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Evaluation of the Environmental Impact and Energy Utilization Efficiency of Wastewater Treatment Plants in Tumen River Basin Based on a Life Cycle Assessment + Data Envelopment Analysis Model

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Abstract: The environmental impacts from energy consumption account for a high percentage of the environmental impacts of wastewater treatment plants (WWTPs) throughout their life cycle; therefore, controlling energy use in WWTPs could bring substantial benefits to the environment. In this study, according to the different percentages of electricity generation from renewable energy compared to fossil energy, the global warming, acidification, eutrophication, human toxicity, and photochemical smog, the environmental impacts of WWTP operation were considered. Furthermore, to explore a more sustainable way of operating WWTPs under the "dual-carbon" strategic decision, the environmental impacts and energy utilization efficiency of different power allocation scenarios at present and in the next 40 years were compared based on the LCA+DEA integrated model. The study revealed that in scenarios 1–5, as the proportion of renewable energy power generation gradually increased, all LCA results showed a gradual decrease, of which GWP decreased by 83.32% and human toxicity decreased by 93.34%. However, in scenarios 2–5, the contribution ratio (proportion) of gas and electricity to GWP and POCP gradually increased, reaching 77.11% and 59.44%, respectively, in scenario 5. The contribution ratio (proportion) of biomass generation to AP and EP gradually increased as well, reaching 65.22% and 68.75%, respectively, in scenario 5. Meanwhile, the combined technical efficiency in energy utilization in the five scenarios showed a decreasing trend; only scenario 1 was fully efficient, and the combined efficiency was 1. The values of combined technical efficiency in scenarios 2, 3, 4, and 5 gradually decreased and were 0.7386, 0.4771, 0.2967, and 0.1673, respectively. This study discusses whether the use of renewable energy in place of fossil energy power elicits an environmental impact in WWTPs. We explore the feasibility of achieving energy savings and emission reductions in WWTPs within the Tumen River Basin, to provide a theoretical basis for their sustainable development.

Keywords: carbon neutrality; clean energy; life cycle assessment; data envelopment analysis; environmental impacts

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1. Introduction

Wastewater treatment is an energy-intensive and high-energy-consumption industry that accounts for approximately 1–2% of the total electricity consumption and has the potential for substantial carbon emission reductions [1]. In China, since the 2015 "Action Plan for Prevention and Treatment of Water Pollution" and the 2019 "Three-Year Action Plan for Improving the Quality and Efficiency of Urban Sewage Treatment (2019–2021)" were implemented, water pollution prevention and control has entered a new stage of development, resulting in substantial improvements to the aquatic environment quality. After these years of upgrading, most urban wastewater treatment plants (WWTPs) have achieved Class A discharge standards [2]. However, high WWTP discharge standards

and excessive wastewater treatment have also led to environmental issues, including high energy consumption, carbon emissions, and resource consumption. According to the National Population Development Plan (2016–2030), carbon emissions from the wastewater industry are expected to reach 82.45 ± 6.65 million tons of CO_2 eq in 2030 [3], accounting for 2.95% of the total observed carbon emissions [4]. In the wastewater treatment industry, over 50% of carbon emissions are from electricity consumption in WWTP operation stages [1,5], while CH_4, N_2O, etc, directly produced by the wastewater treatment process approximately account for 35% [6]. To achieve energy savings and emission reductions, various energy-saving and emission-reduction measures have been proposed in the wastewater treatment industry, such as upgrading equipment [7], upgrading processes [4,8], sludge biogas recycling [9], and installing a water source heat pump [10]. However, under the current "dual-carbon" targets, in addition to measures to reduce electricity consumption, it is necessary to consider the carbon-neutral potential of the wastewater industry regarding the optimization of the electricity structure [11–13].

In 2022, renewable energy took a majority share in China's new power capacity installations; incremental renewable capacity accounted for 76.2% of China's overall newly installed capacity [14]. According to the National Bureau of Statistics [15], hydroelectric, nuclear, wind, photovoltaic, and other clean power sources produced 123.54 billion kWh, representing 12.8% annual growth, and annual thermal power outputs decreased by 3.9%. Indeed, the future use of clean energy will inevitably overtake that of fossil energy in power generation [16], with the energy transition of the power structure in WWTPs currently being realized. However, whether the future clean-energy-based power model plays a role in improving environmental impacts throughout the life cycle of sewage treatment plants, and the specific energy utilization efficiency situation, remain unclear.

Life cycle assessment (LCA) is widely used in the wastewater treatment industry [17,18], primarily when comparing different sizes [19], processes [10,20], treatment stages [21,22], and environmental impacts of different resource recovery and utilization schemes [20,23]. In this way, the root causes of environmental issues in wastewater treatment can be identified, thus facilitating the development of improvement and optimization measures. Rashid et al. [24] assessed the impacts of three different processes on WWTPs in Malaysia from environmental and economic perspectives, using LCA. The results showed that the environmental benefits and costs must be balanced in the choice of technology used to economically realize an environmentally sustainable WWTP. In addition, LCA can be used to assess carbon emissions from wastewater treatment. For example, Parravicini et al. [25] assessed the GHG emissions from WWTPs in Europe using the LCA method and proposed options for mitigating carbon emission reduction, noting that the main contribution to GHG emissions from WWTPs comes from direct N_2O and CH_4 emissions during operation, followed by indirect emissions from power production. They suggested that GHG emissions can be reduced through decarbonization of power production as well as process upgrading and modification. Moreover, Polruang [26] employed LCA to evaluate the environmental impact of seven WWTPs in Bangkok, Thailand, over the next 5 and 20 years under different electricity mixes using clean energy instead of fossil energy generation. The results showed that electricity production and use is the main source of most environmental impacts and that lowering the fossil energy generation dependence can reduce environmental impacts. However, LCA only evaluates the environmental impact potential, without facilitating further analysis of energy use efficiency.

WWTPs are energy-intensive industries with multiple inputs and outputs; their economic efficiency, eco-efficiency, and energy efficiency can be comprehensively analyzed through data envelopment analysis (DEA). Recently, studies have been conducted to apply LCA in combination with DEA for the evaluation of WWTPs. For example, Lorenzo-Toja et al. [19] investigated 113 WWTPs throughout Spain using this combined methodology. They found that small WWTPs lacked continuous monitoring and their efficiencies were lower than those of large WWTPs. Better monitoring and technological improvements in small WWTPs were proposed to improve their environmental statuses. In summary, the use

of LCA and DEA integrated models to analyze WWTPS can facilitate the evaluation of potential environmental impacts and the visualization of WWTP efficiency in terms of energy use, providing scientific recommendations for the sustainable development of WWTPs.

The Tumen River is located in the Yanbian area, Jilin province, Northeast China, bordering North Korea and Russia; it holds considerable ecological and national strategic significance. Therefore, this study focuses on evaluating the environmental impacts of switching from fossil energy power to clean non-fossil energy power in the Tumen River Basin WWTP. To this end, five scenarios with different power-mix ratios were designed for different time scales (i.e., 2021, 2030, 2040, 2050, and 2060), based on different percentages of electricity generation from clean energy sources. Subsequently, the environmental impacts and energy use efficiency of the WWTP were assessed across the five scenarios using the combined LCA+DEA evaluation method. The aim of this study is to analyze improvements in the environmental impact of energy transition and the energy utilization efficiency, and to explore the feasibility of carbon neutrality for WWTPs in the Tumen River Basin.

2. Materials and Methods

2.1. Power Scheme Selection

The cyclic activated system technology (CAST) process is a commonly used method in wastewater treatment; it is suitable for small-town WWTPs with a small treatment scale. In this study, a small-town WWTP in the Tumen River Basin, operated under the CAST process, was selected, with a daily treatment capacity of approximately 25,000 m^3. After upgrading the process in 2020, its discharge water quality now meets the Class I-A discharge standard in the "Pollutant Emission Standards for Urban Wastewater Treatment Plants".

2.2. Scenario Settings for Different Power Structures

Based on the future power-mix ratio of China derived by Liu et al. [27], and using the Verhulst model, we designed five electricity production plans on different time scales: current (2021), 2030, 2040, 2050, and 2060. Scenario 1 (2021) serves as the base scenario and scenarios 2, 3, 4, and 5 serve as control scenarios. The clean energy power generation types used in this study were divided into photovoltaic (PV), hydroelectric, wind, gas, nuclear, and biomass power generation. As shown in Figure 1, in scenario 1, the share of fossil energy generation was 57%, and the shares of photovoltaic power, hydropower, wind power, gas power, nuclear power, and biomass power were 4%, 18%, 8%, 6%, 4%, and 3%, respectively. In scenarios 2–4, the share of fossil energy generation gradually decreased to 40%, 23%, and 10%, reaching the ideal state of zero fossil energy generation in scenario 5. Concurrently, the share of clean energy generation gradually increased, reaching the ideal state of 100% utilization in Scenario 5.

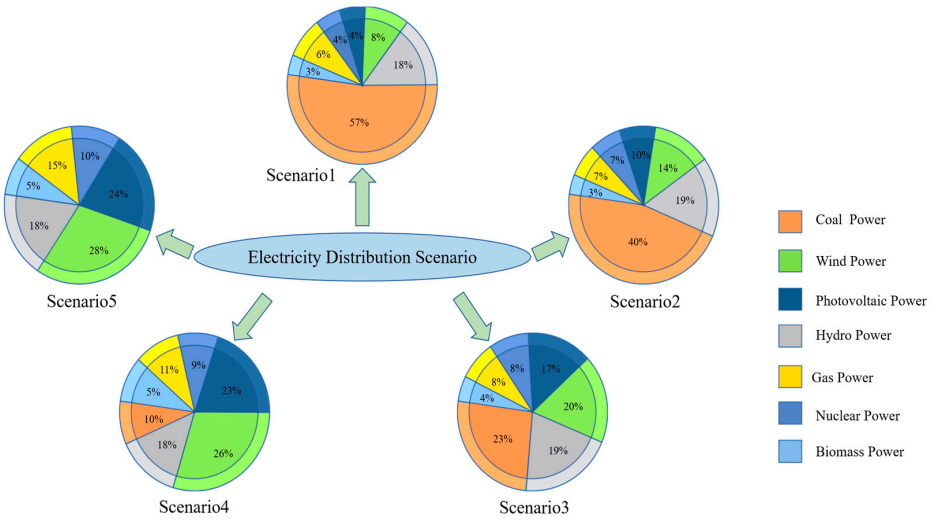

Figure 1. Power distribution scenarios of different energy structures.

2.3. Life-Cycle Assessment of the WWTP

According to the International Organization for Standardization, the basic LCA process includes goal and scope definitions, life cycle inventory (LCI), life cycle impact assessment (LCIA), and life cycle interpretation.

2.3.1. Goal and Scope Definitions

In this study, a case study of a WWTP in the Tumen River Basin was used to compare and evaluate the environmental benefits of the CAST process in terms of resources and energy consumption. The LCA method was applied to optimize the theoretical choices and evaluation of WWTP operation and management. In addition, the environmental impacts of five different power distribution scenarios were compared to investigate the improvement in environmental impacts by utilizing clean energy instead of fossil energy for power generation.

The LCA boundary for this study began with the influent and ended with the effluent and included the sludge treatment process. The final sludge disposal process was not considered due to the low sludge production. Specifically, the electricity and chemicals used in the pretreatment stage, biological treatment stage, and sludge treatment stage, as well as the greenhouse gases (GHGs) emitted during the wastewater treatment process, were included. The boundary diagram is shown in Figure 2. The functional unit was set to a sewage treatment volume of 1000 m^3/d.

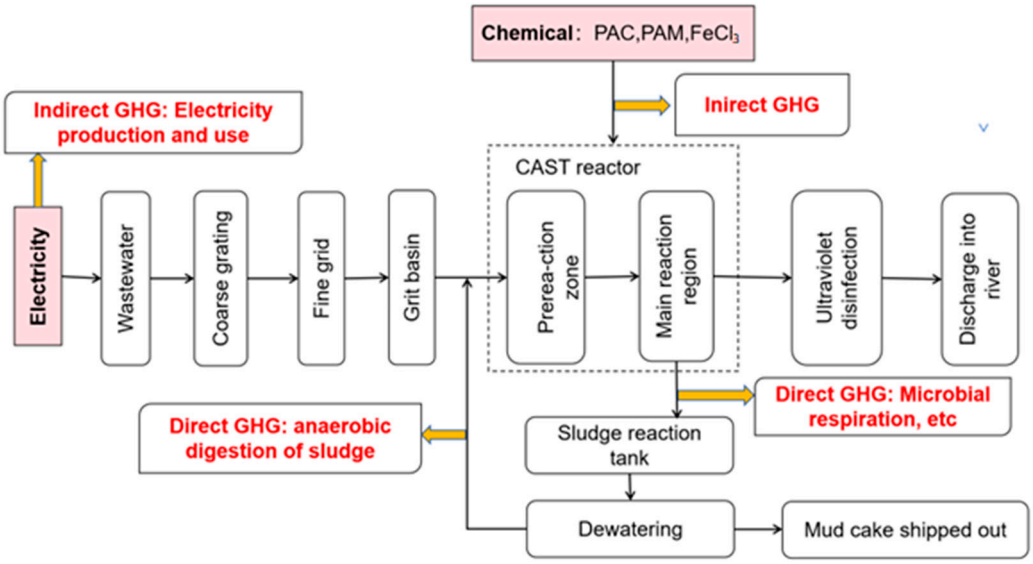

Figure 2. Process flow diagram and system boundaries for LCA of WWTP.

2.3.2. Life Cycle Inventory

Since the wastewater plant was upgraded in 2020 and the operational data for 2020 were not yet stable, the operational data for 12 months in 2021 were selected based on the objectives and scope of the study (see Supplementary Materials for detailed data). Inventory data are shown in Table 1 (functional unit: 1000 m^3/d), including electricity consumption, pharmaceutical consumption, and sludge production, as well as effluent quality and GHG emissions during the wastewater treatment process. The data on electricity consumption, chemicals, and water quality were provided by the WWTP; the background data on electricity and pharmaceutical consumption were obtained from the GaBi Databases in the GaBi 9.2 software. Additionally, the electricity consumption included the processes of the production and use of electric power. The CH_4 and N_2O emissions were calculated using the removal of COD and NH_3-N from the WWTP, and the greenhouse gas emission coefficients were calculated [28] (see Supplementary Materials for details).

Table 1. Life cycle inventory of the WWTP (functional unit: 1000 m^3).

		Unit	Value
Input	Electricity consumption	kWh/d	233.64
	Chemical-PAC	kg/d	46.60
	Chemical-PAM	kg/d	0.24
	Chemical-$FeCl_3$	kg/d	52.25
Output	Sludge	kg/d	174.81
	COD	kg/d	18.90
	BOD	kg/d	3.75
	TN	kg/d	5.38
	TP	kg/d	0.22
	NH_3-N	kg/d	0.84
	Methane	kg/d	3.85
	N_2O	kg/d	0.48

2.3.3. Life Cycle Impact Assessment

Life cycle impact assessment (LCIA) aims to understand and evaluate environmental impacts based on LCI data. In this study, the characterization and normalization results of the environmental impacts were calculated using GaBi9.2. First, the CML2001-Jan.2016 method was selected for characterization, and five environmental impact indicators commonly used to evaluate the environmental impacts of WWTPs [5,29] were selected: global warming (GWP), acidification (AP), photochemical smog production (POCP), eutrophication (EP), and human toxicity (HTP). EP is the impact of treated wastewater on the receiving water body. Second, the CML2001-Jan.2016 World standardization system was chosen to standardize the characterization results, converting them to a uniform value that allowed comparison of all environmental impacts in the same range [30]. Finally, an uncertainty analysis of the environmental impact categories was conducted with seven different generation energy sources as change factors for a 10% increase or decrease in input and output inventory data.

2.4. Data Envelopment Analysis

DEA, originally proposed by Charnes et al. [31], is a nonparametric method for assessing the efficiency of decision-making units (DMUs) using a linear programming model [32] and is particularly suitable for studying the efficiencies of DMUs when they have multiple inputs and outputs. DEA includes the CCR, BCC, and SBM-DEA models, among others. The BCC model—relative to other models—divides the integrated technical efficiency into scale efficiency and pure technical efficiency. In the energy-efficiency analysis of wastewater treatment, the BCC model can be applied through scale efficiency and pure technical efficiency to further analyze the energy efficiency results. Accordingly, the BCC model was selected for the current study. The formula is as follows:

$$\left\{\begin{array}{l} min\theta \\ \text{s.t.}\sum_{j=1}^{n}\lambda_j x_j + s_i^- = \theta x_0, i = 1,2,\cdots,m \\ \sum_{j=1}^{n}\lambda_j y_j - s_r^+ = y_0, r = 1,2,\cdots,s \\ \sum_{j=1}^{n}\lambda_j = 1, \lambda_j \geq 0 \\ s_i^- \geq 0 \\ s_r^+ \geq 0 \end{array}\right\} \quad (1)$$

where the maximum value of Equation (1) is the technical efficiency value of decision unit j_0; x_j is the j-th decision unit input, $x_j > 0$; y_j is the j-th decision unit output, $y_j > 0$; λ_j is the combination ratio of the j-th decision unit in the reconstituted effective decision unit; and the s_i^- and s_r^+ variables have m input and s output variables, respectively.

The efficiency value calculated by the BCC model is the comprehensive technical efficiency (TE), which can be further decomposed into scale (SE) and pure technical (PTE) efficiencies, for which TE = SE × PTE.

2.5. Three-Step LCA+DEA Methodological Framework

To investigate the environmental impact improvements and energy utilization efficiencies using clean energy instead of fossil fuel for power generation, an energy utilization evaluation model based on LCA+DEA was constructed. Five scenarios were set as five DMUs in the DEA analysis. The three-step LCA+DEA method was structured as follows (Figure 3): (i) inventory data were collected for the WWTP and evaluated using LCA to obtain the environmental characterization and normalization values for each scenario; (ii) the values obtained in step i were used as output normalization indicators in the DEA model, and clean energy generation, chemical consumption, and sludge production were used as input indicators, from which the energy utilization rates were evaluated for the five scenarios using the MaxDEA 8 Basic software package; and (iii) the results obtained from steps i and ii were used to analyze the changes in TE, PTE, and SE, which were used to assess feasible actions for attaining energy efficiency and environmental performance benchmarks.

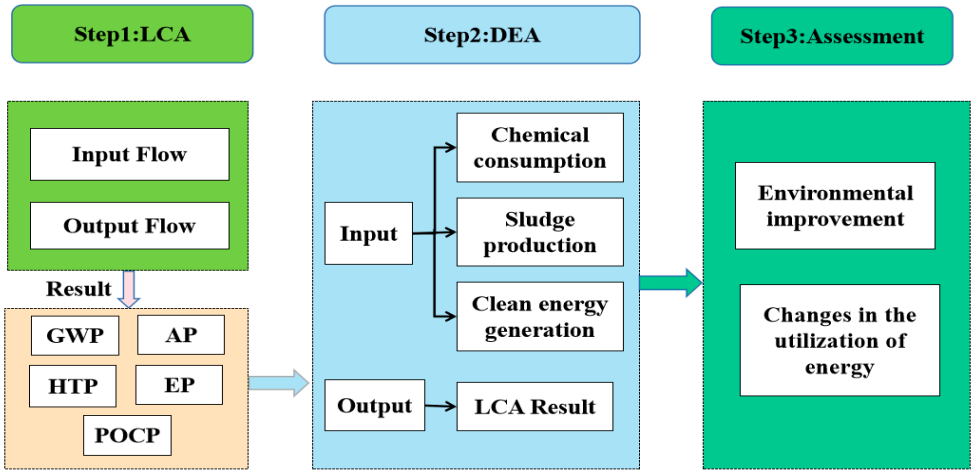

Figure 3. LCA+DEA method framework.

3. Results

3.1. LCA Characterized Results for the WWTP

The environmental impacts of the selected WWTP were divided into three main aspects: wastewater treatment process, electricity consumption, and chemical consumption. The LCA characterization results for the base scenario are shown in Table 2. The results indicate that electricity was a major contributor to almost all of the environmental impacts, except EP. The EP was closely related to the pollutant contents (e.g., organic matter, nitrogen, and phosphorus) discharged into the receiving water body, and the removal of pollutants from the wastewater had the largest impact on EP, accounting for 96.56% of the whole LCA. In contrast, the contributions of electricity and chemical consumption to EP only accounted for 1.16% and 1.82% of the total, respectively. The daily amount of pollutants discharged directly to the receiving water body from the treated effluent was 29.04 kg, of which the main substances were COD (18.9 kg), followed by total nitrogen (TN; 5.39 kg) and biochemical oxygen demand (BOD; 3.75 kg).

Table 2. Characterization results of the WWTP (functional unit: 1000 m^3).

	Total Value	Wastewater Treatment Process	Electricity Consumption	Chemical Consumption
GWP (kg CO_2 eq.)	324.51	108	153	63.51
EP (kg Phosphate eq.)	4.3098	4.16	0.0499	0.0999
AP (kg SO_2 eq.)	1.43	0.24	0.64	0.55
HTP (kg DCB * eq.)	64.65	0.58	52.74	11.33
POCP (kg Ethene eq.)	0.1479	0.0365	0.0625	0.0489

* Remark: DCB = Dichlorobenzene.

The GWP of the WWTP was affected by three processes: wastewater treatment, electricity consumption, and chemical consumption. The GWP of the wastewater treatment process was affected by the degradation activity of microorganisms in the biochemical tanks and endogenous respiration. Direct GHG emissions of CH_4 and N_2O were from aerobic and anaerobic biological treatment processes, and direct GHG emissions contributed 108 kg CO_2 eq to the GWP during wastewater treatment operations, which was 33.28% of the total. Electricity consumption contributed 153 kg CO_2 eq to the GWP, which was 47.15% of the total. Chemical consumption contributed 63.51 kg CO_2 eq to the GWP, accounting for approximately 19.57% of the total.

The total contribution of this WWTP to the AP was 1.43 kg SO_2 eq, of which electricity consumption contributed the most (0.64 kg SO_2 eq; 44.76%). The CAST process requires repeated aeration; the use of electricity in this process increases the contribution to the AP. Second, the sulfide-containing exhaust gas from chemical dosing contributes 0.55 kg SO_2 eq to the AP, accounting for 38.46% of the total. The CAST process aeration basin and other facilities produce sulfide-containing exhaust gases, which may be converted to SO_2 and other gases after metabolism in the air to contribute to the AP. However, the contribution to AP made by this operation is only 16.78%.

The total value of HTP in this WWTP was 64.65 kg DCB eq, of which electricity was the largest contributor (52.74 kg DCB eq; 81.58%). The contribution made by electricity consumption primarily originated from the generation of gaseous benzene and chlorine gas during the fossil energy generation process; the gaseous benzene produced via fossil energy generation was 132.89 kg. Moreover, HTP was also closely related to the use of pharmaceuticals in wastewater treatment, and the contribution of chemicals to HTP was valued at 11.33 kg DCB eq, accounting for 17.53%.

POCP is an irritating smoke produced by the photochemical reaction of nitrogen oxides (NOx) and hydrocarbons (HCs) discharged into the atmosphere by the action of the sun's ultraviolet rays. POCP is mainly related to electricity consumption and hydrocarbons, etc., which are produced during electricity production. The total POCP value in this WWTP was 0.1479 kg Ethene eq: electricity consumption contributed the most (0.0625 kg Ethene eq, accounting for 42%), followed by fossil energy contributing 0.0573 kg Ethene eq. Pharmaceuticals contributed 0.0489 kg Ethene eq (accounting for 33% of the total POCP).

3.2. LCA Analysis of the Five Power Schemes

The proportions of fossil fuel energy generation were 56%, 40%, 23%, 10%, and 0% in scenarios 1, 2, 3, 4, and 5, respectively. In scenarios 1–5, all of the life-cycle environmental impact potentials decreased as the fossil fuel energy generation proportion decreased (Table 3). In particular, as clean energy generation increased, the impacts of gas production and electricity on the GWP and POCP were significant, biomass power had significant impacts on the AP and EP, and wind and PV had significant impacts on the HTP. The individual LCA environmental impact values and specific contributions for scenarios 1–5 are shown in Figures 4–8.

Table 3. Characterization results of different power structures under five scenarios.

Environmental Impact	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
GWP (kg CO_2 eq.)	153	113	73.00	45.40	25.60
EP (kg Phosphate eq.)	0.0499	0.0384	0.0284	0.0222	0.0161
AP (kg SO_2 eq.)	0.64	0.46	0.30	0.18	0.08
HTP (kg DCB eq.)	52.74	38.3	23.1	12.2	3.51
POCP (kg Ethene eq.)	0.0625	0.0457	0.0259	0.0137	0.00439

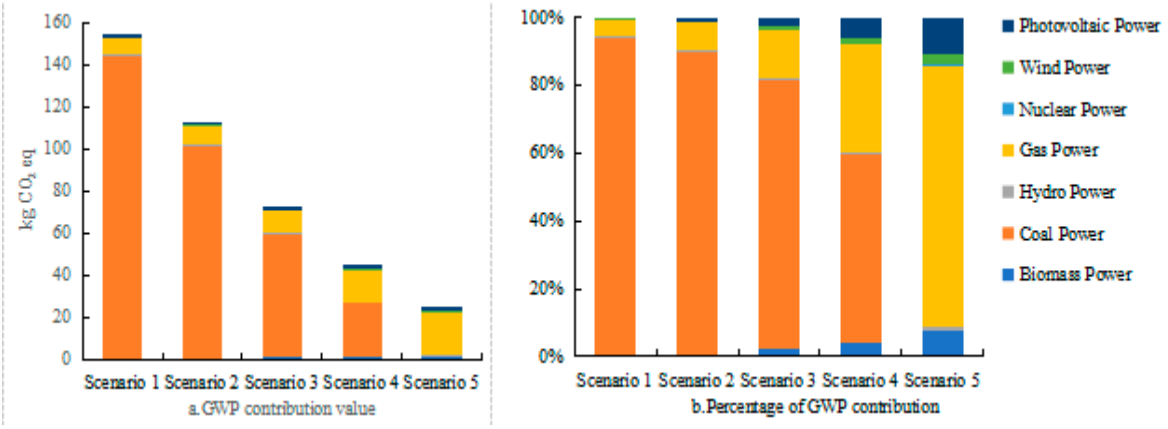

Figure 4. Contribution analysis of five scenarios to environmental impacts under the GWP: (**a**) the specific GWP values of different energy sources and (**b**) the GWP contributions of different energy sources.

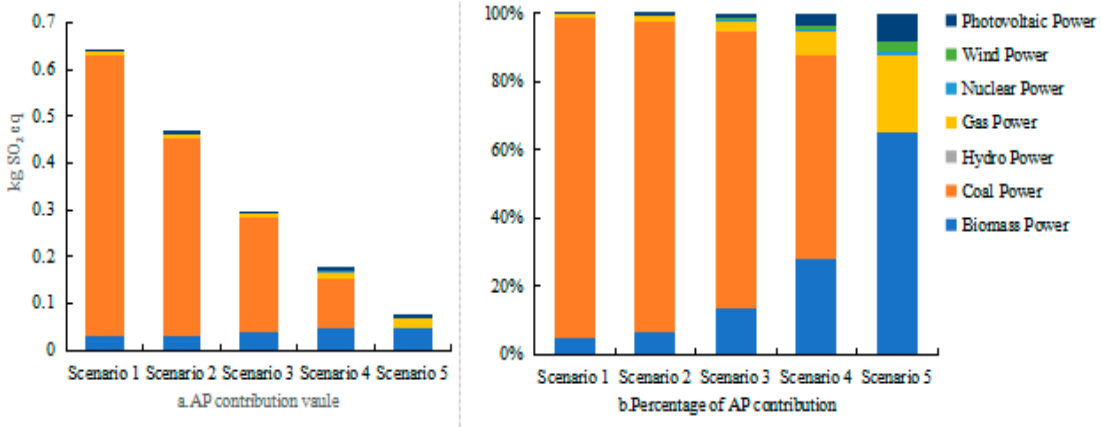

Figure 5. Contribution analysis of five scenarios to environmental impacts under the AP: (**a**) the specific AP values of different energy sources and (**b**) the AP contributions of different energy sources.

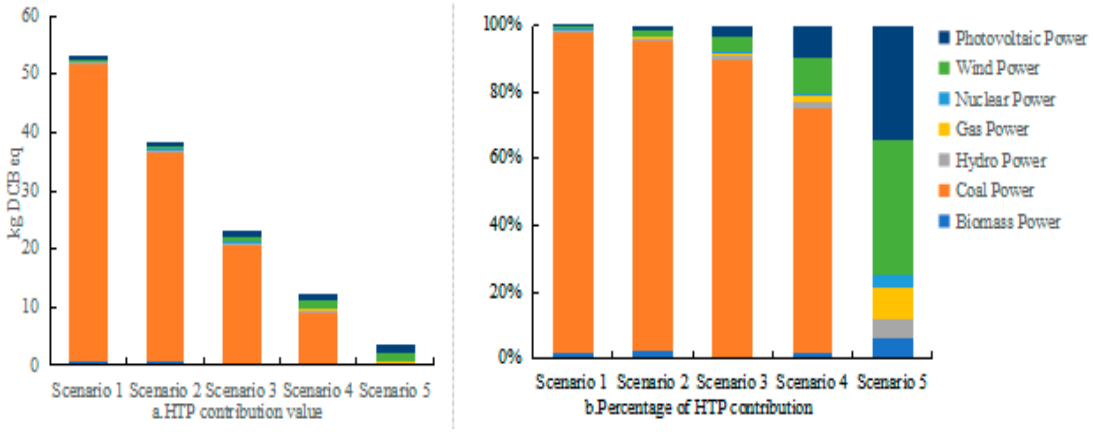

Figure 6. Contribution analysis of five scenarios to environmental impacts under the HTP: (**a**) the specific HTP values of different energy sources and (**b**) the HTP contributions of different energy sources.

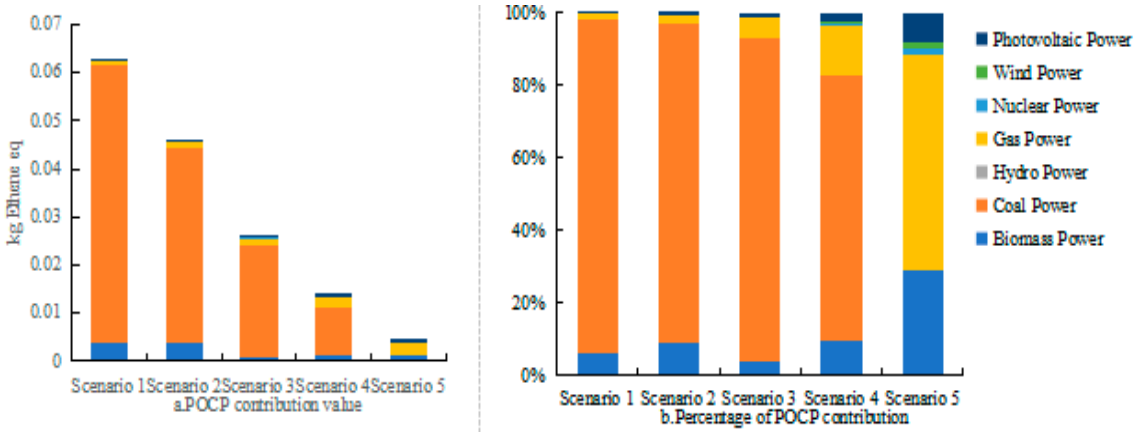

Figure 7. Contribution analysis of five scenarios to environmental impacts under the POCP: (**a**) the specific POCP values of different energy sources and (**b**) the POCP contributions of different energy sources.

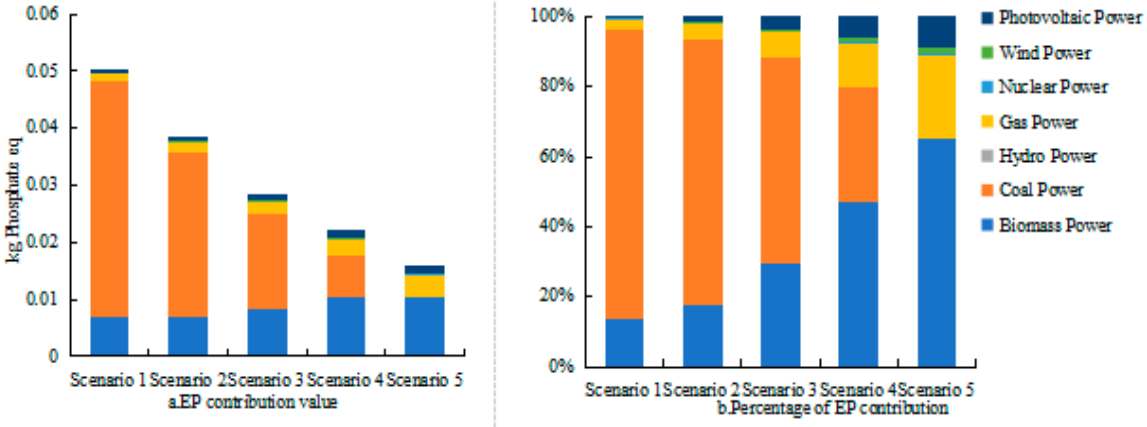

Figure 8. Contribution analysis of five scenarios to environmental impacts under the EP: (**a**) the specific EP values of different energy sources and (**b**) the EP contributions of different energy sources.

As shown in Figure 4a, scenarios 1–5 showed a decreasing trend in the contribution of electricity consumption to GWP as fossil energy generation decreased. Compared with Scenario 1, the GWP in scenarios 2–5 decreased by 26.14%, 52.29%, 70.33, and 83.27%, respectively, with fossil energy power generation contributing 143.89 kg CO_2 eq, 100.99

kg CO_2 eq, 50.07 kg CO_2 eq, and 25.25 kg CO_2 eq, respectively, to GWP in scenarios 1–4 (Figure 4a). Meanwhile, as shown in Figure 4b, the contribution of gas power to GWP gradually increased with the increase in clean energy generation. In scenarios 1–5 the contributions of gas-electricity to the GWP were 5.14%, 8.17%, 14.40%, 31.86%, and 77.11%. When only an idealized electricity mix of clean energy generation was included in scenario 5 (wind: 28%; hydropower: 18%; PV: 24%; gas power: 15%; biomass: 5%; and nuclear: 10%), although the share of gas power in the electricity generation was only 15%, the contribution of gas power to the GWP accounted for 77.11% of the total contribution to the electricity consumption. As such, it became the main contributor to the GWP (Figure 4b). This is because, compared with other clean energy sources, gas power is mainly biogas and natural gas power generation; gas power emits six types of pollutants, namely SO_2, CO_2, CO, NOx, H_4, and volatile organic compounds (VOCs), in the process of generating electricity [33]. Hence, the contribution of gas power to the GWP is larger when the gas power usage increases. Meanwhile, the other clean energy generation sources contribute minimally to GWP in scenarios 1–5 (range: 0.97–22.89%; average: 8.91%).

As can be seen from Figure 5a, the contribution of electricity consumption to AP showed the same decreasing trend as GWP. Compared with scenario 1, AP decreased by 23.33%, 53.13%, 71.88%, and 87.5% in scenarios 2–5, respectively, where the contributions of fossil energy generation to AP were 0.60 kg SO_2 eq, 0.42 kg SO_2 eq, 0.24 kg SO_2 eq, and 0.11 kg SO_2 eq in scenarios 1–4, respectively, and zero in scenario 5. Different types of energy generation contributed to AP in different proportions, with the contribution of biomass generation to AP varying significantly (Figure 5b). The contribution of biomass power generation to AP gradually increased in scenarios 1–5, with shares of 4.69%, 6.46%, 13.42%, 28.28%, and 65.22%, respectively. In scenario 5, biomass power generation became a major contributor to AP even though its share was only 5% (Figure 5b). The biomass power generation process generates flue gas due to the combustion of biomass, which includes gases such as CO, CO_2, NOx, VOCs, and water vapor [34]. In addition, the ash residue in biomass power plants contains a large amount of sulfide [35] and VOCs [4], increasing the contribution of biomass power generation to AP.

The reduction of HTP was greater than GWP or AP (Figure 6a) and gradually decreased in scenarios 2, 3, 4, and 5 compared to scenario 1, by 27.59%, 56.20%, 76.87%, and 93.34%, respectively, with fossil power generation in scenarios 1–4 contributing 50.85 kg DCB eq, 35.69 kg DCB eq, 20.52 kg DCB eq, and 8.92 kg DCB eq to HTP. The contributions of fossil energy to HTP in scenarios 1–4 were 50.85 kg DCB eq, 35.69 kg DCB eq, 20.52 kg DCB eq, and 8.92 kg DCB eq. While that of fossil energy decreased, the contribution of wind energy and hydroelectricity to HTP gradually increased (Figure 6b), and the contributions of wind energy and PV to HTP in scenario 5 were 40.28% and 35.47%, respectively, making them the main contributors to HTP.

POCP also exhibited a decreasing trend (Figure 7a), with scenarios 2–5 decreasing by 26.88%, 58.56%, 78.3%, and 92.98%, respectively, compared to scenario 1. The contributions of fossil energy generation to POCP in scenarios 1–4 were 0.057 kg Ethene eq, 0.040 kg Ethene eq, 0.023 kg Ethene eq, and 0.010 kg Ethene eq, respectively. While clean energy generation gradually increased, gas and biomass power generation gradually became the main contributors to POCP (Figure 7b); the contributions of gas and biomass power generation to POCP were 59.44% and 29.32%, respectively, in scenario 5. POCP is primarily affected by HCs, NOx, and VOCs from industry, and CO_2, CO, NOx, and VOCs generated in the process of gas and biomass power generation [33,34]; all lead to an increased contribution to the POCP.

EP exhibited the smallest change among all environmental impact categories (Figure 8a), decreasing by 28.13%, 53.13%, 71.8%, and 87.5% in scenarios 2–5 compared to scenario 1, respectively. Meanwhile, the contribution of biomass power generation to EP gradually increased in scenarios 1–5 (Figure 8b), to 0.007 kg Phosphate eq, 0.007 kg Phosphate eq, 0.008 kg Phosphate eq, 0.011 kg Phosphate eq, and 0.012 kg Phosphate eq, respectively. Up to scenario 5, biomass was the largest contributor to EP, accounting for ~68.75% of the

total, even though it generated only 5% of the electricity. This is due to the high amount of sulfide in the ash residue of biomass power plants [35] and the production of VOCs during the biomass power generation process [9], causing the contribution of biomass power generation to AP to gradually increase.

3.3. Normalization Results

Figure 9 shows the normalized values of the environmental impacts of the effluent for scenarios 1–5, which were 3.77 × 10, 3.21 × 10, 2.65 × 10, 2.25 × 10, and 1.93 × 10. These results indicate that, as the proportion of clean energy generation increases, EP will be the largest environmental impact category during the next 40 years, with a potential proportion of 47.58%. HTP (27.36%) and GWP (15.18%) were also important environmental impact categories. However, AP and POCP remained nearly unchanged. The total environmental impact potential decreased from 3.77 × 10 in scenario 1 to 1.93 × 10 in scenario 5.

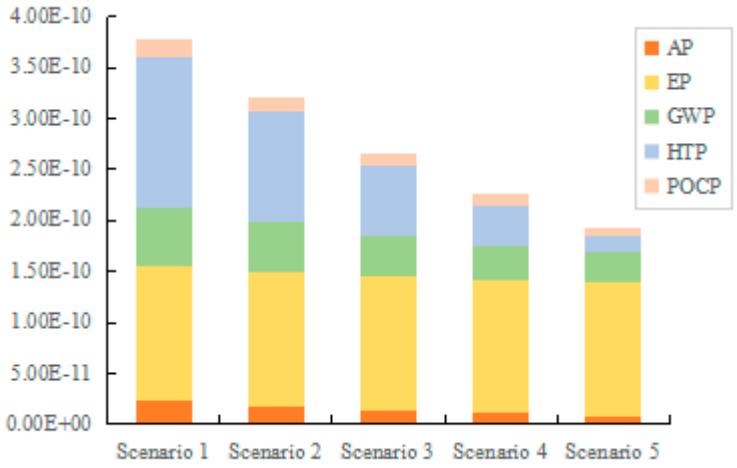

Figure 9. Normalization results for different energy-mix scenarios from scenarios 1 to 5.

3.4. Sensitivity Analysis

Wastewater treatment systems are affected by various disturbances during operation, introducing considerable uncertainty in the input variables and parameters of the model as well as in the output results [36]. Therefore, this paper analyzed the uncertainty of the WWTP under different scenarios, with the change factor being the generation of electricity from seven energy sources (Table 4). Fossil energy generation had the largest change in environmental impact (10% increase and decrease in input and output); however, the overall range of change was <10% and did not alter the order of the LCA results. Nevertheless, the credibility of fossil energy generation data must be fully considered in the actual power structure to improve the feasibility of the LCA results.

Table 4. Sensitivity analysis results for each environmental impact category under five power generation scenarios.

	SE	Coal Power	Photovoltaic Power	Wind Power	Hydro Power	Nuclear Power	Biomass Power	Gas Power
GWP	NSE	−8.76%	−0.03%	−0.02%	−0.02%	−0.00%	−0.70%	−0.48%
	PSE	8.76%	0.03%	0.02%	0.02%	0.00%	0.70%	0.48%
AP	NSE	−9.39%	−0.02%	−0.01%	−0.00%	−0.00%	−0.47%	−0.11%
	PSE	9.39%	0.02%	0.01%	0.00%	0.00%	0.47%	0.11%
EP	NSE	−8.25%	−0.05%	−0.01%	−0.00%	−0.00%	−1.37%	−0.30%
	PSE	8.25%	0.05%	0.01%	0.00%	0.00%	1.37%	0.30%
HTP	NSE	−9.64%	−0.04%	−0.08%	−0.04%	−0.01%	−0.17%	−0.02%
	PSE	9.64%	0.04%	0.08%	0.04%	0.01%	0.17%	0.02%
POCP	NSE	−9.17%	−0.01%	−0.00%	−0.00%	−0.00%	−0.64%	−0.17%
	PSE	9.17%	0.01%	0.00%	0.00%	0.00%	0.64%	0.17%

3.5. DEA Analysis

The energy efficiency scores of wastewater treatment plants under different scenarios were calculated using the DEA model as shown in Table 5. From the table, it can be seen that only scenario 1 was fully efficient, and the comprehensive efficiency was 1. Scenarios 2, 3, 4, and 5 had gradually decreasing values of comprehensive technical efficiency, of 0.7386, 0.4771, 0.2967, and 0.1673, respectively. Pure technical efficiency was the energy efficiency of WWTPs due to factors such as management and technology, and scale efficiency was the energy efficiency due to the factor of the size of the WWTPs. In this study, the results summarized that the combined technical efficiency is consistent with the changes in pure technical efficiency and scale efficiency, and the combined technical efficiency is mainly attributed to the combined results of scale efficiency and efficiency of scale under five scenarios with different clean energy generation shares. The wastewater treatment plant selected for this study is a small wastewater treatment plant (<20,000 population equivalent); the size and capacity of this wastewater treatment plant did not change under the five scenarios, while the results showed a gradual decrease in SE under an increase in the amount of electricity generated from cleanable energy sources. However, sludge production, pharmaceutical consumption, and environmental impact sewage treatment are related to the process, and PTE is affected by a combination of wastewater treatment plant management and technology. From the above, it can be seen that small wastewater treatment plants, to achieve the best energy efficiency, also need to be upgraded and improved in terms of the size of the wastewater treatment plant and the level of technology.

Table 5. DEA results for five scenarios.

DMU	Technical Efficiency	Pure Technical Efficiency	Scale Efficiency
Scenario 1	1.0000	1.0000	1.0000
Scenario 2	0.7386	0.9984	0.9984
Scenario 3	0.4771	0.9954	0.9983
Scenario 4	0.2967	0.9936	0.9967
Scenario 5	0.1673	0.9921	0.9952

Scenarios 1–5 represented DEA energy efficiency analysis under the idealized power structure. The associated result values were high; however, the utilization of clean energy exhibits regional uncertainty. For example, northwest China is more suitable for wind power generation; however, its power generation is impacted by wind speed, and PV power generation is affected by the duration and intensity of radiation. The energy utilization efficiency of using clean energy instead of fossil energy to generate electricity is directly affected by the level of technology. Scenario 5 uses 100% clean energy to generate electricity; however, despite offering the biggest improvement in negative environmental impacts, its energy utilization efficiency was weakly effective; thus, in order to simultaneously achieve the environmental impacts and the comprehensive improvement of energy utilization efficiency, the proportion of clean energy used to generate electricity in scenario 2 was optimal when the proportion of clean energy used to generate electricity was 60%; at this time, the GWP, EP, AP, HTP, and POCP decreased by 26.14%, 23.05%, 28.13%, 27.38%, and 26.88%, respectively. At the same time, from the DEA results, it can be seen that clean energy power generation should not only be improved via changing the size of the sewage treatment plant and process type, but also should be considered comprehensively in terms of the level of technology and the cost of scale.

4. Discussion

Chai et al. [28] demonstrated that electricity consumption is the main cause of GWP in WWTPs and that the GWP in the electricity consumption process primarily arises from greenhouse gas emissions during electricity production and equipment operation. The results of the current study also show that electricity consumption is the main cause of GWP.

However, in our WWTPs, electricity is provided by the national or local grid, making it difficult to manage energy-related environmental impacts. In recent years, many researchers have focused on the energy transition of the electricity mix to explore improvements in the environmental impacts of WWTPs using clean energy instead of fossil energy for power generation. Gözde et al. [37] discussed the impacts of utilizing renewable energy for power generation (such as biogas and PV) in WWTPs from an environmental and economic point of view. They found that when renewable energy power generation reached 23% of the total electricity consumption, the CO_2 emitted by the WWTP was reduced by 15%. The different power-mix scenarios presented in the current study also demonstrate that clean energy generation reduces GWP by replacing fossil energy generation; the results for scenarios 1–5 showed that the reduction in GWP value increases with higher clean energy generation. However, although the GWP value decreased, biogas gradually became the main contributor, and in scenario 5, when the share of biogas power generation was 15%, its contribution to GWP was 19.71 kg CO_2 eq, accounting for 77.11% of the total GWP (25.57 kg CO_2 eq). Unlike Gözde [37], the GWP reduction values in scenarios 1–5 of this study were larger, because the share of clean energy in scenario 1 (43%) was higher than that in the study by Gözde [37]; even scenario 5 assumed 100% clean energy generation. Moreover, the process of generating electricity from clean energy sources had a certain degree of negative environmental impact; however, this impact is much smaller than that imposed by generating electricity from fossil energy sources.

GWP, AP, HTP, POCP, and EP in scenarios 2–5 gradually decreased as clean energy generation increased. The United Nations Environment Program [22] and Permpool et al. [38] similarly pointed out that the generation of electricity from clean energy sources, such as wind, PV, and hydroelectricity, can reduce the negative environmental impacts caused by electricity use. However, the results of this study found that clean energy generation can also cause negative impacts on the environment. In scenario 5, where only clean power generation was available, gas power contributed the most to GWP and POCP, reaching 77.11% and 65%, respectively, when gas power generation reached 15%.

The study by Li et al. [34] found that VOCs produced during biomass power generation due to biomass combustion contribute to POCP. Similarly, the contribution of biomass power generation to POCP gradually increased in the results of this study. In scenario 5, when biomass power generation was only 5%, its contribution to POCP reached 29.23%. In addition, Cai et al. [35] and Kong et al. [4] reported that ash residue from biomass power plants, containing high levels of sulfides and VOCs, can contribute indirectly to AP. The same conclusion was drawn in the current study based on the quantitative LCA results for scenarios 2–5. With an increase in biomass power generation, it gradually became the main contributor to AP, reaching 65.22% in scenario 5. The uncertainty analysis in this study also highlighted biomass power generation as the main contributor to the final environmental impact after fossil energy power generation. Hence, the environmental impacts caused by biomass power generation must be closely considered.

In this study, the energy utilization efficiency of a WWTP in the Tumen River Basin under different scenarios was obtained by constructing an energy utilization evaluation model (LCA+DEA) and drawing on the research methodology proposed by Lorenzo-Toja et al. [19]. The environmental characterization values obtained in LCA were used as the output indicators in the DEA model, and clean energy generation, chemical consumption, and sludge production were used as the input indicators. However, the energy efficiency values were high, as the environmental characterization values of LCA were obtained under an idealized power structure. Nevertheless, the DEA results illustrate that the construction method proposed in this study is feasible even though the data are too idealized; thus, the actual situation of each energy generation in the power structure must be considered in the application of WWTPs to obtain more accurate energy-efficiency values. Therefore, further analyses of the environment and energy of WWTPs in the Tumen River Basin should include the actual power structure.

5. Conclusions

In this study, a case study of low-carbon energy transitions in the power structure of a wastewater treatment plant in the Tumen River Basin, Jilin Province was conducted, using the LCA+DEA model to demonstrate that the use of clean energy instead of fossil energy for power generation in the Tumen River Basin has improved environmental impacts, and to provide a new solution to address the negative environmental impacts of electricity use in water plants in the Tumen River Basin (as well as demonstrating the feasibility of this solution). First, the environmental impacts of the operational phase of the WWTP under the current power structure (Scenario 1) were evaluated based on the LCA method, and it was concluded that electricity is the main contributor to almost all environmental impacts except EP. The characterization results are shown in Table 2 for three aspects: wastewater treatment process, electricity consumption, and pharmaceuticals consumption. Secondly, five scenarios with different power structures were constructed and LCA was performed for the five different power structure scenarios; the following results were obtained: from scenario 1 to scenario 5, the global warming potential (GWP) of this wastewater treatment plant was reduced by 83.27%, the acidification potential (AP) was reduced by 87.50%, the eutrophication potential (EP) was reduced by 67.74%, the human toxicity potential (HTP) was reduced by 93.34%, and the photochemical smog production potential (POCP) was reduced by 92.96%. Finally, the energy efficiency scores of the WWTP under different scenarios were calculated based on the LCA+DEA energy efficiency model to explore the energy utilization efficiency resulting from the proportion of clean energy replacing fossil energy generation. The results showed the integrated technical efficiency of scenarios 1–5; it was shown that only scenario 1 is fully effective, with an integrated efficiency of 1, and the integrated technical efficiency values of scenarios 2, 3, 4, and 5 gradually decreased, with values of 0.7386, 0.4771, 0.2967, and 0.1673, respectively. Although the improvement of the negative environmental impacts was greatest in scenario 5 when achieving 100% clean energy power generation, the energy utilization efficiency was weakly effective, so in order to simultaneously achieve the combined improvement of environmental impacts and energy utilization benefits, the clean energy power generation ratio of 60% in scenario 2 was most effective; thus, in order to achieve the combined improvement of environmental impacts and energy utilization efficiency at the same time, scenario 2 was best when the share of clean energy generation was 60%. The reduction of comprehensive efficiency was mainly attributed to the combined effect of pure technical efficiency and scale efficiency, but the pure technical efficiency had a greater impact on the comprehensive efficiency, so the actual use of the clean energy generation process should take into account that the use of clean energy is characterized by regional uncertainty; this should be combined with the sewage treatment plant's geographical area, scale, and other actual conditions, to improve the efficiency of energy use.

The five power structure scenarios in this study were the most idealized power structure calculated based on the Verhulst model, which deviates to some extent from the future power structure of the Tumen River Basin. If the treatment scale, electricity consumption, and pharmaceutical consumption, as well as the COD, ammonia nitrogen, and total phosphorus abatement of the wastewater treatment plant for different scenario time periods are modeled in future studies, it will improve the results of the subsequent DEA with a more reasonable energy-efficiency analysis. In addition, the evaluation of wastewater treatment plants using the LCA+DEA model could provide a comprehensive assessment of their environmental impacts and ecological and energy efficiencies; based on the results, reasonable recommendations for the ecological benefits of wastewater treatment plants can be made. Further research could use the LCA+DEA model to comprehensively evaluate the green-power generation structure of sewage out-treatment plants in the Tumen River Basin in terms of technological, ecological, and economic costs, and to rationally develop and utilize clean energy by combining the topography of the Tumen River Basin with its energy advantages, so as to provide a concrete plan for the sustainable development of sewage treatment plants in the Tumen River Basin.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16041690/s1, Detailed data_WWTP; GHG-Emission factor method; Background data—hard coal; Background data—natural gas; Background data—hydro power; Background data—wind power; Background data—nuclear power; Background data—biomass power; Background data—solar thermal.

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