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Study on the implementation and operational cost calculation of by-product utilization system in sewerage management

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ABSTRACT

Global environmental issues have become increasingly serious in recent years and have had a major impact on the economy and society. Water-related problems are one of these environmental issues, and effective utilization of water resources is required. One such measure is the utilization of energy from by-products generated in sewerage projects. It has been proven that the utilization of energy from by-products in sewage systems contributes to substantial reductions in greenhouse gas emissions, but in Japan, the utilization rate is not high. One of the reasons for this is a lack of consideration of the economic aspects of the project and concerns about investment costs. Therefore, in order to increase the utilization rate, it is necessary to verify the economic feasibility of this project, and this study will conduct such verification. In order to verify the economic feasibility of this project, the city of Yokohama, which already has several years of experience in this field, was selected as the target city, and a hypothesis was formulated that the project would be economically useful. Specifically, it was assumed that energy utilization of by-products would lead to lower energy demand and energy sales, which would contribute to lower running costs. In addition, two sub-hypotheses were developed for specific verification. Sub-hypothesis 1 assumes a large-scale investment type that comprehensively implements everything from sewage treatment to the conversion of by-products into energy. Sub-hypothesis 2 assumes a small-scale investment type in which the fuel and energy conversion portions are outsourced. The verification of sub-hypothesis 1 and sub-hypothesis 2 was conducted by simulation and by using the financial data of Yokohama City, respectively, and it was confirmed that each of them contributes to the reduction of running costs. Based on the above, the hypothesis was judged to be valid.

KEYWORDS

Sewerage; By-product; Cost calculation; System dynamics

ARTICLE HISTORY

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Introduction

On 23 July 2023, the World Meteorological Organization announced that the month is on track to be the hottest July and the hottest month on record [1]. Coupled with this announcement, António Guterres, the Secretary General of the United Nations, stated, "The Era of Global Warming has ended; the Era of Global Warming has arrived and urged countries to take immediate action to address the problem of rising temperatures. As his remarks make clear, today's environmental problems are serious, and their impact on the economy and society is significant.

The United Nations adopted 17 Sustainable Development Goals (SDGs) in the General Assembly as part of international goals, including addressing environmental issues [2]. However, as evident from the opening remarks of the United Nations Secretary-General, it is challenging to claim substantial progress in these efforts.

One of these goals, Goal 6, titled "Ensure availability and sustainable management of water and sanitation for all," faces significant challenges. According to the UNESCO (United Nations Educational, Scientific, and Cultural Organization), approximately 26% of the world's population, equivalent to 2 billion people, lack access to safely managed drinking water services, and about 46%, or 3.6 billion people, lack access to safely managed sanitary facilities [3]. Thus, the widespread availability of hygienic water environments remains elusive. Furthermore, it also indicates that over the past 40 years, water usage has increased by 1% annually, and it is predicted that the population facing water scarcity could rise from 930 million to as high as 2.4 billion in 2050. In essence, there is significant room for expansion in water-related initiatives, and the demand for these services in the business sector is expected to remain high.

On the other hand, concerning Goal 7 of the SDGs, "Ensure access to affordable, reliable, sustainable, and modern energy for all," according to the Energy Institute, global electricity generation from renewable energy sources has experienced an average annual growth rate of 14.0% from 2012 to 2022 [4]. However, the current situation remains that electricity generation from fossil fuels such as oil, coal, and natural gas still accounts for over 60% of total electricity generation.

When considering the consumption of primary energy, as of 2022, it has swelled to approximately 1.5 times that of the year 2000 on a global scale. At any given point, the renewable energy share of the total energy mix remains below 10%.

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One solution to the issues is the effective utilization of by-products generated in wastewater treatment, such as sludge and biogas. In particular, sludge, which was previously disposed of primarily through incineration, causing environmental burdens, can now be carbonized and used as fuel for thermal power generation, contributing to a significant reduction in greenhouse gas emissions.

In the Energy Institute, such energy generation is considered part of renewable energy [4]. Table 1 presents the actual energy generation from renewable sources in exajoules for G20 countries in 2022, excluding the EU government. It also shows the annual growth rate from 2012 to 2022.

Table 1. Amount of renewable energy generated and growth rate per annum.

Country Name	Amount of Renewable Energy Generated (2022) (Exajoules)	Growth Rate per Annum (2012-2022)
Argentina	0.19	24.80%
Australia	0.7	17.80%
Brazil	1.66	13.60%
Canada	0.51	7.50%
China	13.2	25.20%
France	0.66	10.00%
Germany	2.33	6.20%
India	2.02	14.50%
Indonesia	0.39	15.60%
Italy	0.71	3.30%
Japan	1.51	15.10%
Mexico	0.44	15.50%
Russian Federation	0.07	30.40%
Saudi Arabia	Not Available	41.00%
South Africa	0.15	2.50%
South Korea	0.48	30.00%
Turkey	0.69	25.10%
United Kingdom	1.29	13.00%
United States	6.87	11.30%

Sources: Energy Institute [4]

As of 2022, Japan has been generating more than 1.5 exajoules of renewable energy, ranking sixth among 19 countries in this regard. The growth rate per annum from 2012 to 2022 is approximately 15%, indicating sustained efforts toward expansion.

However, according to the World Bank, Japan, with a GDP comparable to Germany's in 2022, falls noticeably behind in renewable energy generation, as shown in Table 1 [5]. There appears to be room for improvement.

According to Japan's Ministry of Land, Infrastructure, Transport, and Tourism, the effective utilization rate of by-products discharged from sewage, or the recycling rate, was 77% in 2021 [6]. However, when it comes to energy utilization within this category, it stands at only 28%. Therefore, there is significant potential for the expansion and promotion of energy utilization from sewage by-products in Japan.

Literature Review

Existing studies on environmental impact and sewage by-product treatment or utilization were surveyed. Mouri & Oki, and Jin et al. have discussed the energy consumption and CO2 emissions in sewage treatment processes and their associated processes [7,8]. From the perspective of Life Cycle Assessment, Yoshida et al. have examined the methodology and technical assumptions regarding the Life Cycle Assessment of sewage sludge [9].

In terms of research on the effective utilization of sludge, Jama-Rodzenska et al., and Wollmann et al. have focused on the recovery of phosphorus from sewage treatment processes and discussed the efficiency of the production process and components for use as fertilizers [10,11]. Rezaee et al. have verified the effectiveness and impact of using sewage sludge as one of the raw materials in cement manufacturing [12]. Murray et al. have discussed the productive utilization of sludge, stating that incineration using coal is the most environmentally and economically costly treatment method [13].

From the perspective of sludge energy utilization, researchers have considered sewage sludge as an energy source and discussed its utilization process and effectiveness as fuel [14-17].

As mentioned above, the utilization of sewage by-products is actively promoted as one of the solutions to environmental issues, and many existing studies have emphasized its importance. However, upon surveying existing research, it is evident that while there are numerous documents discussing sewage by-product utilization, especially regarding treatment processes and environmental impacts, there is a relatively limited discussion from an economic perspective, including topics such as introduction costs. Given the importance of addressing economic challenges for the widespread adoption of such utilization, this study focuses on this aspect.

Hypotheses

Sewage by-products such as sludge and digester gas are typically disposed of as waste, incurring processing costs. However, considering that conventional incineration using coal, as pointed out by Murray et al., is the most expensive treatment method, it can be argued that the conversion of by-products into energy is cost-effective [13].

The mechanism behind this argument is that the reduction in overall running costs due to decreased energy demand or the sale of excess energy at the municipal level is expected to outweigh the initial costs incurred in setting up facilities for converting these by-products into renewable energy. This perspective assumes the need for a long-term view to recover the initial investment.

Hence, the hypothesis posits that "utilizing sewage by-products for energy contributes to a reduction in running costs." To validate this hypothesis, two business models are considered. One is an investment model that involves comprehensive and large-scale energy utilization projects, including conversion of by-products to fuel and electricity generation, all integrated as part of the wastewater treatment process. The other is a small-scale investment model in which

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sludge carbonization and power generation are outsourced to external companies with minimal process modifications.

Based on these two models, two sub-hypotheses are formulated, sub-hypothesis 1 posits that in the large-scale investment model, there are substantial initial costs associated with the construction of facilities required for the conversion of by-products into fuel and electricity generation. However, it assumes that the reduction in overall running costs due to decreased energy demand will offset these initial costs.

Sub-hypothesis 2 posits that in the small-scale investment model, reduced incineration disposal costs and increased revenue from selling fueled by-products will result in economic benefits.

Regarding the subjects of verification, it is expected that Japan will continue to make efforts in the utilization of by-products for energy, and several major cities in Japan already have operational data spanning multiple years. Additionally, equipment and facility manufacturers relevant to this field exist, and their data is accessible. Therefore, Yokohama City, where there is existing performance data in Japan, is chosen as the subject of verification. For items without existing performance data or non-public data, data from relevant equipment and facility manufacturers will be used.

Regarding the verification method for Sub-hypothesis 1, although there is no existing performance data for cases involving large-scale energy utilization projects in Yokohama City, a comparison will be made between the cumulative costs over a certain period, assuming the implementation of such a project and the costs associated with continuing the conventional treatment method. Verification will be conducted by analyzing the results of this comparison and explaining the Analytical Framework for the verification of Sub-hypothesis 1. 5. Through Simulation Analysis, the results of the calculations can be analyzed, and verification can be carried out.

For Sub-hypothesis 2, since operational data from Yokohama City has already been publicly disclosed, verification and evaluation can be conducted based on this existing data. This verification will be carried out using empirical analysis.

Analytical Framework

The implementation of the verification for Sub-hypothesis 1 requires comparing the cumulative costs over long-term time spans for scenarios involving significant investments and for scenarios continuing with the conventional treatment method. There are various methods available for cost estimation. Table 2 presents four candidate methods.

Considering the research utilizing both the Top-Down Approach and the Bottom-Up Approach, Routh et al. performed a comparison between the two methods for cost and radiation dose estimation in the initial imaging diagnosis of pediatric urinary tract infections [18]. While the Bottom-Up Approach was more common traditionally, the study highlighted the increasing use of the Top-Down Approach. The results demonstrated significant discrepancies in both cost and radiation dose estimations between the two approaches.

In existing research on the analogy-based method, Auer et al. pointed out and examined the following aspects [19]. Analogy-based cost estimation is particularly transparent because it relies on historical information from similar past projects to determine similarities by comparing the key attributes and features of projects. However, it is noted that the consideration of various attributes' differing impacts and weighting on a project-by-project basis is often incomplete, leading to discussions on improvement using quality metrics.

As for simulation modeling in previous studies, Forrester and Karnopp used system dynamics to define different variables, including economic aspects, to simulate how they interacted to solve urban problems [20]. Forrester applied it to industrial simulations, and Meadows et al. defined variables such as population, food production, capital, non-renewable resources, and environmental pollution in the context of the world at that time [21,22]. They simulated how these variables interacted and changed over time.

System Dynamics allows the user to simulate the behavior of a system as it changes over time by creating a simulation model and defining numerical values and equations for its components. It is suitable for the verification of Hypothesis 1, which requires analysis over a period of time, not just at a certain point in time.

Therefore, for the verification of Hypothesis 1, a simulation model was created using System Dynamics for the behavior of a business model that assumes large-scale energy use, including power generation, and a business model that assumes conventional incineration without considering energy use of sludge, each for a certain period of time, and calculations were the results of these simulations will be used for comparison and analysis. A comparative analysis will be performed based on the results of these simulations.

Simulation Analysis

As mentioned in the Hypotheses section, the verification of Sub-hypothesis 1 involves comparing the cumulative costs over

Table 2. Comparison of cost estimation methods.

Method Name	Method Description
Bottom-Up Approach	By providing detailed cost estimates for each module in a product or for each specific task within a project, the total cost can be calculated. While allowing for more accurate estimations, it demands more time and effort.
Top-Down Approach	Estimated costs are calculated from a bird's-eye view of the product and the business as a whole. It takes less time and effort than the Bottom-Up Approach but lacks accuracy.
Analogy-Based Method	Use cost data from actual or similar cases to estimate the cost of new projects.
Simulation Modeling	By modeling the project and incorporating scenarios, it is possible to estimate costs assuming various patterns.

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a certain period between the scenario where Yokohama City assumes the implementation of a large-scale energy utilization project and the scenario where the traditional treatment method is continued. For simplification in this comparison, only the by-product generated from sewage, specifically sludge, will be considered.

The simulation will be conducted using the System Dynamics simulation model for both the business model assuming large-scale energy utilization, as described in the Analytical framework, and the business model involving the traditional incineration disposal method. Comparative analysis will then be carried out based on the results. Table 3 presents the main data to be used in the simulation model.

The simulation model for the large-scale energy utilization project is Figure 1, where the running cost is shown as a flow, and the demand for electric power and maintenance cost, which affect the running cost, are shown as converters using the above data. The total cost is represented as a stock, and changes in the stock over time are examined.

Table 3. Source of each value quoted.

Data Item	Value	Source
Construction cost of sludge carbonization facility	¥ 5,600 million	Ministry of Land, Infrastructure, Transport and Tourism [23]
Maintenance cost of sludge carbonization facility	¥ 560 million	Ministry of Land, Infrastructure, Transport and Tourism [23]
Construction cost of power plant	¥ 100,000 million	Tokyo Metropolitan Government Bureau of Environment [24]
Maintenance cost of power plant	¥ 205 million	Tokyo Metropolitan Government Bureau of Environment [24]
Volume of sewage water	Approx. 578,000,000 (㎥)	Yokohama City [25]
Electricity demand for sewage treatment per unit	0.5kWh/1 ㎥	Ministry of Land, Infrastructure, Transport and Tourism [23]
Moisture content	78%	Ministry of Land, Infrastructure, Transport and Tourism [23]
Electricity demand for Sludge Carbonization per unit	49kWh/1t-wet	Ministry of Land, Infrastructure, Transport and Tourism [23]
Manufacturing efficiency of carbonized sludge	17.29%	Tsukishima Holdings Co., ltd. [26]
Generation efficiency of carbonized sludge	3,601kWh/1t	Tsukishima Holdings Co., ltd. [26]

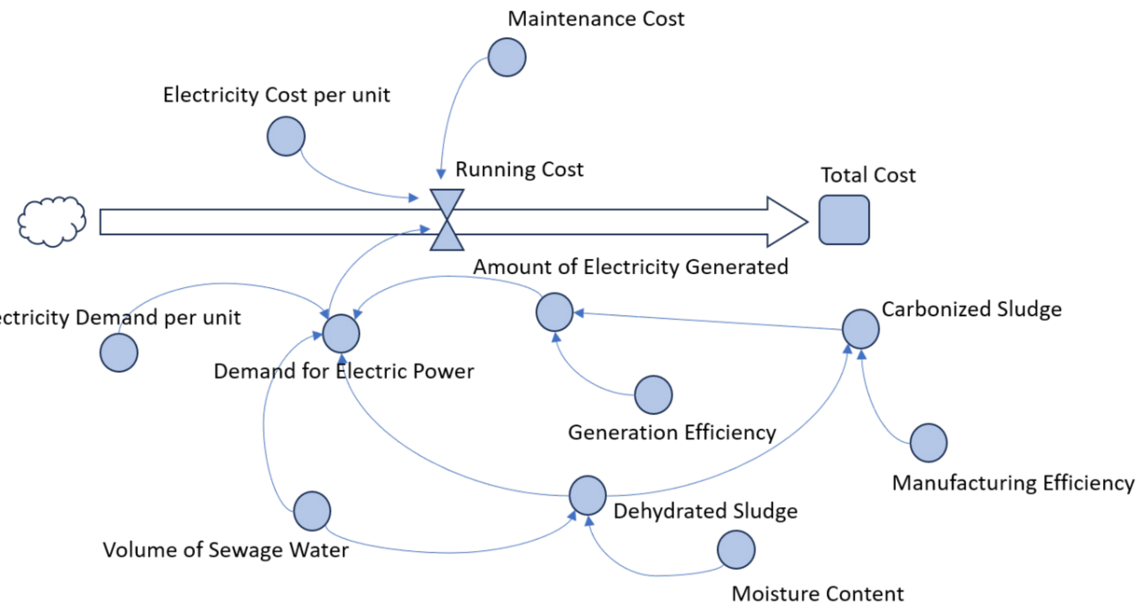

Figure 1. Simulation model assuming large-scale energy utilization of sludge.

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The primary relationships between elements are as follows: the annual sewage treatment volume serves as the starting point and has a positive impact on both electricity demand and the quantity of dehydrated sludge. The quantity of dehydrated sludge has a positive impact on electricity demand since it requires power for carbonization, i.e., conversion into fuel, but it also adds to the fuel quantity produced. The fuel quantity is multiplied by the power generation efficiency to calculate the electricity generated, which has a negative effect on electricity demand. The electricity cost is calculated by multiplying the electricity demand by the unit price of electricity, and the running cost is calculated by adding the maintenance costs of the carbonization and power generation facilities. The initial value for the total cost is set as the construction cost of the carbonization and power generation facilities.

Next, a simulation model of a conventional incineration business model is Figure 2.

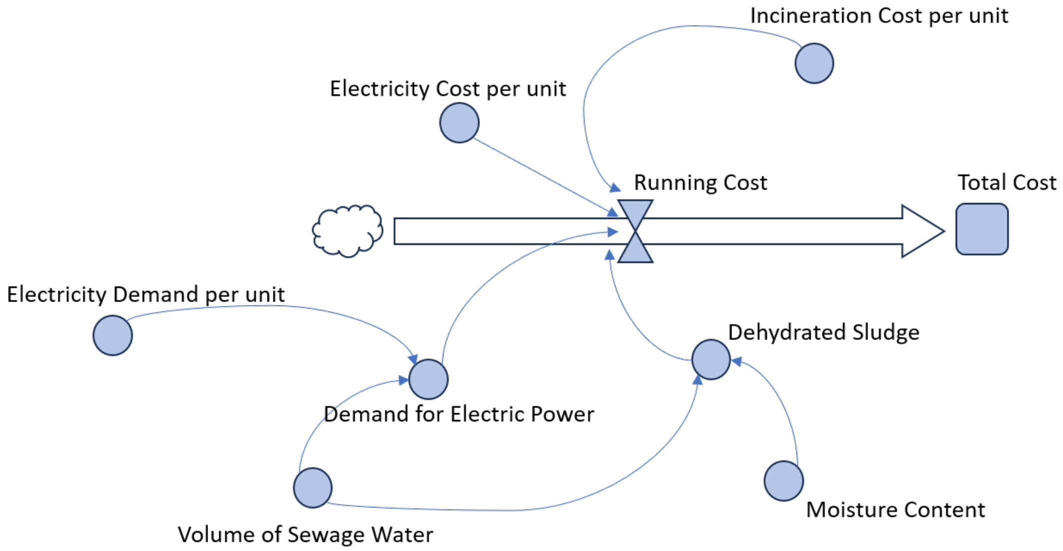

Figure 2. Simulation model for conventional incineration disposal business.

Figure 2 also starts with the annual volume of sewage water, which has a positive impact on the electricity demand and the amount of dehydrated sludge. However, in this case, there is no carbonization process for the sludge, so incineration cost is calculated from the quantity of dehydrated sludge by multiplying it by its unit cost. The electricity cost obtained by multiplying the electricity demand and price of an electricity unit is added to this cost, to calculate the cost of running. Since there are no new carbonization and power generation facilities in this scenario, there are no maintenance costs, and the initial value for the stock is set to "0."

Figure 3 presents the results of the verification showing the changes in stock, i.e., cumulative cost values, after running each simulation.

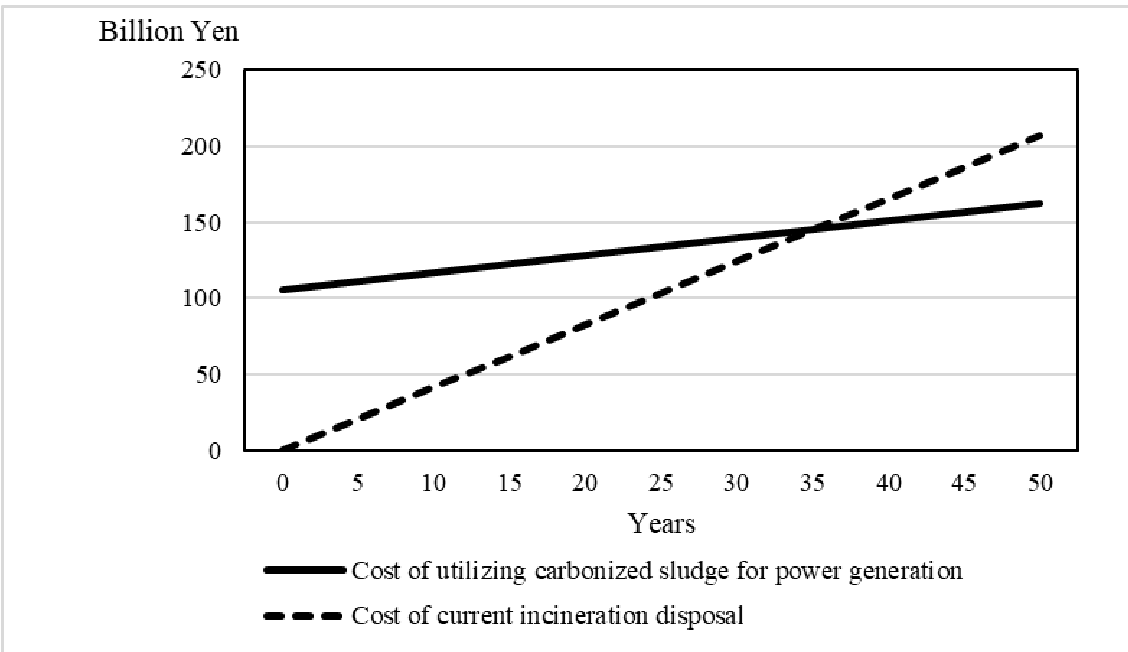

Figure 3. Cost comparison of two models.

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The solid line represents the values from the simulation results for the large-scale energy utilization of the sludge business, while the dashed line represents the values from the simulation results for the conventional incineration disposal business.

The simulation model for the large-scale sludge energy utilization project was initialized with an initial value of approximately 100 billion yen in cumulative costs. However, it was found that the cumulative costs of the traditional incineration disposal project would be lower at the point when 35 years have passed. This result is primarily due to the running costs indicated by the slope of the line, and the significant factors contributing to this difference are the substantial reduction in electricity demand in the large-scale energy utilization project and the cost savings in the incineration process. Although a large initial investment is required for a large-scale project, taking a long-term perspective, it can be said that energy utilization is more cost-effective in terms of cumulative costs than proceeding with the traditional incineration project. Based on the above, it is concluded that Sub-Hypothesis 1 is supported.

Empirical Analysis

In the Empirical Analysis, regarding Sub-Hypothesis 2 related to the small-scale investment model, it is noteworthy that the city of Yokohama has already initiated efforts to outsource the carbonization and power generation of sludge. Therefore, the verification is conducted based on Yokohama City's performance. Specifically, a comparison is made using financial data for the ten years before and after the operation of the outsourcing-based business model that Yokohama City has implemented [27].

First, to illustrate this business model, an overview of the actual sewer business in Yokohama is shown in Figure 4.

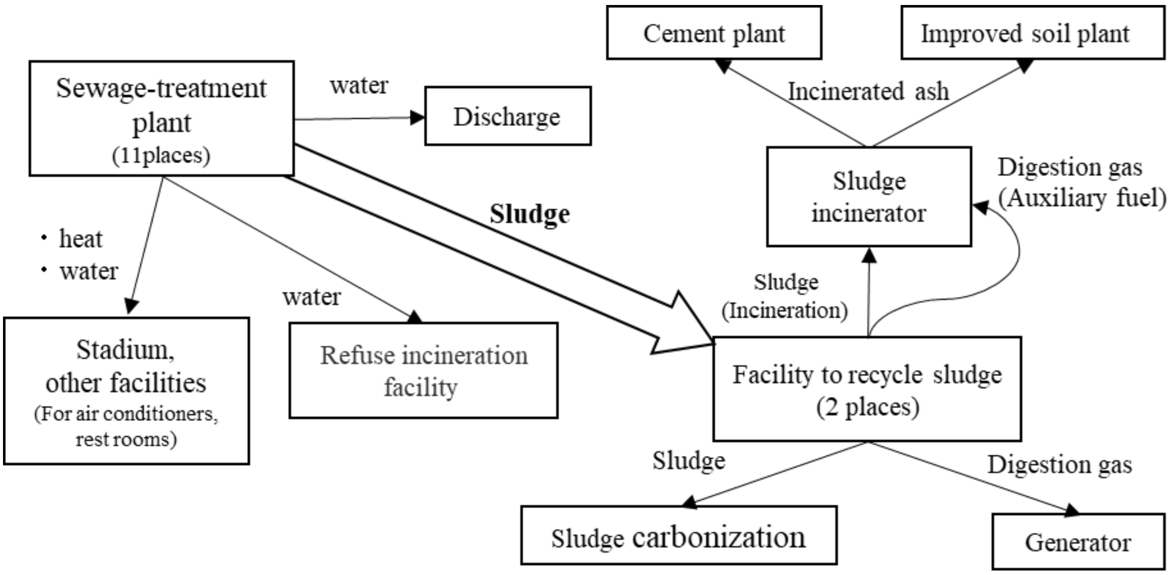

Figure 4. Summary of the sewer business in Yokohama city.

The first major process is to send the sludge generated from sewage treatment at the sewage treatment plant to a facility that reuses the sludge, as shown in Figure 4. At this facility, sludge is subjected to carbonization and power generation using digester gas. However, the current situation is that not 100% of the quantity can be utilized in this manner. The surplus portion is disposed of through conventional incineration, and the resulting incineration ash is used in cement production and soil improvement.

Secondly, Figure 5 provides an overview of Yokohama City's Private Financial Initiative (PFI) sewage system project. The flow is similar to what was shown in Figure 4 and represents the overall flow of the project. However, the project is structured with different entities, as indicated in Figure 5.

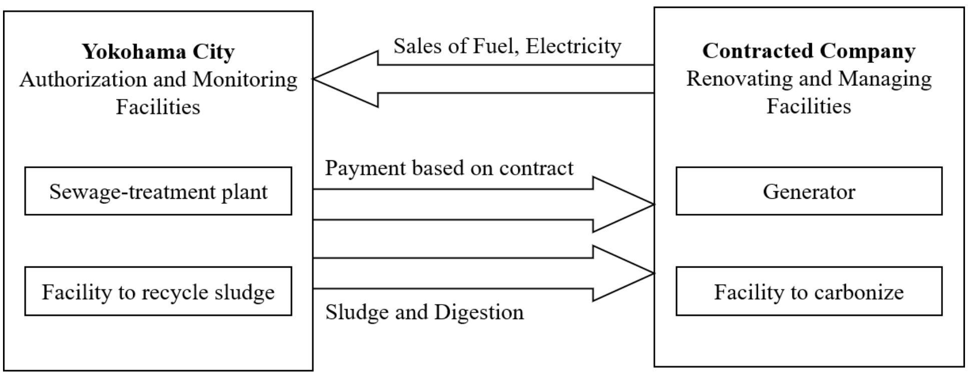

Figure 5. Summary of PFI project for sewerage business in Yokohama city.

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The role of the Contracted Company involves the operation and management of facilities for digester gas power generation and sludge carbonization, as well as the sale of carbonized sludge to power generation companies. Yokohama City pays a contract fee to the operator and sends digester gas and sludge to the operator. The operator uses digester gas as fuel for power generation and sells the carbonized sludge to a company responsible for power generation after carbonization. The revenue generated from this power generation and the sale of sludge fuel is returned to Yokohama City. The contract prices for these operations are approximately 15 billion yen over 20 years, with the digester gas power generation business totaling around 8 billion yen over the same period.

The financial impact resulting from the initiation of such business operations will be examined to confirm Sub-hypothesis 2. The initiatives for effective utilization of by-products, shown in Figures 4 and 5, have gradually progressed from contract agreements with multiple operators to actual operation between 2012 and 2020. Therefore, it is believed that the ten-year period from 2012 to 2021 allows us to discern the financial changes resulting from the initiation of these efforts.

By dividing the data into two periods, the first five years from 2012 to 2016 and the subsequent five years from 2017 to 2021, and calculating the average values of the financial data for each period, we identified two significant changes.

One of these changes relates to "Other operating revenues," and the average values for these two periods are presented in Figure 6.

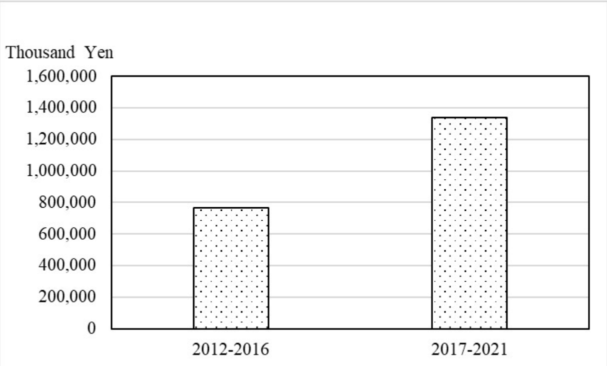

Figure 6. Average amounts of other operating revenues.

The main sources of revenue in the sewage business are the usage fees for water charges and subsidies from other accounting divisions and the government. Since subsidies are not considered as operating income, it is likely that revenues from carbonized sludge sales, among other things, fall under "Other operating revenues."

In Figure 6, the average values for the latter five years are higher. To confirm the significance of the difference in means, independent t-tests were conducted using the values from each of the two time periods (Table 3).

Table 3. Results of t-test on other operating revenues.

df	t-value	p-value	critical t-value
8	-4.936326	0.001140	2.306004

Table 3 shows that the p-value is less than 0.05, and the t-value is in the rejection range, indicating that the difference in means is significant.

This rise in value suggests that the efforts in by-product utilization, as demonstrated in Figures 4 and 5, have expanded and reached a scale significant enough to impact financial data.

The other kind of value is "Fuel Costs for Sewage Treatment," which is shown as its average values for both periods in Figure 7.

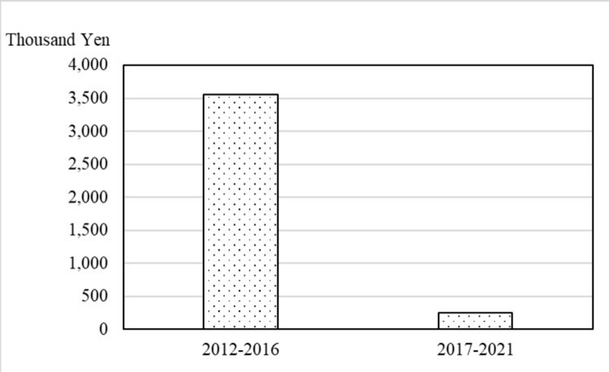

Figure 7. Average amounts of fuel costs for sewage treatment.

In Figure 7, the average values for the latter five years have decreased to less than one-tenth of the previous five years. To confirm the significance of the difference in means, independent t-tests were conducted using the values from each of the two time periods. The results are shown in Table 4.

Table 4. Results of t-test on fuel costs for sewage treatment.

df	t-value	p-value	critical t-value
8	5.129994	0.000896	2.306004

In Table 4, the p-values are less than 0.05 and in the rejection range in the t-values, indicating that the difference in means is significant.

The factors contributing to this cost reduction include the fact that the electricity generated by gas digestion is returned to the city of Yokohama and reused in sewage treatment, as well as the expansion of initiatives for effective by-product utilization, which has led to a reduction in the incineration of sludge. It is believed that this initiative has a significant impact on reducing fuel costs, contributing to cost reduction from a running cost perspective.

In other words, in the case of the small-scale investment model, it has been demonstrated that increased income from selling outsourced, fueled by-products, along with significant cost reductions in incineration expenses, has occurred. Considering the relatively short period since the start of operations, it can be inferred that these benefits were realized shortly after the investment.

Based on the verification results above, Sub-hypothesis 2 has been supported.

Conclusions

This study addressed the utilization of by-products from sewage as an environmental measure. It hypothesized that the utilization of sewage by-products for energy would contribute to reducing running costs.

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For verification, two scenarios were considered: a comprehensive large-scale investment model, including power generation, and a small-scale investment model involving outsourcing to external parties. Sub-hypotheses were formulated for each scenario and tested. The results showed that both scenarios achieved a cost reduction in running costs. Therefore, the hypotheses were supported.

In today's world, where environmental issues are a concern, effectively utilizing sewage by-products for energy, which will always be generated as long as humanity exists, can contribute to achieving a sustainable society, particularly in terms of substantial reduction in greenhouse gas emissions. While previous studies have already conducted sufficient verification in this regard, concerns about the cost aspect have persisted. However, this verification has shown that, compared to continuing the traditional incineration process, it is economically beneficial in terms of cost reduction to pursue energy utilization, both from an environmental and financial perspective.

On the one hand, initiating a comprehensive and large-scale energy utilization project, including the conversion of by-products into fuel and the construction of power generation facilities, requires a significant initial investment, and its recovery requires long-term operation. On the other hand, small-scale investment models involving outsourcing to external companies can diversify risks and yield financial impact in a short time, but they also carry the risk of whether the business will be operated according to the contract.

Therefore, to deploy sewage by-product energy utilization projects effectively, it is necessary to choose or combine appropriate business models based on factors such as the region and the entity, considering aspects like financial flexibility and the time frame for achieving results.

Hypotheses were formulated and verified accordingly. As a result, Sub-hypothesis 1, which suggests that large-scale investments reduce overall running costs, and Sub-hypothesis 2, which proposes that small-scale investments can yield cost benefits shortly after implementation, were both supported.

Based on these verification results, it is considered necessary to gradually build the required facilities and infrastructure, as well as a large-scale investment model, while ensuring the stability of the business by using outsourcing, as it is in the case of small-scale investments when by-product utilization systems are introduced and expanded.

This study primarily focused on the cost aspects of sewage by-product energy utilization. However, it should be noted that this analysis assumes normal operation and does not consider the risks associated with large-scale natural or human-made disasters, internal issues, or equipment aging. Therefore, addressing these risks and the associated costs for mitigation and risk management is an important aspect that requires further investigation.

Disclosure statement

No potential conflict of interest was reported by the authors.

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