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Integration of energy and environmental systems in wastewater treatment plants

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Abstract
Most wastewater treatment facilities were built when energy costs were not a concern; however, increasing energy demand, changing climatic conditions, and constrained energy supplies have resulted in the need to apply more energy-conscious choices in the maintenance or upgrade of existing wastewater treatment facilities. This research develops an integrated energy and environmental management systems model that creates a holistic view of both approaches and maps linkages capable of meeting high-performing energy management while meeting environmental standards. The model has been validated through a case study on the Rolla, Missouri Southeast Wastewater Treatment Plant. Results from plant performance data provide guidance to improve operational techniques. The significant factors contributing to both energy and environmental systems are identified and balanced against considerations of cost.

Keywords: Energy conservation; Environmental management; Process integration; Strategic management; Wastewater treatment systems.

1. Introduction

Green environmental practices are increasingly important in combating serious global energy and environmental issues. Water and wastewater facilities are among the largest and most energy-intensive systems owned and operated by local governments and account for approximately 30 to 50% of municipal energy use. Most wastewater treatment facilities were built when energy costs were not a concern; however, increasing energy demand, changing climatic conditions, and constrained energy supplies have resulted in the need to apply more energy-conscious choices in the maintenance or upgrade of existing wastewater treatment facilities. Energy represents the largest controllable cost of water and wastewater treatment since energy use directly affects the amount of greenhouse gas (GHG) emissions, and indirectly affects the biological oxygen demand (BOD), chemical oxygen demand (COD), and pollutions levels. By controlling the level of energy consumption, wastewater treatment facilities can reduce the operating costs, increase efficiency, and reduce pollution in an effort to provide cleaner environments. In addition, increased training on advanced equipment by well-trained employees can lead to improved effluent and surface water quality and more compliant facilities [1, 2]. A strategic process to control these various factors could provide significant benefits to local governments and the communities they serve.

The major expense of any wastewater treatment facility is the electricity. Water and wastewater systems account for nearly 3% of U.S. electricity consumption. The consumption rate is estimated at 75 billion kWh at a cost of $4 billion to pump, treat, deliver, collect, and clean water. Pumping and aeration alone account for approximately 75% of the total energy budget of a facility [3]. These electricity requirements are estimated to increase by 20% during the next 15 years, primarily due to the expansion of treatment capacity to serve a growing population. If these facilities reduce their energy usage by 10%, they could save approximately $400 million and 5 billion kWh annually [3, 4].

A detailed analysis of water and wastewater treatment services shows that most facilities operate far below the efficiency levels needed for effective energy use. Failure to comply with regulated environmental standards is also a problem. Aging equipment drives up maintenance costs and energy consumption to unacceptable levels. Effective energy management plans can positively affect energy use in the future. Environmental protection is equally important and plays a major role in reducing the pollution levels. Wastewater treatment plants (WWTP) should be designed not only to clean wastewater, but also to supply nutrients. These plants should be better integrated with municipal ecosystems and function as a component of local water and nutrient cycles so that natural systems also play a role in the treatment of wastewater.

Many tools exist for either energy or environmental management. Energy management tools include abatement cost curves [5], strategic decision-making [6] the use of neural networks, [7] and budget allocation systems [8]. Tan et al. [9] developed a superiority-inferiority-based inexact fuzzy two-stage mixed-integer linear programming model that addresses uncertainty. Environmental management tools include municipal solid waste (MSW) decision models [10], groundwater transition zone management [11], industrial chemical management [12], and the use of multilayer media for wastewater treatment [13]. The sustainability assessment model (SAM) was developed to assess water main replacement options [14] and reduce environmental impact.

Although standards exist for both energy and environmental management systems, no integrated process has been developed to address the concerns of those communities which enables facilities to lessen their environmental impact while also reducing energy consumption. This research presents an integrated energy and environmental management systems model. It offers a holistic view of both approaches, maps linkages, and suggests an integrated process design capable of meeting high-performing energy management and environmental standards. In addition, the approach was applied and validated through a case study.

2. Materials and methods

A successful wastewater utility management system combines strategic planning, measurement, implementation, and continuous improvement techniques. This research integrates inputs from energy and environmental management systems to create a process model capable of evaluating strategic decision points for energy and environmental management simultaneously. A comparative summary of energy and environmental management systems is provided in Table 1 and serves as the beginning point for the integrated process map.

Table 1. Goals of energy versus environmental management systems

Goals of Energy Management System	Goals of Environmental Management System
Optimize energy efficiency	Reduce pollution levels
Minimize energy waste	Decrease chemical effects on filtered water
Increase energy efficiency	Follow ISO 24511 standards
Measure energy consumption accurately and apply methodologies appropriate to facility conditions	Measure performance data accurately

2.1 Energy management system

Generally, most wastewater treatment plants follow similar energy management systems. Depending on the facilities available, measuring techniques may vary from one WWTP to another. A large variety of technologies and opportunities exist for increasing energy efficiency and reducing energy consumption in the wastewater management sector while maintaining the productivity levels. These technologies can be categorized based on their design, control, and efficiency, among other factors. Improved equipment operates more efficiently compared to standard equipment; i.e., delivers the same service for less energy

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input, improves controls, and use is based on the demand to minimize losses. The most common energy uses in wastewater treatment are for aeration and pumping. Other common processes that consume energy during the wastewater treatment are mechanical mixing, chemical dosing, media and membrane filtration, dissolved air floatation, sludge handling and disposal, and digester heating. Wastewater treatment managers are attempting to include more energy intensive treatment processes over time which will allow wastewater facilities to meet stringent water quality standards. These processes will also involve additional steps to remove emerging contaminants and thus permit the reuse of more wastewater. Although such processes will extend the water supply, they will also increase energy use [3]. Table 2 lists the most common energy efficiency technologies used in wastewater treatment facilities.

Table 2. Common energy efficiency technologies [3]

Energy Efficiency Technology/Strategy	**Description**	**Typical Payback (Years)**
High efficiency motors	Motors with lower internal losses; used for pumps, blowers, mixers, etc.	Variable
Variable frequency drives (VFDs)	Electronic controller that matches motor speeds to the required load; avoids running at constant full power	½ to 5
High-efficiency pumps	Pumps with lower internal friction and head losses	Variable
Variable air flow rate blowers	Variable rate blowers efficiently match air supply to aeration requirements	<3
High-efficiency blowers	Air blowers with lower internal losses	Variable
Dissolved-oxygen controls	Maintains the dissolved oxygen (DO) level of the aeration tank(s) at a preset control point by varying the air flow rate to the aeration system	2 to 3
Supervisory control and data acquisition (SCADA) system	Supervisory control and data acquisition system collects facility-wide data and allows control of equipment to more precisely meet required flows	Variable
Fine-bubble aeration	Fine-pore diffusers generate smaller bubbles for aeration processes; improves oxygen transfer to wastewater	1 to 7
Staging of treatment capacity	Treatment systems designed and installed to operate efficiently at multiple stages (i.e., across a range of flow conditions)	<2
Recover excess heat from wastewater	Excess heat from wastewater reused in low temperature heating applications	<2
Efficient mixing of aerobic digesters	Mechanical mixing used rather than aeration where possible; mechanical mixing uses less energy	1 to 3
Efficient sludge handling	Screw presses and gravity belt thickening use less energy for sludge dewatering and thickening	Variable
Efficient ultraviolet (UV) disinfection lamps and controls	High efficiency UV lamps convert more of the power they consume into useful light; controls turn down lights when not needed	Variable

Figure 1 illustrates a general energy management process flow model. The process map details the steps involved in a general wastewater energy audit to identify decision points for WWTP managers to reduce energy consumption rates.

2.2 Environmental management system

ISO 24511 is the standard set for environmental management systems to ensure an appropriate assurance to environmental issues and provide guidelines for various elements, implementations, and applications

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of environmental management systems. Table 3 lists the common environmental issues as well as control strategies currently used in WWTPs.

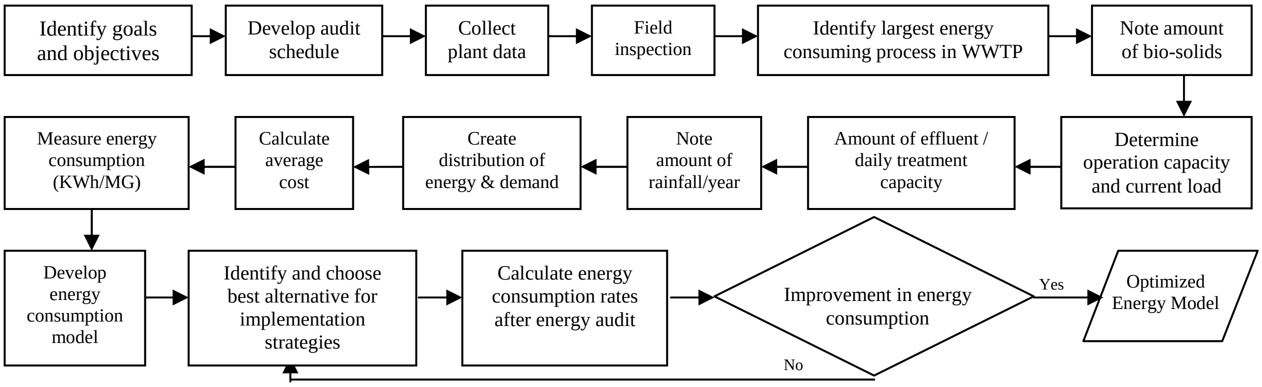

Figure 1. Energy management systems process flow model

Table 3. Environmental issues in WWTPs and measures to control them [15]

Effect	**Measure**
Overflow or bypassing of wastewater	Install stand-by equipment at pumping stations; use dual power source supply system; implement proper maintenance program; enhance operational monitoring and emergency measures
Wastewater discharge to watercourses	Intercept discharges; impose stringent environmental management and pollution controls
Contamination of raw water source	Implement and enforce water and land protection zones
Water stress/ insufficient water allocation	Study water yields; draft and conclude allocation contract
Damage to sewers or wastewater treatment plant from corrosive industrial discharges	Adequately pre-treat industrial wastewater; select appropriate construction materials; adequately control WWTP processes
Pollution of receiving water courses following upset of wastewater treatment process by industrial discharges	Adequate pretreatment of industrial wastewater; efficient monitoring and enforcement
Pollution of receiving water courses caused by improper operation of WWTP	Control of WWTP processes
Odor	Cover potential odor sources; transport sludge and other residues in covered containers
Safety risk from toxic gases	Install inspection and control equipment; spacing manholes appropriately; provide ventilation; monitor atmospheric conditions; adopt safe working systems and emergency measures
Noise generated by pumps and machinery	Select low noise machines; locate high noise equipment indoors; install noise enclosures or buffers; install semi-underground pump stations
Pollution by sludge from water and wastewater treatment plants	Dispose of sludge at sanitary landfills if testing shows sludge to be unsuitable for beneficial reuse
Sludge or silt from wastewater pumping stations and wastewater collection systems	Clean up quickly; transport in covered containers
Pollution of raw water supply from upstream wastewater discharge from communities, industries, agriculture, and soil erosion runoff	Implement appropriate water and soil conservation and environmental management plan

Figure 2 illustrates a general environmental protection model that follows procedures similar to the energy management model, but collects different data. It relies primarily on the Energy Star rating provided by the Environmental Protection Agency (EPA) to determine the efficiency of the WWTP and detail the process steps.

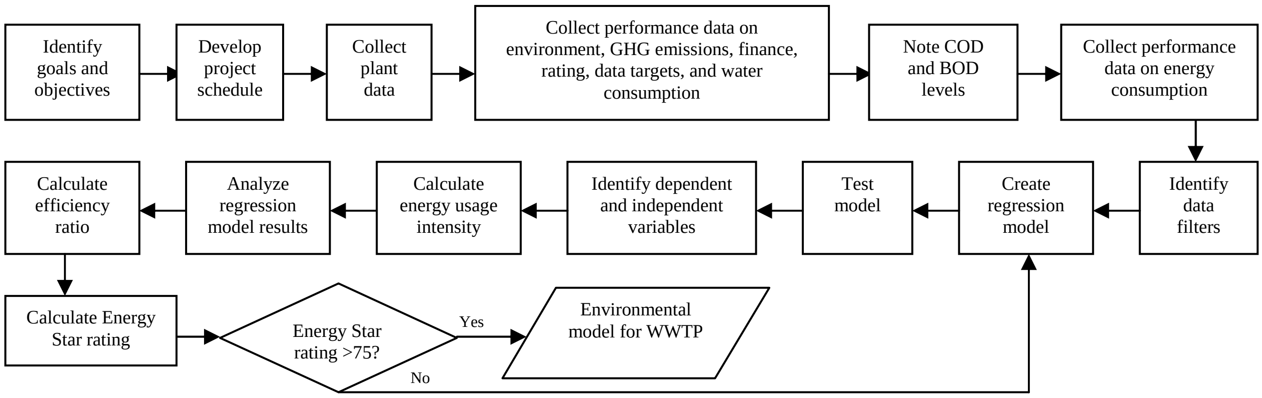

Figure 2. Environment management systems process flow model

2.3 Integration model

Until recently, research has concentrated on energy management or environmental management separately. In an energy management model, an energy audit is preferred. Based on the results, measures are taken to reduce the energy consumption at specified points in the process; however, the control of environmental effects is not addressed. Energy reduction, therefore, can be achieved at the cost of environmental considerations. Similarly, in an environmental management model, the primary focus is on controlling the environmental effects, although energy consumption is also considered. There is a need to maintain a proper balance between the energy and environmental factors so that both energy efficiency and the environmental system can be improved concurrently. This work uses strategic process integration to combine the two systems.

The integration model presented in Figure 3 is a holistic approach to process design that considers the interaction among various sections of the process flow and shares the benefits of each individual process design model. The main objective of this model is to integrate and optimize each process by conducting a detailed study of the benefits of each approach. A study conducted sponsored by the EPA and Siemens shows that most water and wastewater treatment plants operate far below their efficiency capacity [16]. This cross functional model guides the plant manager in developing strategies, scheduling operations, and implementing optimization techniques to increase efficiency while following the environmental policies. This study collected data on performance, emissions, and energy consumption to determine the plant's Energy Star rating. This rating permits the evaluation of suitable techniques to optimize energy consuming processes.

To use this model, the processes and factors that contribute to energy consumption or environmental issues are identified. Starting with energy management, the process or the factor most significant to energy consumption is found by evaluating data collected over a period of time. The amount of rainfall and average flow per day is measured. Rainfall has a direct impact on energy consumption and decreases the BOD level in the influent water. The integrated model requires that distribution be created between the demand and the energy consumption. Energy efficiency improvement techniques are then applied based on the plant conditions. Energy consumption is monitored to evaluate the success of these techniques. If there is no significant improvement, then an alternate technique can be applied. This process is repeated until sufficient energy efficiency is achieved.

Environmental management factors are identified in a similar manner. Plant performance data is collected and the chemical composition of the discharged water is evaluated. The GHG emissions are measured along with BOD and COD levels, nutrients, chlorine, odor, and the suspended solids in effluent. The results are measured and compared to the ISO 24511 norms, required discharge characteristics, and the EPA standards.

The factors considered as part of the integrated model for energy and environmental management are then divided into dependent and independent variables, and the correlation among them is identified. The factors are then subjected to regression analysis. Next, the energy usage intensity per environmental impact is calculated, the results are analyzed, and the most significant factors are identified. The performance rating is generated by taking the ratio of a facility's actual energy intensity and comparing it to the energy intensity predicted by the Energy Star model. A multivariate regression analysis is then conducted to identify the significant factors and determine the effect of one variable on another. This analysis is repeated, changing the dependent and independent variable and thus the effect of one factor on the other. Based on the results of each multivariate regression model, the significant factors contributing to both energy and environmental systems are identified. By controlling these factors, a balance can be maintained between energy and environmental management models. Once these factors are identified techniques that help to improve energy efficiency while simultaneously conforming to environmental norms can be applied. The proposed integrated approach was validated through the application of the integrated model to a WWTP in Rolla, Missouri. This is discussed in detail in Section 3.0.

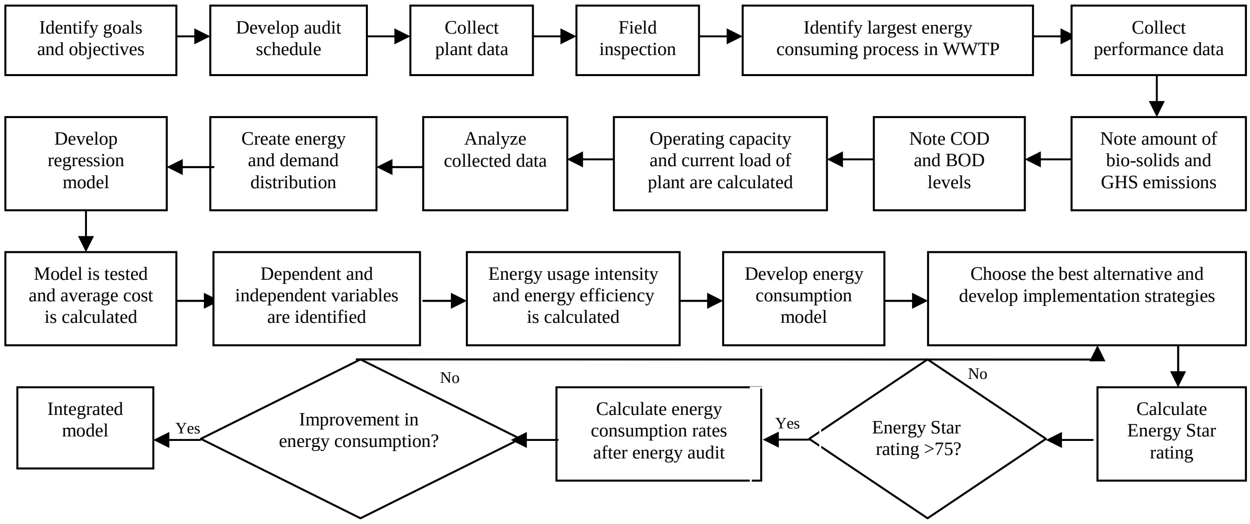

Figure 3. Energy and environment management systems integrated process flow model

3. Case study: Rolla southeast WWTP

This section details the advantages of our model over individual approaches and also discusses the limitations it imposes on plant capacity. Rolla is a small rural community located in south central Missouri. The Rolla Southeast wastewater treatment plant processes an average of 3 million gallons of wastewater daily. The main step in the treatment process is the separation of solids, which accounts for about 2% of wastewater. Wastes are separated and filtered by various processes such as aeration, trickling filter, sand filter, primary and secondary clarifier, and oxidation. Figure 4 illustrates the various processes used at the plant, the flow of influent through various filters, and the capacity of each process. Initially the influent flows from mechanical filtration tanks where solids are separated. It is then allowed to flow through clarifiers where it captures a majority of the solid wastes. The oxidation process reduces the odor and maintains the chemical oxygen demand and biological oxygen demand levels. No disinfection process is run in this plant. After the oxidation process, the effluent is directly discharged into the water bodies [12].

The performance data of the plant for each month was collected over a period of two years. The energy consumed by the plant per month was collected and then the energy consumed by each process was estimated based on the specifications of equipment of the facility and the run time. There are mainly three processes that consume energy in the Rolla South East WWTP [17]. These include blower and oxidation ditch, pump and trickling filter, and clarifier. Based on the literature review, specifications, operating time, and capacity, it was estimated that blower and oxidation ditch consume 75% of the total energy, the pump and trickling filter consume 10%, and the clarifier consumes 15%.

In this analysis, the energy consumption values are estimated based on the other factors such as BOD, suspended solids, average flow, and observations from the other plants with similar conditions. The BOD level of the influent is noted for every month, and the change in the BOD level of the influent in each

process is estimated based on the purification process. The BOD level is mainly affected in the oxidation ditch; the dissolved oxygen brings down the BOD level in the influent. Based on the literature review, capacity and specifications of the equipment, it is estimated that the clarifier reduces the BOD level by 10%, pump and trickling filter by 25%, and rest of the 65% by blower and oxidation ditch. The clarifier initially separates the suspended solids and removes most of the solids. The amount of suspended solids in each process is measured and noted. It is estimated that 86% of the suspended solids are reduced by the clarifier, 9% by the trickling filter, and the remaining 5% are reduced by the oxidation ditch.
The amount of rainfall per each month is also collected. The amount of rainfall has a great influence on BOD and eventually on the energy. When there is more rainfall the BOD level in the influent is reduced, since rainwater is considered to be fresh water. Thus, the energy required for reducing the BOD to the desired level will be less. The average flow is directly proportional to the energy. As the average flow increases, the energy consumption also increases. The daily flow rate of the wastewater is taken and an average flow rate for every month is calculated.
In our analysis, energy was taken as the dependent variable and BOD, suspended solids, average flow, and rainfall are taken as the independent variables. The change in energy was observed and the significant variables affecting were identified.
Table 4 shows the data collected by the portfolio manager used by the EPA's Energy Star [18]. The Energy Star rating shows that this plant operates far below than the required value of 75. This low rating occurs because the plant relies on older equipment that consumes a great deal of energy and produces high emission levels.

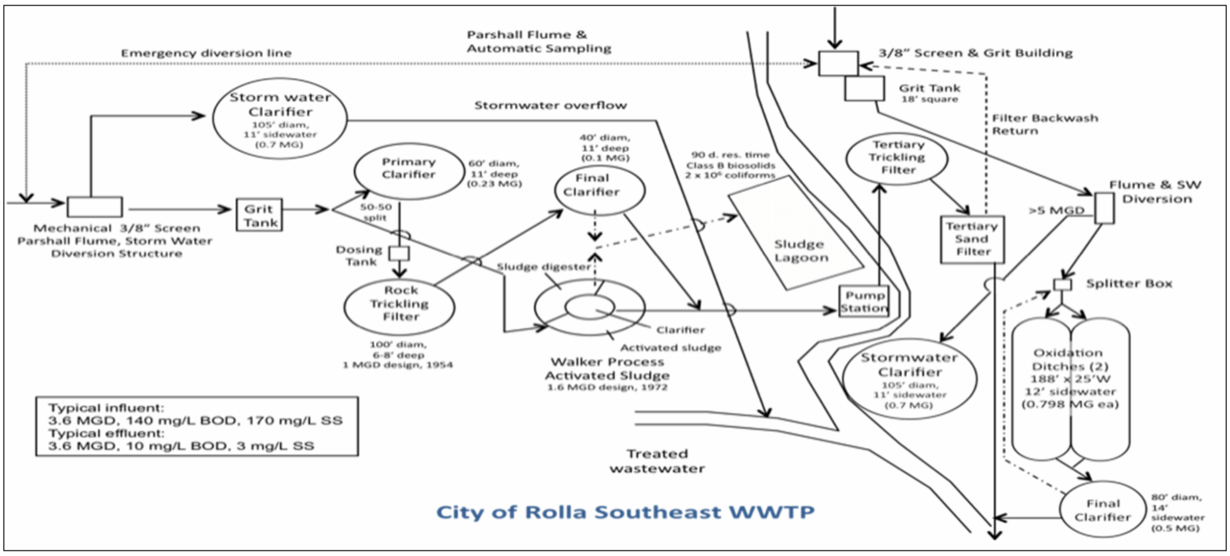

Figure 4. Flow of influent in the Rolla SE-WWTP

Table 4. Rolla SE-WWTP performance data [17]

Category	**Value**
Current Energy Star rating	58
Baseline rating (1-100) (kBtu/Sq.Ft.)	58
Annual energy cost (US Dollar $)	$168,551.61
Average flow (MGD)	3.2
Baseline energy/flow	1.9498
National average site energy usage intensity (EUI) (kBtu/MGD)	2.2
Baseline total GHG emissions	1526.69
Influent BOD5 (mg/l)	200.0000

Multilinear regression analysis was employed to model and analyze the variables. The analysis was conducted with energy as a dependent variable and BOD, suspended solids, average flow, and rainfall as independent variables. Energy consumption is divided among the three main processes of clarifying, oxidation, and filtering. Similarly, BOD and suspended solids values for each process are estimated and divided accordingly. Data was collected over a twenty-three month period for the characteristics listed in Table 5. Multilinear regression gives the results as shown in Table 6. The value of the adjusted R-square is 0.8617 for the three main process clarifying, oxidation, and filtering which illustrates the effectiveness of the model.

Table 5. Process variables

Aeration (Influent)	Average Flow
	Biological Oxygen Demand
	Suspended Solids
Oxidation (Influent)	Average Flow
	Biological Oxygen Demand
	Suspended Solids
Aeration and Oxidation (Effluent)	Average Flow
	Biological Oxygen Demand
	Suspended Solids
Storm water Clarifier 002 (Influent)	Average Flow
Storm water Clarifier 002 (Effluent)	Biological Oxygen Demand
	Suspended Solids
Storm water Clarifier 003 (Influent)	Average Flow
Storm water Clarifier 003 (Effluent)	Biological Oxygen Demand
	Suspended Solids
Rain	Average Flow

Table 6. Regression analysis

Regression Statistics	
R	0.9283
R-Square	0.8617
Adjusted R-Square	0.5655

Applying the integrated model to the Rolla Southeast WWTP reveals opportunities to upgrade the functionality in ways that provide energy efficiency while reducing the environmental impact. The WWTP at Rolla follows few of the norms issued by ISO and demonstrates poor energy management. Performance data and capacity levels reveal that the plant is not performing at its best; its Energy Star rating is 58, well below the required 75. Application of the integrated methodology will improve the plant's performance rating and ensure that local bodies of water will be able to supply nutrients for agriculture. Energy costs are a major concern for a small community such as Rolla; reduced energy consumption and an optimized maintenance schedule help reduce costs. The filtered water can be used as a source of nutrients for plants, thus providing an additional benefit.

Improvement in energy and environmental efficiency strengthens the communities' sustainability plan. In addition, using the energy efficiently and following ISO norms can minimize infrastructure costs. The proposed energy and environmental management program, in coordination with the efforts of local electric utility authorities, can be used to develop energy benchmarks and assessments to provide financial incentives for efficiency and renewable investments.

4. Conclusions and future work

This research evaluates the relationship between environmental and energy factors and explores the value in tracking energy and environmental processes through a common management system. The proposed integrated energy and environmental management model developed in this research provides a mechanism for achieving a practical balance between two complex systems. This integrated approach minimizes energy consumption and maintains the environmental efficiencies suggested by the EPA Energy Star rating system. The work fills a gap in the literature and offers benefits over individual approaches. The case study conducted at Rolla Southeast WWTP provides an overview of the processes in a WWTP, as well as consumption rates and areas for improvement. The process validated through this case study can be applied to other WWTPs seeking to improve their energy consumption while reducing their environmental impact.

This work offers the WWTP manager a formalized action plan presented as a process flow that considers multiple risk factors. The integrated model provides guidance for the development of an energy efficient and environmentally friendly WWTP. An integrated model that includes benefits for both energy use and environmental impact makes this management model a unique and holistic approach.

Future work exists for evaluating strategic industrial partnership options that will allow a WWTP to improve its performance and quality through the use of innovative funding strategies such as performance contracting and public private partnerships. In addition, the effectiveness of the integrated model can be further tested by implementation in a WWTP and constant monitoring of the effect of the model on the plant performance. This would enable sustainability and sensitivity of the integrated model to be analyzed in greater detail. In addition, by including more factors such as cost and time more reliable results can be achieved through linear programming techniques. Energy conservation techniques should be explored in more detail in future studies.

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