sustainability

Article

Sustainable Energy Management Benchmark at Wastewater Treatment Plant

Andrey Kiselev [1,*], Elena Magaril [1], Deborah Panepinto [2], Elena Cristina Rada [3], Marco Ravina [2] and Maria Chiara Zanetti [2]

[1] Department of Environmental Economics, Ural Federal University, Mira str., 19, 620002 Ekaterinburg, Russia; magaril67@mail.ru
[2] Department of Environment, Land and Infrastructure Engineering, Politecnico di Torino, Corso Duca degli Abruzzi, 24, 10129 Torino, Italy; Deborah.panepinto@polito.it (D.P.); marco.ravina@polito.it (M.R.); mariachiara.zanetti@polito.it (M.C.Z.)
[3] Department of Theoretical and Applied Science, University of Insubria, Via G.B. Vico, 46, 21100 Varese, Italy; elena.rada@uninsubria.it
* Correspondence: avkise1ev@yandex.ru; Tel.: +7-908-914-0208

Citation: Kiselev, A.; Magaril, E.; Panepinto, D.; Rada, E.C.; Ravina, M.; Zanetti, M.C. Sustainable Energy Management Benchmark at Wastewater Treatment Plant. *Sustainability* **2021**, *132*, 12885. https://doi.org/10.3390/su132212885

Academic Editor: Shahryar Jafarinejad

Received: 28 October 2021
Accepted: 19 November 2021
Published: 21 November 2021

Abstract: Urban wastewater effluents bring large amounts of nutrients, organic matter, and organic microcontaminants into freshwater ecosystems. Ensuring the quality of wastewater treatment (WWT) is one of the main challenges facing the management of wastewater treatment plants (WWTPs). However, achievement of high-quality standards leads towards significant energy consumption: usually the more intensive WWT process requires additional energies. Energy efficiency at WWTP is actual mainstream on the current sustainable development agenda. The WWTP processes and methods can be considered from the standpoint of material and energy flows according to circular economy paradigm, which offers great possibilities to reuse waste originating from WWT in order to receive renewable energy. The correlation between energy and quality issues to evaluate WWTP efficiency is of a great scientific and practical interest. The main goal of the paper is to check the dependency between these two main issues in WWTP management—WWT quality and energy efficiency—and to determine possible limits of such relation. The municipal sewerage system of Ekaterinburg, Russia was studied within this paper. The total length of centralized sewerage system in Ekaterinburg is over 1500 km of pipes within two main sewerage basins: northern and southern. The methodological framework for the current research consisted of three steps: (i) WWT quality evaluation, (ii) energy efficiency evaluation, and (iii) WWTP Quality/Energy (Q/E) efficiency dependency matrix. For the purpose of research, authors investigated the 2015–2018 period. The results showed that the outputs correlate with the technical conditions of WWTPs and the implementation of the best available techniques (BATs): most of the northern WWTP values are referred to the green zone (good rank), while the southern WWTP values are situated generally in the orange zone (unsatisfactory rank). The proposed methodological approach for Q/E dependency of WWT process creates a strong but simple tool for managers to evaluate the current success of the operation of WWTP and progress towards circular economy practices implementation.

Keywords: wastewater; sustainable management; circular economy; benchmark; energy

1. Introduction

Humans and their activities produce wastewaters that are generally referred to as 'urban wastewaters', which are generally a mix of metabolic residues from humans and drainage waters [1]. WWTPs act as terminal shields for urban cities to protect the water environment from contamination and achieve water resource circulation [2]. Urban wastewater effluents bring large amounts of nutrients, organic matter, and organic microcontaminants into freshwater ecosystems [3]. Ensuring the quality of WWT is one of the main challenges facing the management of WWTPs. The high standard in WWT is achieved through the implementation of the best available techniques (BAT).

WWT is an energy intensive process. The specific electric energy consumption in different countries generally ranges from 0.4 to 0.9 kWh per cubic meter of treated wastewater [4–6], depending on the inflow quality, WWTP’s scale, climate, and distribution. The smaller WWTPs are characterized by a high energy consumption compared to relatively larger-scale WWTPs. Even though small-scale WWTPs have simplified configuration and wastewater and sludge handling processes, the unit energy consumption is greater than larger WWTPs due to less frequent optimizations and hurdles associated with simplified management [6]. Energy efficiency at WWTP is an urgent issue in the current sustainable development agenda. According to the circular economy (CE) paradigm, the WWTP can now have a positive energy balance through the application of energy recovery techniques. Sewage sludge (SS) as main byproduct of WWTPs could be used as an energy resource for producing electricity and heat through conventional technologies [7,8]. Anaerobic digestion (AD) is the popular treatment process within WWTPs due to its proven efficiency to further reduce pollutant levels, yield a fairly stabilized sludge, substantially reduce sludge tonnage needing disposal, use of minimum input energy, and generate biogas [9].

The achievement of WWT quality through the introduction of modern technologies and the increase in the number of technological stages usually leads towards an increase in overall energy consumption. Modernization process at WWTP can be fulfilled via several alternative technological solutions—every solution has its own WWT quality and energy efficiency indicators, as well as investment and operational costs. In order to make a decision about which technologies should be introduced, it is necessary to consider them both in terms of the WWT quality and energy efficiency. Moreover, today there is a need for managers to conduct an express assessment of the current progress in the development of specific WWTP and compare results with typical objects. Eventually, WWTPs can become engines for the circular economy, playing an important role in the water cycle that allows water sanitation and reuse, facilitating energy production and allowing the recovery of various products from wastes [10].

Most investigations on WWT and WWTP are focused on either quality or energy efficiency issues. However, some manuscripts devoted to single quality/energy framework were still found. These papers use the following methodological approaches: Life Cycle Assessment (LCA), Benchmark Simulation Model (BSM and BSM2) and other WWTP models, Performance Assessment System (PAS), and Data Envelopment Analysis (DEA).

The LCA methodology is described in ISO 14040:2006 standard and addresses the environmental aspects and potential environmental impacts of WWTP products and processes [11]. In particular, this methodology considers, among other issues, the relationship between WWT quality and energy issues, but generally it is focused on evaluation of potential environmental impact [12]. Rebello et al. [13] conducted a literature review of 111 studies on LCA of WWTP and proposed a guideline framework suitable for urban WWT utilities. Lopes et al. [14] presented and discussed environmental performance of full-scale WWTP using LCA approach, including construction and operation phases. Lorenzo-Toja et al. [15] examined two WWTPs, located in different climatic regions (Atlantic and Mediterranean) of Spain, using LCA approach. Chen et al. [16] used a novel technique, multi-agent deep reinforcement learning (MADRL), based on LCA methodology, to examine and optimize dissolved oxygen and chemical dosage at WWTP. All these manuscripts include both quality and energy issues but have some limitations. LCA is a strong tool—it can be applied for the great variety of cases depending on the project’s scope. This is a great challenge because you can analyze any issue; however, it imposes high requirements on the quality of such analysis, requires skilled personnel and special software, it is rather complex to understand for common users, it is difficult to scale, and finally we have no opportunity to check direct relation between WWT quality and WWTP’s energy efficiency.

Benchmark Simulation Model (BSM) is a simulation environment defining a plant layout, a simulation model, influent loads, test procedures, and evaluation criteria. For each of these items, compromises were pursued to combine plainness with realism and accepted standards. Once the user has validated the simulation code, any control strategy can be applied and the performance can be evaluated according to a defined set of criteria [17]. Revollar et al. [18] proposed the plant-wide control strategy using BSM2 in order to improve eco-efficiency of WWTP. In particular, performance indicators that measure potential energy recovery from biogas, electricity consumption, CO_2, emissions, production of sludge for disposal, and effluent quality have been considered. The approach proposed by these authors is aimed towards choosing the most appropriate operating strategy for specific WWTP and analyzing a large set of indicators, including energy and quality. However, the direct relation between energy and WWT quality is absent. De Ketele et al. [19], as well as the team considered above, analyze WWTP operation strategies in terms of transition towards Waste Resource Recovery Facilities using BSM under performance indexes—effluent quality index (EQI) and operation cost index (OCI). There is also no direct connection between quality and energy issues within this paper.

Zaborowska et al. [20] proposed an authentic plant-wide model for evaluation of the energy balance and greenhouse gas footprint at large WWTPs. The model is used to predict future conditions using KPIs to measure effluent quality, energy, and GHG emissions in order to choose the best operational strategy and technological upgrades. The integrated model has a high forecast accuracy but it's difficult to scale as adaptation is required.

The manuscripts of Cassidy et al. [21] and Silva et al. [22] are devoted to PAS methodology. According to the case studies, WWTPs were examined by the following KPIs: energy performance (both manuscripts), effectiveness and reliability (both manuscripts), and sludge management (Cassidy et al.). The proposed tools have excellent intuitive interpretation for different stakeholders and can be used as a sectoral benchmark, but these KPIs have no relation to each other.

Longo et al. [23] presented an improved DEA methodology: Robust Energy Efficiency DEA (REED). In other words, REED is DEA designed for WWTP. The authors have analyzed 399 real WWTP using REED; therefore, we can conclude that it is a very scalable tool and can be used as a sectoral benchmark. However, REED is rather complex because it has several different conditions and indicators, and has no clear dependency between energy and quality.

The main goal of current investigation is to check the dependency between two main issues in WWTP management—WWT quality and energy efficiency—and to determine possible limits of such relation. The specific objectives of the paper are:

- to identify the main criteria affecting the efficiency of WWTP under CE paradigm;
- to propose a correlation framework for WWTP' efficiency evaluation under CE paradigm;
- to apply a correlation framework as a benchmark tool for sectoral competitive comparison of WWTPs.

2. Materials and Methods

2.1. Study Area

Authors have studied the municipal sewerage system of Ekaterinburg, Russia. Ekaterinburg is the largest industrial, scientific, and commercial center in Russia, which is situated on the border of Europe and Asia. With a population of almost 1.5 million inhabitants, it is the fourth largest city in Russia. The total length of centralized sewerage system is over 1500 km of pipes within two main sewerage basins: northern and southern. Each sewerage zone has its own wastewater treatment plant with corresponding titles.

About 85% of total wastewater from the city is transported to the southern WWTP. It was designed in early 1970th and put into operation in 1975. These utilities have traditional 2-stage treatment technology (mechanical and biological) with chlorine disinfection before discharge. Primary sludge and waste-activated sludge are fed to the mechanical dewatering workshop where the sludge mixture is dehydrated up to 75% humidity. The originated cake is transported at landfills. The maximum wastewater inflow performance is 550,000 m^3 per day. Since 1975, there have been no modernization or reconstruction activities and nowadays this WWTP is morally and technically obsolete. Modern energy recovery techniques are absent. Furthermore, several concrete settling and aeration tanks began to crumble due to aggressive impact of wastewaters (acid exposure, e.g., H_2SO_4).

The remaining amount of wastewater from the city goes to the northern WWTP. These utilities have the same age and technological process line as the former one but have passed through total modernization in 2002–2008 with introduction of the BAT, including rotary drum fine screens, sand traps with aeration, aeration tanks with nitrification and denitrification, UV-disinfection before discharge, and others. Sewage sludge treatment include anaerobic digestion with biogas generation at two methane tanks with maximum capacity 2 × 5000 m^3 and mechanical dewatering. The methane tanks are working under mesophilic digestion terms with average hydraulic retention time (HRT) of 27 days. Biogas is transported at CHP-unit for electric and thermal energy generation. Nowadays the WWT process conforms the basics of CE practices.

2.2. Methodology of Research

Methodological framework for current research consists of three steps: (i) WWT quality evaluation, (ii) energy efficiency evaluation, and (iii) WWTP Quality/Energy (Q/E) efficiency dependency matrix. For the purpose of research, authors have investigated the 2015–2018 annual reports on the quality of WWT and energy efficiency of the WWTPs, mentioned above.

2.2.1. WWT Quality Evaluation

Authors have selected the six most critical pollutants that have significant pollution effect while insufficiently treated wastewaters enter a water body. These pollutants were mentioned by Kiselev et al. [24], including (i) suspended solids; (ii) biochemical oxygen demand in 20 days (BOD20); (iii) phosphorus phosphate; (iv) nitrate-ion; (v) nitrite-ion; and (vi) ammonium-nitrogen.

As previously was proposed by Rukavishnikova et al. [25], authors used the annual multiplicity and frequency indicators for the samples that have been taken through the corporate laboratory control activities. The multiplicity of pollutant *i* is calculated as follows:

$$\mathrm{M}_i = \frac{\mathrm{C}_i^P}{\mathrm{MPC}_i^P}, \tag{1}$$

where C_i^P-annual average concentration of *i* substance (mg/dm^3) and MPC_i^P-maximum permissible concentration of *i* substance (mg/dm^3).

The frequency of pollutant *i* is calculated as follows:

$$\mathrm{F}_i = \frac{\mathrm{Q}_i^{ex}}{\mathrm{Q}_i}, \tag{2}$$

where Q_i^{ex} is the annual number of samples of *i* substance with excess MPC (pcs.) and Q_i is the annual number of all samples of *i* substance (pcs.).

Authors concluded that it would be quite compelling to offer expert evaluation weights (EW, see Table 1) for frequency/multiplicity assessment of each pollutant previously selected. As the basis, authors have used the classification of water in water bodies according to frequency and multiplicity of pollution mentioned in the guiding document

RD 52.24.643-2002, "Methodological guidelines. Method for comprehensive assessment of the degree of surface water pollution by hydrochemical indicators" [26].

Table 1. WWT quality expert EW.

Multiplicity Frequency	M ≤ 1	1 < M ≤ 2	2 < M ≤ 10	M > 10
0.0–0.1	1	1	0.6	0.25
0.1–0.3	1	0.9	0.5	0.2
0.3–0.5	0.95	0.8	0.4	0.1
0.5–1.0	0.9	0.7	0.25	0

Resulting evaluation weight (REW) for the 6 pollutants is calculated as follows:

$$\mathrm{REW} = \frac{\sum_{i=1}^{6} \mathrm{EW}_i}{6}, \tag{3}$$

2.2.2. WWT Energy Efficiency Evaluation

WWTP operational activities require significant energy consumption. Energy benchmarking at WWTP is a powerful management tool for continuous improvement [27]. According to Gurung et al. [6], one of the most popular indicators of energy efficiency is average energy consumption per unit of treated wastewater (AEC), which is calculated as follows:

$$\mathrm{AEC} = \frac{\mathrm{EC}}{\mathrm{Q}}, \tag{4}$$

where EC-energy, consumed from the grid (kWh/year), and Q-total volumetric flow of treated wastewater (m^3/year).

Application of relevant CE practices at WWTP implies the evaluation of Net Energy Consumption indicator. According to [28], the average net energy consumption per unit of treated wastewater (ANEC) is calculated as follows:

$$\mathrm{ANEC} = \frac{\mathrm{EC} - \mathrm{EG}}{\mathrm{Q}}, \tag{5}$$

where EG-energy, self-generated at WWTP (kWh/year).

2.2.3. Quality/Energy Dependency Matrix

The last step of methodology is to assess the relationship between WWT quality and energy costs. Authors suggested the Q/E dependency matrix, which contains boundary values both for energy and for quality. The quality and energy efficiency outputs, obtained via Equations (3)–(5), are plotted on the graph along the corresponding axes. The resulting value falls into a certain square zone. The matrix is presented in Figure 1.

Several color squares are used to evaluate the current position of WWTP. They measure the Q/E benchmarking ranking for the WWTPs under consideration as follows:

- Dark green: an excellent rank;
- Green: good rank;
- Yellow: average rank;
- Orange: unsatisfactory rank;
- Red: critical rank.

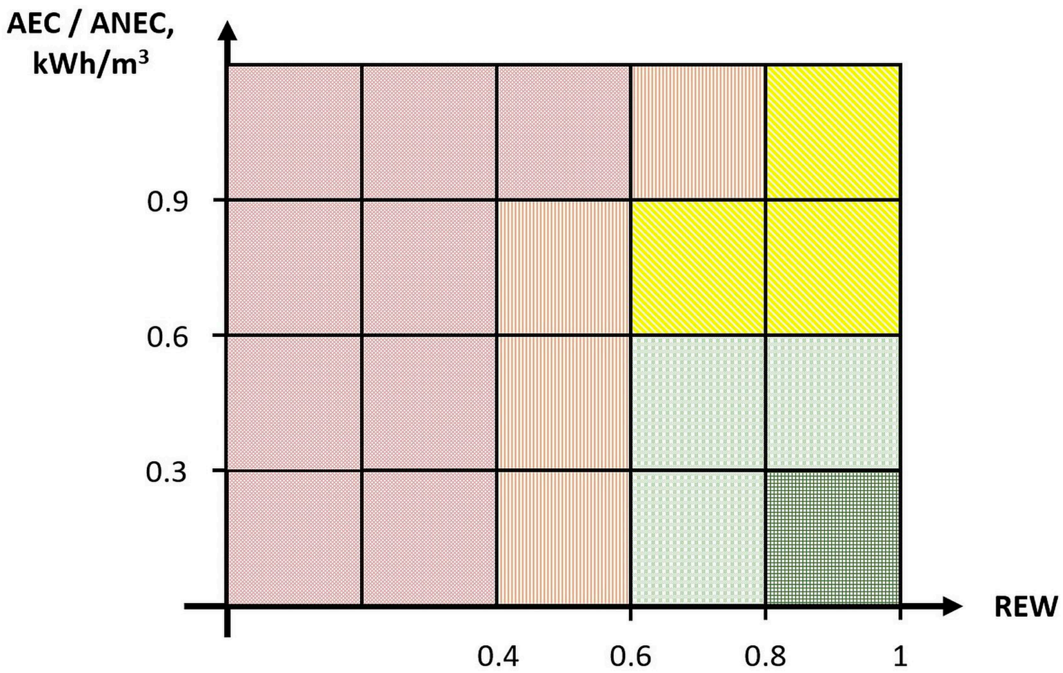

Figure 1. Q/E dependency matrix.

3. Results and Discussions

WWT samples were collected through laboratory control, analyzed for six main substances, and averaged into annual values. The data are reported in Table 2.

Table 2. Sample data for northern and southern WWTPs (2015–2018).

Substance	WWT	2015		2016		2017		2018	
		MPC_i^P	C_i^P	MPC_i^P	C_i^P	MPC_i^P	C_i^P	MPC_i^P	C_i^P
Suspended solids	Southern	15.00	23.50	15.00	24.30	15.00	34.30	15.00	71.40
	Northern	15.00	4.02	15.00	3.45	7.74	1.99	7.74	3.83
BOD(20)	Southern	11.19	13.50	11.19	15.20	11.19	28.00	3.00	23.00
	Northern	6.00	7.72	6.00	6.13	6.00	6.66	3.00	5.13
Phosphorus phosphate	Southern	0.20	2.27	0.20	2.36	0.20	2.62	0.20	2.6
	Northern	0.20	2.53	0.20	3.26	0.20	3.88	0.20	3.45
Nitrate-ion	Southern	40.00	30.40	40.00	27.80	40.00	40.90	40.00	32.20
	Northern	40.00	45.00	40.00	32.17	40.00	40.33	40.00	40.17
Nitrite-ion	Southern	0.20	0.30	0.20	0.53	0.20	0.33	0.08	0.33
	Northern	0.19	0.12	0.19	0.14	0.08	0.03	0.08	0.17
Ammonium-nitrogen	Southern	0.39	2.20	0.39	4.80	0.39	2.20	0.39	3.40
	Northern	0.62	0.54	0.62	0.59	0.40	0.70	0.40	0.33

The MPC_i^P indicator is set up by local authorities responsible for nature protection for each WWTP under several criteria—so we have different values both for WTTPs and years.

Multiplicity and frequency indicators were calculated using Equations (1) and (2). The outputs are presented in Table 3.

Table 3. Multiplicity and frequency outputs.

Substance	WWT	2015		2016		2017		2018	
		$\mathbf{M}_i$	$\mathbf{F}_i$	$\mathbf{M}_i$	$\mathbf{F}_i$	$\mathbf{M}_i$	$\mathbf{F}_i$	$\mathbf{M}_i$	$\mathbf{F}_i$
Suspended solids	Southern	1.57	0.903	1.62	0.876	2.29	0.591	4.76	0.959
	Northern	0.27	0.000	0.23	0.000	0.26	0.000	0.49	0.065
BOD(20)	Southern	1.21	0.667	1.36	0.556	2.50	0.500	7.67	0.528
	Northern	1.29	0.639	1.02	0.389	1.11	0.528	1.71	0.778
Phosphorus phosphate	Southern	11.35	1.000	11.80	1.000	13.10	1.000	13.00	0.583
	Northern	12.65	1.000	16.30	1.000	19.40	1.000	17.25	0.220
Nitrate-ion	Southern	0.76	0.267	0.70	0.130	1.02	0.198	0.81	0.266
	Northern	1.13	0.802	0.80	0.101	1.01	0.336	1.00	0.348
Nitrite-ion	Southern	1.50	0.579	2.65	0.806	1.65	0.429	4.13	0.970
	Northern	0.63	0.138	0.74	0.093	0.38	0.138	2.13	0.494
Ammonium-nitrogen	Southern	5.64	1.000	12.31	1.000	5.64	1.000	8.72	0.200
	Northern	0.87	0.842	0.95	0.263	1.75	0.401	0.83	0.207

The first element of Q/E dependency pair was obtained with the help of WWT quality expert evaluation weights, described in Table 1. These results are mentioned in Table 4.

The result obtained by authors considers the excess of actual indicators over the maximum permissible concentrations in contrast to results mentioned in manuscripts of Revollar et al. [18] and Longo et al. [23], where the weight of purified through WWT process pollution was taken into account. The authors believe that there is no need to overcome the MPCs, established by local authorities, because it can lead towards energy consumption increase.

Table 4. EW and REW for northern and southern WWTPs.

Substance	WWT	2015	2016	2017	2018
Suspended solids	Southern	0.70	0.70	0.25	0.25
	Northern	1.00	1.00	1.00	1.00
BOD(20)	Southern	0.70	0.70	0.40	0.25
	Northern	0.70	0.80	0.70	0.70
Phosphorus phosphate	Southern	0.00	0.00	0.00	0.00
	Northern	0.00	0.00	0.00	0.20
Nitrate-ion	Southern	1.00	1.00	0.90	1.00
	Northern	0.70	1.00	0.80	0.95
Nitrite-ion	Southern	0.70	0.25	0.80	0.25
	Northern	1.00	1.00	1.00	0.40
Ammonium-nitrogen	Southern	0.25	0.00	0.25	0.50
	Northern	0.90	1.00	0.80	1.00
REW (Total)	Southern	0.56	0.44	0.43	0.38
	Northern	0.72	0.80	0.72	0.71

The second element for Q/E dependency pair was obtained using Equations (4) and (5). Result are shown in Table 5. We can observe equal AEC and ANEC values both for northern and southern WWTPs and years, except the 2018 for northern WWTP. The anaerobic digestion process at northern WWTP has been recently introduced with CHP-unit. In 2018, this unit has not yet been finished; however, we made a small approximation for EG indicator and included project performance (kWh) as input data.

Table 5. The inputs for AEC and ANEC calculations and outputs for northern and southern WWTPs.

Substance	WWT	2015	2016	2017	2018
EC	Southern	44,894,113	43,934,976	42,859,122	45,202,702
	Northern	6,983,065	6,720,995	7,487,034	6,927,041
EG	Southern	0	0	0	0
	Northern	0	0	0	4,642,800
Q	Southern	113,033,880	103,380,680	95,086,100	89,874,300
	Northern	23,819,410	22,201,630	21,046,310	20,722,530
AEC	Southern	0.397	0.425	0.451	0.503
	Northern	0.293	0.303	0.356	0.334
ANEC	Southern	0.397	0.425	0.451	0.503
	Northern	0.293	0.303	0.356	0.110

With compliance to the methodology, we have made the last step and transferred our data into graphical view. The results for the research are shown in Figure 2.

As one can see from the matrix presented, the outputs correlate with the technical conditions of WWTPs and the implementation of the BAT: most of the northern WWTP values are referred to the green zone, while the southern WWTP values are situated generally in the orange zone.

Speaking about the northern WWTP, the main conclusions that managers can come to are the need for further implementation of energy recovery techniques, as well as the superintendence over single quality indicators, especially for the phosphorus phosphates. If current technologies do not allow meeting high quality standards, it is desirable to check possible solutions using the Q/E dependency matrix.

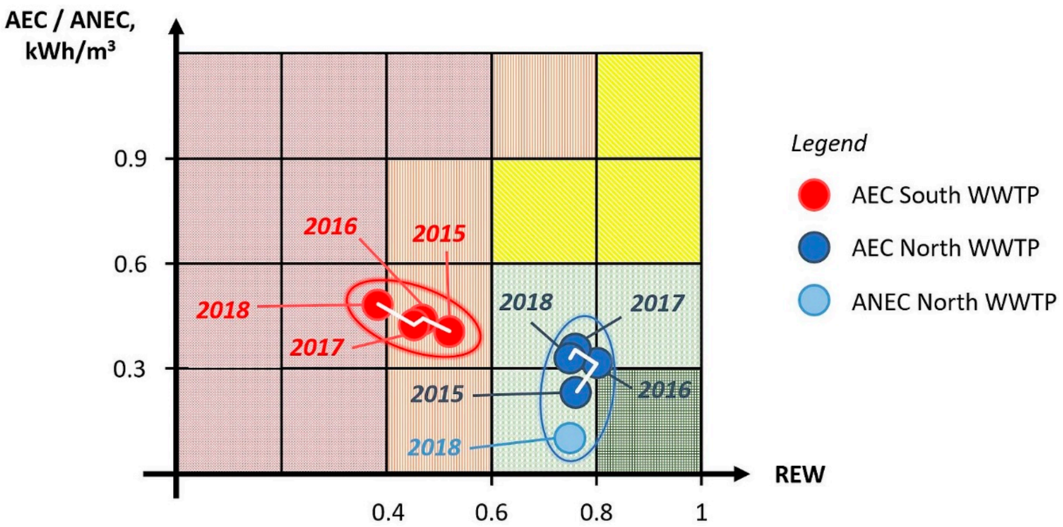

Figure 2. Outputs for South and North WWTPs.

There is no doubt that the transition to the green zone for southern WWTP requires global modernization activities throughout the WWT process.

Discussing the possible operational strategies of WWTP based on the results within different color zones on the Q/E dependency matrix, the following features can be highlighted:

Dark green zone: wastewater treatment technology provides the highest efficiency with minimum energy consumption (from the grid)—this is the most sustainable result, which can be achieved to a greater extent using waste-to-energy technologies. The best example is the use of anaerobic digestion of sewage sludge and the production of biogas, which is then used in CHP units for electricity and heat generation. Another good example is the application of pyrolysis technology. Besides providing high energy efficiency with renewable energies for self-consumptions (and even for electricity surplus supplying into the grid), these technologies solve the problem with sewage sludge treatment and utilization.

However, the methodological approach under consideration has some limitations, since it does not take into account the emission of pollutants into the air. Speaking about the impact on the environment, the authors in this study specifically focused on water use, because the impact that WWTP has on water bodies significantly exceeds the impact on any other environments.

Green zone: also considered to be a fairly sustainable result. Getting into the green zone means that WWTPs have either an effective treatment technology with the achievement of the standard quality of discharged wastewater without the use of modern energy-efficient solutions, or vice versa: there are certain limitations (technological or organizational) in achieving MPCs for few indicators using modern energy-efficient solutions.

Yellow zone: indicates satisfactory performance in terms of the quality of treated wastewaters, but extremely high electricity costs which do not meet modern energy efficiency standards.

The orange and red zones: imply the overall low and even threating efficiency of WWTP, which requires an immediate resolution. These utilities discharge wastewater with significant excess of the MPCs, while the energy costs do not matter within this context. It is urgently required to conduct an audit and make management decisions regarding the modernization of such facilities.

The Q/E dependency matrix has a clear and intuitive vision of retrospective of several WWTPs, but the visualization of hundreds of WWTPs will lead to poor readability. However, the graphical output, mentioned by Longo et al. [23], when the integrated results are depicted using bar chart, might be a good solution within this situation.

4. Conclusions

The application of proposed methodological tool on centralized sewerage system of Ekaterinburg, Russia showed the strong connection of resulting rank with technical and technological condition of the utilities:

- The northern WWTP rating falls into the green zone thanks to the recent modernization activities. However, it can reach the dark green zone through the implementation of actual CE applications (in particular, it is necessary to increase the intensity of anaerobic digestion and biogas yield and utilize heat energy from CHP-unit).
- The southern WWTP has unsatisfactory rating and since 2015 the situation has worsened, because the actual rating has entered the red zone. The major factors of this negative trend are the WWT quality degradation through extremal deterioration of concrete basins and equipment, and an increase of unit energy consumption per treated wastewater (the total treated wastewater has decreased). The key managerial decision for current WWTP is to conduct complete modernization with BAT implementation taking into account the positive experience of northern WWTP reconstruction.

The proposed methodological approach for Q/E dependency of WWT process creates a strong but simple tool for managers to evaluate the current success in operation of WWTP to work on the transition towards CE. It is intuitive and easy to understand for uninitiated users. The comparison of the results of the current year with the previous ones allows the wide range of stakeholders to assess the performance of both the team and the leader himself objectively. The monitoring framework can also be used as the common benchmark for the total sector contribution continuous improvement based on seeking and meeting the best practices as well as the tool for public control over WWT activities and CE practices implementation.

Technological development in the spheres of WWT and energy efficiency will inevitably lead towards incorrect matrix interpretation—modern techniques and not yet discovered breakthroughs will not give managers a clear view of the effectiveness of their WWTPs, because the resulting values will always fall into the green zone. In the future, it will be necessary to update the matrix thresholds to meet the technologies known and applied at the time of review, as well as to expand the plotting area of the matrix, that will be below zero for the AEC/ANEC axis. In addition, it is possible to apply different matrix boundaries (matrix patterns) for different countries or cross-border associations (like European Union or Eurasian Economic Union), when taking into account the difference in technological level in the world, especially the gap between developed and developing countries.

Author Contributions: Conceptualization, A.K. and E.M.; methodology, A.K.; validation, D.P. and M.C.Z.; formal analysis, A.K. and E.C.R.; writing—original draft preparation, A.K.; writing—review and editing, E.M., M.R., and M.C.Z.; visualization, A.K. and M.R.; supervision, E.M. and E.C.R.; project administration, D.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: All data generated or analyzed during this study are included in this published article.

Acknowledgments: This research was supported by Act 211 Government of the Russian Federation, contract № 02.A03.21.0006.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Ostoich, M.; Serena, F.; Zacchello, C.; Falletti, L.; Zambon, M.; Tomiato, L. Discharge quality from municipal wastewater treatment plants and the Sludge Biotic Index for activated sludge: Integrative assessment. *Water Pract. Technol.* **2017**, *12*, 857–870, doi:10.2166/wpt.2017.092.
2. Huang, B.; He, C.; Fan, N.; Jin, R.; Yu, H. Envisaging wastewater-to-energy practices for sustainable urban water pollution control: Current achievements and future prospects. *Renew. Sustain. Energy Rev.* **2020**, *134*, 110134, doi:10.1016/j.rser.2020.110134.
3. Mor, J.; Dolédec, S.; Acuña, V.; Sabater, S.; Muñoz, I. Invertebrate community responses to urban wastewater effluent pollution under different hydro-morphological conditions. *Environ. Pollut.* **2019**, *252*, 483–492, doi:10.1016/j.envpol.2019.05.114.
4. Zaborowska, E.; Czerwionka, K.; Makinia, J. Strategies for achieving energy neutrality in biological nutrient removal systems—a case study of the Slupsk WWTP (northern Poland). *Water Sci. Technol.* **2017**, *75*, 727–740, doi:10.2166/wst.2016.564.
5. Siatou, A.; Manali, A.; Gikas, P. Energy Consumption and Internal Distribution in Activated Sludge Wastewater Treatment Plants of Greece. *Water* **2020**, *12*, 1204, doi:10.3390/W12041204.
6. Gurung, K.; Tang, W.; Sillanpää, M. Unit Energy Consumption as Benchmark to Select Energy Positive Retrofitting Strategies for Finnish Wastewater Treatment Plants (WWTPs): A Case Study of Mikkeli WWTP. *Environ. Process.* **2018**, *5*, 667–681, doi:10.1007/s40710-018-0310-y.
7. Valenti, F.; Toscano, A. A GIS-based Model to Assess the Potential of Wastewater Treatment Plants for Enhancing Bioenergy Production within the Context of Water-Energy Nexus. *Energies* **2021**, *14*, 2838, doi:10.3390/en14102838.
8. Borzooei, S.; Campo, G.; Cerutti, A.; Meucci, L.; Panepinto, D.; Ravina, M.; Riggio, V.; Ruffino, B.; Scibilia, G.; Zanetti, M. Feasibility Analysis for Reduction of Carbon Footprint in a Wastewater Treatment Plant. *J. Clean. Prod.* **2020**, *271*, 122526, doi:10.1016/j.jclepro.2020.122526.
9. Shrestha, B.; Hernandez, R.; Fortela, D.; Sharp, W.; Chistoserdov, A.; Gang, D.; Revellame, E.; Holmes, W.; Zappi, M. A Review of Pretreatment Methods to Enhance Solids Reduction during Anaerobic Digestion of Municipal Wastewater Sludges and the Resulting Digester Performance: Implications to Future Urban Biorefineries. *Appl. Sci.* **2020**, *10*, 9141, doi:10.3390/app10249141.
10. Fighir, D.; Teodosiu, C.; Fiore, S. Environmental and Energy Assessment of Municipal Wastewater Treatment Plants in Italy and Romania: A Comparative Study. *Water* **2019**, *11*, 1611, doi:10.3390/w11081611.
11. "LCA—ISO 14040:2006". Available online: https://www.iso.org/obp/ui/#iso:std:iso:14040:ed-2:v1:en (accessed on 28 April 2021).
12. Li, Y.; Luo, X.; Huang, X.; Wang, D.; Zhang, W. Life Cycle Assessment of a municipal wastewater treatment plant: A case study in Suzhou, China. *J. Clean. Prod.* **2013**, *57*, 221–227, doi:10.1016/j.jclepro.2013.05.035.
13. Rebello, T.; Roque, R.; Goncalves, R.; Calmon, J.; Queiroz, L. Life cycle assessment of urban wastewater treatment plants: A critical analysis and guideline proposal. *Water Sci. Technol.* **2021**, *83*, 501–514, doi:10.2166/wst.2020.608.

14. Lopes, T.; Queiroz, L.; Torres, E.; Kiperstok, A. Low complexity wastewater treatment process in developing countries: A LCA approach to evaluate environmental gains. *Sci. Total Environ.* **2020**, *720*, 137593, doi:10.1016/j.scitotenv.2020.137593.
15. Lorenzo-Toja, Y.; Alfonsin, C.; Amores, M.; Aldea, X.; Marin, D.; Moreira, M.; Feijoo, G. Beyond the conventional life cycle inventory in wastewater treatment plants. *Sci. Total Environ.* **2016**, *553*, 71–82, doi:10.1016/j.scitotenv.2016.02.073.
16. Chen, K.; Wang, H.; Valverde-Perez, B.; Zhai, S.; Vezzaro, L.; Wang, A. Optimal control towards sustainable wastewater treatment plants based on multi-agent reinforcement learning. *Chemosphere* **2021**, *279*, 130498, doi:10.1016/j.chemosphere.2021.130498.
17. Alex, J.; Benedetti, L.; Copp, J.; Gernaey, K.V.; Jeppsson, U.; Nopens, I.; Pons, M.-N.; Rieger, L.; Rosen, C.; Steyer, J.P.; et al. Benchmark Simulation Model no. 1 (BSM1), 2008. Available online: https://www.iea.lth.se/publications/Reports/LTH-IEA-7229.pdf (accessed on 28 April 2021).
18. Revollar, S.; Meneses, M.; Vilanova, R.; Vega, P.; Francisco, M. Eco-Efficiency Assessment of Control Actions in Wastewater Treatment Plants. *Water* **2021**, *13*, 612, doi:10.3390/w13050612.
19. De Ketele, J.; Davister, D.; Ikumi, D. Applying performance indices in plantwide modelling for a comparative study of wastewater treatment plant operational strategies. *Water SA* **2018**, *44*, 539–550, doi:10.4314/wsa.v44i4.03.
20. Zaborowska, E.; Czerwionka, K.; Makinia, J. Integrated plant-wide modelling for evaluation of the energy balance and greenhouse gas footprint in large wastewater treatment plants. *Appl. Energy* **2021**, *282*, 116126, doi:10.1016/j.apenergy.2020.116126.
21. Cassidy, J.; Silva, T.; Semiao, N.; Ramalho, P.; Santos, A.; Feliciano, J. Improving wastewater treatment plants operational efficiency and effectiveness through an integrated performance assessment system. *H2Open J.* **2020**, *3*, 276–287, doi:10.2166/h2oj.2020.007.
22. Silva, C.; Saldanha Matos, J.; Rosa, M. A comprehensive approach for diagnosing opportunities for improving the performance of WWTP. *Water Sci. Technol.* **2016**, *74*, 12, doi:10.2166/wst.2016.432.
23. Longo, S.; Hospido, A.; Lema, J.M.; Mauricio-Iglesias, M. A systematic methodology for the robust quantification of energy efficiency at wastewater treatment plants featuring Data Envelopment Analysis. *Water Res.* **2018**, *141*, 317–328, doi:10.1016/j.watres.2018.04.067.
24. Kiselev, A.; Magaril, E.; Rada, E.C. Energy and sustainability assessment of municipal wastewater treatment under circular economy paradigm. *WIT Trans. Ecol. Environ.* **2019**, *237*, 109–120, doi:10.2495/ESUS190101.
25. Rukavishnikova, I.; Kiselev, A.; Berezyuk, M.; Ashirova, I. Improvement of the methodology for assessing domestic wastewater treatment quality using benchmarking tools. *WIT Trans. Ecol. Environ.* **2018**, *228*, 209–2019, doi:10.2495/WP180211.
26. The Guiding document RD 52.24.643-2002 “Methodological guidelines. Method for Comprehensive Assessment of the Degree of Surface Water Pollution by Hydrochemical Indicators”, Appendix E, J. Available online: https://base.garant.ru/70467388/, (accessed on 28 April 2021).
27. Belloir, C.; Stanford, C.; Soares, A. Energy benchmarking in wastewater treatment plants: The importance of site operation and layout. *Environ. Technol.* **2015**, *36*, 260–269, doi:10.1080/09593330.2014.951403.
28. Kiselev, A.; Glushankova, I.; Rudakova, L.; Baynkin, A.; Magaril, E.; Rada, E.C. Energy and material assessment of municipal sewage sludge applications under circular economy. *Int. J. Energy Prod. Mgmt.* **2020**, *5*, 234–244, doi:10.2495/EQ-V5-N3-234-244.