green transition strategy for achieving sustainability in the transport sector, but its use requires investments in new power plants and fuelling stations, as well as the implementation of policies on both the local and national level to accelerate this process (D’Adamo et al., 2021).

### 3.2 Technologies and scenario impact analysis

Table 3 presents the results from the survey of the investments required for implementing the two technological alternatives analyzed in this study for recovering energy from methane gas. The value of the investment required for implementing the STHIL technology can vary, depending on the adaptations that must be made to the existing drying bed infrastructure, the connections between the biogas outlet in the anaerobic reactor and the bed, the biogas-powered water heater, and labor costs (Possetti et al., 2012).

Figures 1 and 2 show the results of the financial impact simulation for the projects involving the implementation of STHIL and motor-generator technologies in the 159 WWTPs analyzed. Results are shown for both the scenario with no methane emission tax (C1) and with methane emission tax (C2). The data have been grouped into categories based on the affluent flow of each plant.
In the scenario with no methane emission tax (C1), it was found that implementing the STHIL system becomes financially attractive in WWTPs whose flow rate is greater than 50 L s\(^{-1}\) (6.5 years), between 40 and 50 L s\(^{-1}\) (11.5 years) and between 30 and 40 L s\(^{-1}\) (20 years), categories which together represent 18.2\% of the WWTPs. For the remaining categories (flow rate < 30 L s\(^{-1}\)), this technology was not attractive for the analyzed time horizon. On the other hand, for the scenario with methane emission tax (C2), the simulation revealed that all WWTPs exhibit a positive return on the investment beginning 3 years after the STHIL system is implemented, regardless of their flow rate (Fig. 1).

Based on these results, the sanitation company should consider in its short-term plans the implantation of the STHIL system in WWTPs with flow rates above 30 L s\(^{-1}\), since these exhibited a shorter time for return on the investment and account for 12.8\% of the total investment. Medium-term plans should focus on implementations in WWTPs with flow rates lower than 30 L s\(^{-1}\) (which represent 81.8\% of all WWTPs and account for 59.8\% of total investment), since it is expected that methane emission taxes will be incorporated into the operation costs of WWTP in Brazil over the next several years, just as it is already practiced in several other countries (HÁJEK et al., 2019; LIU et al., 2017). According to scenario 2, the annual cost of methane emissions may reach approximately R$ 6.5 million (86.7\% of the total cost); therefore, WWTPs with a flow rate lower than 30 L s\(^{-1}\) must be gradually modernized to receive the STHIL technology.

The results also showed that in scenario 1, the 2 WWTPs with the potential to generate electric power by means of a motor generator exhibit a positive return on the investment beginning in the fourth year after the project implementation, and in scenario 2, after the second year (Fig. 2). Although this technology requires an investment of R$ 2.4 million for only 2 WWTPs (27.4\% of the total investment), its financial return represents 64.7\% of the total annual cost that can be avoided for the 159 WWTPs studied, according to scenario 1. For this reason, it is strongly recommended that the technology be implemented in these WWTPs.

Although the scenario 1 simulation showed that small WWTPs (< 9.9 L s\(^{-1}\)) did not exhibit a positive financial return for the implementation of the STHIL system during the 20-year horizon, these plants are more numerous (49.9\%). Therefore, a detailed spatial analysis is recommended to determine the feasibility of the project in the case of a centralized integrated management of dry sludge (after STHIL) to feed a thermal dryer.
Available studies involving STHIL technology report results only for thermal sludge drying in a single sewage treatment plant (Posseti et al., 2012) or for cogeneration from biogas (Santos et al., 2016); there is a lack of detailed information regarding its implementation in small WWTPs. It is strongly recommended that regional studies be conducted, which consider the local characteristics of the sewage treatment plants (such as generation capacity, and recovery potential, necessary investments, national regulations, and public support), an aspect that has been little explored by developed countries (Ocana et al., 2020).

This study estimated the potential for energy recovery from biogas and the financial viability of using this energy (heat) for drying sludge and generating electricity (cogeneration) for both scenarios (with and without methane tax) in small WWTPs in the state of Paraná (Brazil). However, the methodology applied in this study may be reproduced at any sewage treatment plant with similar characteristics for the purpose of informing decision makers in public or private companies.

The results of this research may provide necessary information for policy makers to establish guidelines for taxing methane emissions in the sanitation sector (conditions, horizon, and values), as well as financing lines for the purpose of updating technologies and infrastructure in priority applications, in order to transform small WWTPs into sustainable energy sources on an urban scale, considering their enormous potential for implementing waste-to-energy in Brazil.

### 3.3 Overview of emissions taxing

Laws are in place in several countries for the purpose of penalizing companies that produce GHG emissions at levels above current limits. In England, companies in certain areas of operation must submit a request for permission to emit greenhouse gases during their activities. This request must include a full description of the company’s activities and the quantities of GHGs to be emitted, in addition to other required descriptions. Once the permission is granted, the company must comply with all rules established by the legislation so that the GHG emission does not exceed the permitted amount. In cases of non-compliance, civil financial penalties are applied to companies with excess greenhouse gas emissions (United Kingdom, 2012).

In addition to reducing greenhouse gas emission, sewage treatment plants can also reduce costs related to fines that may be applied due to the emission of high CO\textsubscript{2eq} loads. For example, in Canada, the British Columbia State government as of April 1, 2018, has set fines at $35.00 per ton of CO\textsubscript{2eq} emissions. This rate is to increase by US$ 5.00 per ton each year until it reaches US$ 50.00 per ton by 2021 (Canada, 2020).

The same may be said of the Australian government, where fees have been adopted for the methane emissions from sewage treatment in WWTPs. In 2011, the government began collecting fines of US$ 25.00 per ton of CO\textsubscript{2eq} (Hutton et al., 2011). The US government predicts a gradual increase in the tax rate on GHG emissions in the energy sector (Goulder et al., 2013) for raising the cost of generating energy from fossil fuels (Zhang et al., 2013). The national carbon tax (US$ 40.00 per ton) is expected to increase at an annual rate of 5.6%, and it is expected that approximately US$ 2.5 trillion in revenue will be collected over a 10-year period (Thompson et al., 2013).

However, for the WWTPs to be able to implement the appropriate technologies for the recovery of energy from the by-products of sewage treatment in view of the reality of methane emissions taxes, it is necessary to invest heavily in infrastructure. Therefore, it is
essential that the government participate in the creation of specific lines of credit for meeting the needs of this sector (Werner, 2009). The combination of an efficient investment support system and taxation of GHG emissions is a powerful tool the central government may use to stimulate the use of alternative sources of renewable energy (Lyng et al., 2020).

States have a fundamental role in regulating the market, whether by establishing carbon taxation programs, emission limits or carbon trading, for mitigating the GHG emissions of their respective countries (Abdallah et al., 2012). In other words, the State has the sovereignty to define limits for carbon emissions for achieving the national goal of reducing GHGs, based on scenarios of financial and technological feasibility. Companies that do not adapt to this new reality and world trend are taxed based on their emissions that exceed the limit allowed for their type of activity; they may also acquire credits issued by other companies that have not reached their limit, by means of transactions on the carbon market (Zakeri et al., 2015). In several countries, however, these regulatory instruments are not yet used, and many governments do not encourage trade in energy produced, for example, in sewage treatment plants (Schafer et al., 2020).

The transport sector is responsible for high levels of GHG emissions worldwide (Irena, 2017). The generation of biomethane (obtained from treated biogas) from anaerobic WWTPs is another alternative for reducing carbon emissions in vehicles, since it replaces fossil fuels with renewable energy (Zhu et al., 2019) and minimizes dependence on natural gas (Ferella et al., 2019). However, biogas-biomethane power plants still present several obstacles, such as low acceptance among final consumers (due to a lack of clear and consistent information), current regulations that are out of step with technological updates (laws and regulations need to be updated) (Budzianowski et al., 2017), technical challenges (involving production, infrastructure, delivery, distribution) and environmental obstacles (odor, water demand, dependence on ambient temperature) (Nevzorova and Kutcherox, 2019). These obstacles may only be overcome by means of a solution that integrates the economic sectors, government, and society.

4 Conclusion

The current work verified the viability of the using thermal drying of the sludge from the biogas energy in a scenario in which methane emissions are taxed. For both time horizons analyzed, the 159 WWTPs in the State of Paraná showed a positive return on the technological investment in infrastructure required for energy recovery. The return on the investment may be higher or lower, depending on the amount of methane produced, but the scenario with a methane emissions tax exhibited an estimated loss of revenue of approximately R$ 6.5 million. The WWTPs analyzed were shown to be capable of producing biogas in sufficient quantities to dry sludge, and some of them produced an excess that may be used to generate electricity.

The data obtained in this study may aid decision makers in public or private sewage treatment plants by showing more efficient alternatives that maximize energy recovery (heat or cogeneration) and minimize costs (both investment and operating costs). These alternatives would result in benefits for the environment (reduction of GHG emissions, circularity of production, reduction of wastes, best use of materials, etc.) as well as economic gains (by reducing operating costs and generating new business and trade opportunities). The sanitation sector shows great potential for being incorporated into a
low-carbon economy, and one of the tools available for this incorporation is the implementation of a methane emissions tax.

The results obtained also showed that in scenario 2 (with a methane emissions tax) the 2 WWTPs that have the potential to generate electricity using a generator exhibit a positive return on the investment beginning in the second year. Although the implementation of this technology requires an investment of R$ 2.4 million (27.4% of the total investment), its financial return represents 64.7% of the total annual cost that can be avoided for the 159 WWTPs studied under scenario 1. For this reason, it is strongly recommended that the technology be implemented in these two plants.

In the methane emissions taxation scenario, STHIL technology exhibited more favorable financial results as compared to the motor generator. Positive results may be achieved during the first year for 58 WWTPs and beginning in the third year for all other WWTPs, regardless of their flow rates, if the parameters used in the simulation of the scenarios are assumed. Based on these results, it is recommended that the sanitation company begin plans for the short-term implementation of the STHIL system in WWTPs with flow rates above 30 L s\(^{-1}\) (those with the shortest return on the investment) and the medium-term implementation for the remaining 81.8% of WWTPs (with flow rates less than 30 L s\(^{-1}\)), since it is expected that beginning in the next few years the operating costs of WWTPs in Brazil will also include a methane emissions tax.

However, although the installation of STHIL technology requires a lower initial investment, the implementation of the motor-generator system brings several direct and indirect advantages, among which the authors would like to highlight the following: the reduction of overload in the power grid; an increase in the electricity supply of the existing power generation facilities (hydroelectric or thermoelectric); the reduction of GHG emissions into the atmosphere; contribution toward the achievement of the national emissions reduction target; and the use of clean and renewable electric energy. Its feasibility must therefore be analyzed on a case-by-case basis.

The implementation of a methane emission fee in the Brazilian sanitary sewage sector is a process that still requires much discussion, given the complexity involved in the establishing emissions limits and unit rates, as well as in the consolidation of a strong carbon market for supporting this decision. Moreover, the socioeconomic situation in the country is currently in a weakened state, making it even more difficult to establish a carbon tax system in the short term (for example, several municipalities do not even have sewage treatment plants, and sanitation companies require the contribution of resources for investing in WWTP infrastructure). Ultimately, taxation must not be viewed simply as a punitive instrument; on the contrary, it should be seen as a tool to encourage continuous process improvement. Therefore, efforts should be made to strengthen the dialog between the public, private, and civil sectors of society for the joint formulation of an articulated proposal in which the interests of all parties converge.

The authors recommend that future studies investigate other potential technologies and management strategies for waste-to-energy that may be implemented in small WWTPs, such as heat production to warm the biological reactors, a combination of biogas, solar, and wind energy, new biogas engines, centralization of sludge in a single plant (spatial analysis). The authors also highlight the importance of studies that seek to establish a system for measuring methane emissions that adequately addresses the reality in developing countries. As a final observation, the authors would like to point out that the current period through which the Brazilian economy is passing as a result of the Covid-19 pandemic may be a deterrent factor for the short-term implementation of a methane emissions tax.
References

Abdallah, T., Farhat, A., Diabat, A., & Kennedy, S. (2012). Green supply chains with carbon trading and environmental sourcing: Formulation and life cycle assessment. Applied Mathematical Modelling, 36, 4271–4285.

Adamo, I., Falcone, P. M., Huisings, D., & Morone, P. (2021). A circular economy model based on biogas: What are the opportunities for the municipality of Rome and beyond? Renewable Energy, 163, 1660–1772.

ANP, Agência Nacional de Petróleo. (2017) Resolution n. 685 - Establishes the rules for the approval of quality control and the specification of biomethane from landfills and sewage treatment plants for vehicular use and residential, industrial, and commercial facilities at be marketed throughout the national territory. Brasília, DF.

Appels, L., Lauwers, J., Degreve, J., Helsen, L., Lieve, B., Willems, K., Impe, J. V., & Dewil, R. (2011). Anaerobic digestion in global bio-energy production: Potential and research challenges. Renewable and Sustainable Energy Reviews, 15, 4295–4301.

BCB. Banco Central do Brasil. Available in: http://bcb.gov.br/Access in: 20 March 2021.

Beegle, J. R., & Borole, A. P. (2018). Energy production from waste: Evaluation of anaerobic digestion and bioelectrochemical systems based on energy efficiency and economic factor. Renewable and Sustainable Energy Reviews, 96, 343–351.

Bilotta, P., & Ross, B. Z. L. (2016). Estimativa de geração de energia e emissão evitada de gás de efeito estufa na recuperação de biogás produzido em estação de tratamento de esgotos. Revista Engenharia Sanitária e Ambiental, 21, 275–282.

Brown, S., Beecher, N., & Carpenter, A. (2010). Calculator tool for determining greenhouse gas emissions for biosolids and end use. Environmental Science and Technology, 44, 9509–9515.

Budzianowski, W. M., & Brodacka, M. (2017). Biomethane storage: Evaluation of technologies, end uses, business models, and sustainability. Energy Conversion and Management, 141, 254–273.

CANADA. (2020) Carbon tax regulation. Consolidated regulations of British Columbia. 06 June2008. Provides for greenhouse gas emissions criteria for companies, as well as establishes rates on emissions emitted that exceed the established limits. Last updated September 20, 2020.

Carvalho, M. E. (2016). Guidelines for promoting a low carbon economy in the sanitary sewage sector in Paraná based on the recovery of biogas generated in anaerobic reactors, 2016, 118f. Dissertation (Professional Master’s in Governance and Sustainability) - Faculty ISAE Brazil, Curitiba

Chrispim, M. C., Scholz, M., & Nolasco, M. A. (2021). Biogas recovery for sustainable cities: A critical review of enhancement techniques and key local conditions for implementation. Sustainable Cities and Society., 72, 103033.

Dong, X., Zhang, X., & Zeng, S. (2017). Measuring and explaining eco-efficiencies of wastewater treatment plants in China: An uncertainly analysis perspective. Water Research, 112, 195–207.

EPA. (2017). Environmental Protection Agency. Oil and natural gas sector: emission standards for new, reconstructed, and modified sources. United States.

Ferella, F., Cucchiella, F., D’Adamo, I., & Galuucci, K. (2019). A techno-economic assessment of biogas upgrading in a development market. Journal of Cleaner Production, 210, 945–957.

Filippini, R. M. K. (2018) Subsidies for corporate guidelines for the management of greenhouse gas emissions at a sanitation service provider in the state of Paraná, 2018, 129f. Dissertation (Master’s in Urban and Industrial Environment) – Federal University of Paraná, Curitiba

Geisdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2017). The circular economy – A new sustainability paradigm? Journal of Clear Production, 143, 757–768.

Gherghel, A., Teodosiu, C., & Gisi, S. (2019). A review on wastewater sludge valorization and its challenges in the context of circular economy. Journal of Cleaner Production, 28, 244–263.

Gontijo, J. C., Wagner, L. G., Souza, M. E., & Possetti, G. R. C. (2018). Sanitation and drying of sewage sludge on radiant floors using solar energy and biogas: comparison between different thicknesses of deposited mass. Brazilian Archives of Biology and Technology, 61, e1800037.

Gould, L. H., & Schein, A. (2013). Carbon taxes versus cap and trade: A critical review. Cambridge: National Bureau of Economic Research.

Hájek, M., Zimmermannová, J., Helman, K., & Rozenksy, L. (2019). Analysis of carbon tax efficiency energy industries of selected EU countries. Energy Policy, 134, 110955.

Hutton, B; Horan, E; Rouch, D. (2011). Calculating the cost of gas emissions from wastewater: Calculating carbon tax liabilities from wastewater treatment and biosolids stockpiling. Water.

IPCC. INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE. (2014). Fifth assessment Report of the Intergovernmental Panel on Climate Change, Available in: www.ipcc.ch/pdf/assessment-report/ar5/wg3/ipcc_wg3_ar5_full.pdf Access in: 05 February 2021.
IRENA. (2017). Biogas for road vehicles technology brief, Int. Renew. Energy Agency, 1–62. www.irena.org/

Kutcherov, V., & Nevzorova, T. (2019). Barriers to the wider implementation of biogas as a source of energy: A state-of-the-art review. Energy Strategy Reviews, 26, 100414.

Lauer, M., Hansen, J. K., Lamers, P., & Thran, D. (2018). Making money from waste: The economic viability of producing biogas and biomethane in the Idaho industry. Applied Energy, 222, 621–636.

Liu, L., & Wu, G. (2017). The effects of carbon dioxide, methane, and nitrous oxide emissions taxes: An empirical study in China. Journal of Cleaner Production, 142, 1044–1054.

Lovisek, V. (2021). Triple bottom line toward a holistic framework for sustainability: A systematic review. Revista Administração Contemporânea. https://doi.org/10.1590/1982-7849rac2021200017.

Lylv, K., Skovsgaard, L., Jacobsen, H. K., & Hanssen, O. (2020). The implications of economic instruments on biogas value chains: A case study comparison between Norway and Denmark. Environment, Development and Sustainability, 34, 185–195.

Mittal, S., Ahlgren, E. O., & Shukla, P. R. (2019). Future biogas resource potential in India: A bottom-up analysis. Renewable Energy, 141, 379–389.

Mo, W., & Zhang, Q. (2012). Can municipal wastewater treatment systems be carbon neutral? Journal of Environmental Management, 112, 360–367.

Mulinari, R., Bilotta, P., Possetti, G. R. C. (2017). Analysis of the energy sustainability of the implantation of a thermal sludge dryer using biogas and dry sludge as fuel in an anaerobic sewage treatment plant. Brazilian Congress of Sanitary and Environmental Engineering.

Ocana, A. B., Borjas, P. S., & Pena, S. O. (2020). Scientific and technological trajectory in the recovery of value-added products from wastewater: A general approach. Journal of Water Processing Engineering, 39, 101692.

Oladejo, J. M., Shi, K., Luo, X., & Yang, G. (2018). A review of sludge-to-recovery methods. Energies, 110, 12–60.

Pereira, I. Z., Dos Santos, I. F., Barros, R. M., Silva, H. C., Filho, G. L. T., & Silva, A. P. M. (2020). Vinasse biogas energy and economic analysis in the state of São Paulo, Brazil. Journal of Cleaner Energy., 260, 121018.

Pili, S., Yan, S., Tyagi, R. D., & Surampali, R. Y. (2015). Overview of Fenton pre-treatment of sludge aiming to enhance anaerobic digestion. Reviews in Environmental Science and Biotechnology, 14, 453–472.

Pin, B. V. R., Barros, R. M., Lora, O. O. A., Santos, I. F. S., Ribeiro, E. M., & Rocha, J. V. F. (2020). Energetic use of biogas from anaerobic digestion of coffee wastewater in southern Minas Gerais Brazil. Renewable Energy, 146, 2084–2094.

Possetti, G. R. C., Jasinski, V. P., Andreoli, C. V., Bittencourt, S., Carneiro, C. (2012). Thermal system for sanitation of sewage sludge powered by biogas for medium and small WWTPs. Annals. Brazilian Congress of Sanitary and Environmental Engineering.

Rosa, A. P., Conesa, J. A., Fullana, A., Melo, G. C. B., Borges, J. M., & Chernicharo, C. A. L. (2016). Energy potential and alternative usages of biogas and sludge from UASB reactors: Case study of the Laboreaux wastewater treatment plant. Water Science & Technology, 71, 315–328.

Santos, I. F. S. D., Barros, R. M., & Filho, G. L. T. (2016). Electricity generation from biogas of anaerobic wastewater treatment plants in Brazil: an assessment of feasibility and potential. Journal of Cleaner Production, 126, 504–514.
Impact of a methane emission tax on circular economy scenarios…

Santos, I. F. S., Vieira, N. S. B. V., Barros, R. M., Filho, G. L. T., Soares, D. M., & Alves, L. V. (2016). Economic and CO2 avoided emissions analysis of WWTP biogas recovery and its use in a small power plant in Brazil. *Sustainable Energy Technologies and Assessments, 17*, 77–84.

Schafer, M., Gretzschel, O., & Steinmetz, H. (2020). The possible roles of wastewater treatment plants in sector coupling. *Energies, 13*, 2088.

Senante, M. M., Sancho, F. H., Arce, M. M., & Garrido, R. S. (2014). Economic and environmental performance of wastewater treatment plants, Potential reductions in greenhouse gases emissions. *Resource and Energy Economics, 38*, 125–140.

Song, C., Li, R., Zhao, Y., Ma, D., & Kansha, Y. (2019). Assessment of four sewage sludge treatment routes with efficient biogas utilization and heat integration. *Process Safety and Environmental Protection, 126*, 205–213.

Sperling, M. von. (2016). Urban wastewater treatment in Brazil. Technical Note: n. IDB-TN-970. Inter-American Development Bank. Water and Sanitation Division.

Sun, Q., Li, H., Yan, J., Liu, L., Yu, Z., & Yu, X. (2015). Selection of appropriate biogas upgrading technology: A review of biogas cleaning, upgrading and utilization. *Renewable and Sustainable Energy Reviews, 51*, 521–532.

Taschelmayer, C., & Bilotta, P. (2021). Spatial and temporal analysis of energy recovery strategies for sewage treatment by-products in the metropolitan region of Curitiba. *Journal Geosul, 79*, 495–517.

Thompson, E., Wang, Q., & Li, M. (2013). Anaerobic digester systems (ADS) for multiple dairy farms: A GIS analysis for optimal site selection. *Energy Policy, 61*, 114–124.

UNITED KINGDOM. The greenhouse gas emissions trading scheme regulations. Provides for greenhouse gas emission criteria for companies, as well as establishes conditions and permission standards for the release of greenhouse gases. 05 December 2012.

Wang, X., Guo, M., Koppelaar, R. H. E. M., Dam, K. H., & Shah, N. (2018). A nexus approach for sustainable urban energy-water-waste systems planning and operation. *Environmental Science and Technology.*, 52, 3257–3266.

WEBSTER, K. (2015). *The circular economy: a wealth of flows*. England. Ellen MacArthur Foundation, Isle of Wight. p. 200.

Werner, C. (2009). *Biogas capture and utilization: An effective, affordable way to reduce greenhouse gas emissions and meet local energy needs*. Environmental and Energy Study Institute.

Zakeri, A., Dehghanian, B., & Sarkis, J. (2015). Carbon pricing versus emissions trading: A supply chain planning perspective. *International Journal of Production Economics, 164*, 197–205.

Zhang, L., Osmani, I. A., & Gonela, V. (2013). An integrated optimization model for switchgrass-based bioethanol supply chain. *Applied Energy, 102*, 1205–1217.

Zhu, T., Curtis, J., & Clancy, M. (2019). Promoting agricultural biogas and biomethane production: lessons from cross country studies. *Renewable Sustainable Energy Reviews, 114*, 109332.

Zivkovic, M., Ivezic, D. (2021). Utilizing sewage wastewater heat in district heating systems in Serbia: effects on sustainability. *Clean Technologies and Environmental Policy*.

**Publisher’s Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.