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Renewable Energy Generation and GHG Emission Reduction Potential of a Satellite Water Reuse Plant by Using Solar Photovoltaics and Anaerobic Digestion

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Abstract: Wastewater treatment is a very energy-intensive process. The growing population, increased demands for energy and water, and rising pollution levels caused by fossil-fuel-based energy generation, warrants the transition from fossil fuels to renewable energy. This research explored the energy consumption offset of a satellite water reuse plant (WRP) by using solar photovoltaics (PVs) and anaerobic digestion. The analysis was performed for two types of WRPs: conventional (conventional activated sludge system (CAS) bioreactor with secondary clarifiers and dual media filtration) and advanced (bioreactor with membrane filtration (MBR)) treatment satellite WRPs. The associated greenhouse gas (GHG) emissions were also evaluated. For conventional treatment, it was found that 28% and 31.1% of the WRP's total energy consumption and for advanced treatment, 14.7% and 5.9% of the WRP's total energy consumption could be generated by anaerobic digestion and solar PVs, respectively. When both energy-generating units are incorporated in the satellite WRPs, MBR WRPs were on average 1.86 times more energy intensive than CAS WRPs, translating to a cost savings in electricity of \$7.4/1000 m^3 and \$13.3/1000 m^3 treated, at MBR and CAS facilities, respectively. Further, it was found that solar PVs require on average 30% longer to pay back compared to anaerobic digestion. For GHG emissions, MBR WRPs without incorporating energy generating units were found to be 1.9 times more intensive than CAS WRPs and 2.9 times more intensive with energy generating units. This study successfully showed that the addition of renewable energy generating units reduced the energy consumption and carbon emissions of the WRP.

Keywords: wastewater treatment; water reuse; energy consumption; treatment plant design; photovoltaics; carbon emissions

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1. Introduction

In recent decades, small, decentralized wastewater treatment plants (WWTP), termed satellite water reuse plants (WRP), have become very prevalent. WRPs are satellite treatment facilities that treat wastewater from a specific part of the community and reuse the effluent in or around the location where the wastewater was collected. Growing population and decreasing water reserves warrant utilizing reuse water to mitigate the effects of water scarcity [1,2]. Due to the close proximity and/or potential direct contact of reclaimed water with the general public, regulations and effluent standards for water reuse over recent decades have become stricter [3–8]. To achieve these stricter standards, additional and/or advanced treatment technologies are needed [9,10]. Wastewater treatment is energy intensive. Despite the obvious benefits of water reuse and recycle, the application of these treatment technologies in WRPs, to meet the stringent effluent discharge standards, would result in greater energy consumption [11]. The goal of the current study is to assess the renewable energy generation potential of a satellite WRP with the addition of solar photovoltaics (PVs) and anaerobic digestion to offset this energy consumption.

Fossil fuels, at present, provide over three-quarter of the world's energy [12]. Current known petroleum reserves are projected to be exhausted in less than 5 decades, according to [13]. The use of these fuels produces enormous amounts of greenhouse gas (GHG) emissions, which subsequently result in crucial environmental problems including climate change [14–16]. Worldwide, United States is the second largest contributor of carbon emissions (15%) after China (30%) [17]. The growing pollution levels caused by the fossil fuels as well as their continuously changing prices, warrants the need for energy conservation and transition from fossil fuels to renewable energy [18,19].

Wastewater treatment is energy intensive. About 4% of the energy use and 3–7% of the GHG emissions is related to water and wastewater facilities globally [20]. In the United States, 2–4% of the total energy consumed is for the collection, distribution, and treatment of wastewater and drinking water, accounting for 45–90 million tons of GHG emissions [21]. To curb this energy consumption and the associated emissions, system-specific and/or site-specific analysis of a WWTP is required [22]. There are, however, constraints to how much energy use within an existing plant can be curbed, because the current design requires a minimum amount of energy to run installed processes. To decrease the GHG emissions and dependency on fossil fuels, the use of renewables as energy source in wastewater treatment has become popular. Efforts to offset the energy consumption of the WWTPs include methane generation from anaerobic sludge digestion and the installation of PV solar panels [23–27].

Renewable energy is rapidly gaining popularity. In the United States, in 2019, energy consumption through renewable energy resources (11.5% of total energy consumption) exceeded the consumption of energy through coal (11.3%), predominantly due to the increased growth rate of solar and wind installations, since 2015 [28]. In the year 2019, 2% of the total electricity generation was achieved through solar [29]. Solar PVs is a popular type of solar technology, which generates electricity directly through the photoelectric and photovoltaic effect. It has the advantage of being employed for both utility-scale and distributed generation. Further, with the development of new technology, solar energy has become more cost effective and efficient. Reference [25] reported that some WWTPs in the U.S. have adopted solar PV for energy consumption offset. However, the deployment of solar PV requires large land acreage [30–32]. In this study, the PV system was sized for the WRP using acreage available from basin and membrane/clarifier area.

Using methane gas released through anaerobic sludge digestion is another source of renewable energy. Anaerobic sludge digestion is generally not found in satellite WRPs, due to the lack of solids handling at the facility to achieve a smaller real estate area. However, the introduction of membrane bioreactors (MBRs) into satellite reuse plants may significantly reduce the land acreage needed. Therefore, the application of anaerobic digesters at these facilities should be the focus of re-evaluation. With the increase of pretreatment requirements before the use of an MBR, solids screening removal has become more stringent; thus, a richer thicker primary sludge is obtained that can be processed directly in a digester without the need for thickening. Thus, the digester is the only unit that needs to be added to have an energy-producing unit at the facility. In using digesters at a WRP, only primary (screened) sludge can be diverted to the digester. This is because the addition of waste activated sludge (WAS) even in a small amount would lead to a decreased rate of biological reaction in the digester and thus less energy generation [33]. With the WAS being directly discharged back into the collection trunk without processing through the digester, the volume and the overall acreage of the digester will be smaller. Using a single-stage high-rate mesophilic anaerobic digester also provides a small acreage for the digester.

Using advanced treatment technologies to treat reuse water requires a large increase in energy consumption compared to conventional unit processes. The current efforts of the water sector to reduce the energy consumption and the related GHG emissions of water infrastructure, challenges the actual benefits of WRPs using advanced treatment. An evaluation of the GHG emissions and the renewable energy potential of WRPs have been investigated by few studies [11,34–36]. In this research, a WRP was evaluated to offset the energy consumption, determine the associated GHG emissions, and analyze the economics of conventional activated sludge (CAS) and MBR systems by incorporating and comparing solar PV and biosolid digestion from fine-screened (primary) sludge.

2. Material and Methods

The flow diagram for the WRP considered in this study is presented in Figure 1. In order of treatment, the unit processes include coarse screen, aerated grit chambers, fine screen, conventional activated sludge (CAS) system, membranes, and UV disinfection. When comparing conventional versus advanced unit processes, the membranes were replaced by the combination of secondary clarification and dual media filtration, and UV disinfection by chlorination.

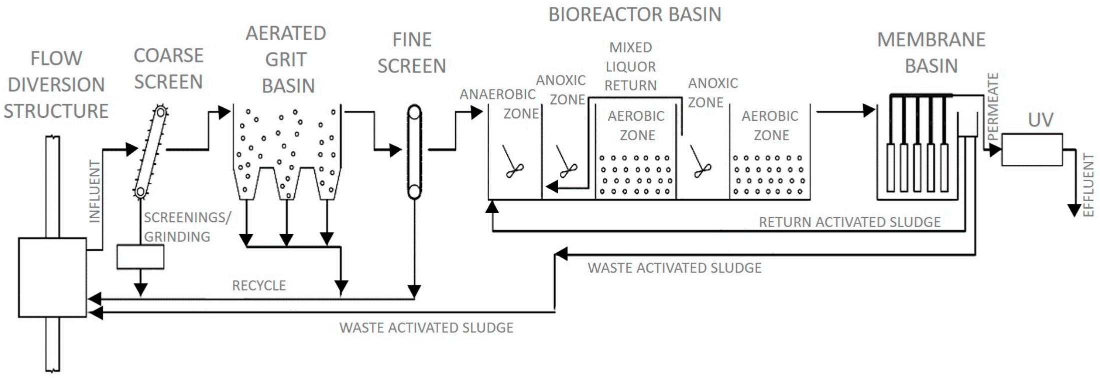

Figure 1. Process flow diagram of the selected water reuse plant.

2.1. Influent and Effluent Quality

The influent characteristics and effluent requirements (based on water reuse standards for California and Florida state) for the WRP are presented in Table 1. The effluent requirements are typical, with the exception for the need to remove nutrients. A five-stage modified Bardenpho CAS system was provided at the facility for the removal of the nutrients: phosphorous and nitrogen [37,38].

Table 1. Plant influent and effluent process characteristics found in the water reuse plant.

Parameter	Influent Characteristics	Effluent Requirements
BOD (mg/L)	250	30
TSS (mg/L)	309	30
TKN (mg/L as N)	42	–
NH_3 (mg/L as N)	34	0.5
TN (mg/L as N)	–	10
TP (mg/L as P)	8	0.2
TC (MPN/100 mL)	–	2.2
TC, daily max (MPN/100 mL)	–	23
Minimum Temp (°C)	18.3	18.3

BOD: Biochemical oxygen demand, TSS: Total Suspended Solids, TKN: Total Kjeldahl Nitrogen, NH_3: Ammonia, TN: Total Nitrogen, TP: Total Phosphorus, TC: Total Coliform Bacteria, MPN: Most Probable Number .

2.2. Energy Consumption for the Unit Processes of the Water Reuse Plant

To determine the energy consumption associated with the reuse plant, the energy driving units from each process were identified, and the associated energy was computed. These computations were done using typical design equations available in reference literature [10,33,37,39–41]. Energy consumption levels for advanced treatment processes and comparable conventional treatment processes in the satellite WRPs were computed and reported by [11] (Table 2).

Table 2. Energy consumption per unit flow of each unit process in a satellite reuse plant.

Facility Type	Unit Process	Energy Consumption per Unit Flow kWh/1000 m^3					
		2.6 m^3/min (1 MGD)	5.3 m^3/min (2 MGD)	10.5 m^3/min (4 MGD)	15.8 m^3/min (6 MGD)	23.1 m^3/min (8.8 MGD)	28.9 m^3/min (11 MGD)
MBR Facility	Coarse Screens	0.31	0.15	0.08	0.05	0.03	0.04
	Grit Chamber	28.4	16.6	11.8	9.5	7.5	6.4
	Fine Screens	9.5	4.7	2.4	1.6	1.1	1.3
	Bioreactor	420.5	421.1	421.1	421.1	424.6	424.6
	Membranes	238.9	238.9	238.9	238.9	221.7	221.7
	UV Disinfection	25.9	27.7	26.7	25.7	25.2	25.9
	Total	723.4	709.1	700.9	696.7	680.1	680.1
CAS Facility	Coarse Screens	0.31	0.15	0.08	0.05	0.03	0.04
	Grit Chamber	28.4	16.6	11.8	9.5	7.5	6.4
	Fine Screens	9.46	4.73	2.36	1.58	1.08	1.29
	CAS	311.7	307.6	307.6	307.6	310.7	310.7
	Secondary Clarifier	2.36	1.77	1.77	1.77	1.61	1.61
	Dual Media Filters	1.33	1.32	0.99	0.88	0.85	0.85
	UV Disinfection	36.5	36.5	35.6	36.6	36.9	35.4
	Total	390.0	368.6	360.1	358.0	358.8	356.4

MBR: bioreactor with membrane filtration; CAS: conventional activated sludge.

2.3. Design Parameters and Consideration

Typical design values, as reported in design literature, were used to size the PV solar systems and anaerobic digesters (Table 3). All energy consumption computations for the anaerobic digester were for monthly average flow conditions. Details of the design for each process are discussed below.

Table 3. Photovoltaic solar system and anaerobic digester Design parameters.

Renewables	Parameter	Value	Unit	References
Photovoltaic Solar System	Average Solar Insolation	6.31	kWh/m^2/day	[42–44]
	Performance Ratio	80	%	[18,43–45]
	Power Generated per Panel Area	200	W/m^2	[43,44,46]
Anaerobic Digester	Solid Retention Time (SRT)	15	day	[33,47]
	Temperature	35	°C	[33,40,47]
	Methanogenic Bacterial Yield for Cell Synthesis	0.08	kg VSS/kg bCOD	[33,40]
	Bacterial Endogenous Decay Coefficient	0.03	day^{-1}	[33,40]
	Waste Utilization Efficiency	70	%	[33]
	Percentage of Methane in Digester Gas	65	%	[33,40,47]

2.3.1. Anaerobic Digester

Key parameters used in the design of the single-stage high-rate mesophilic anaerobic digester can be found in Table 3. The hydraulic retention time, HRT, equivalent to the solid retention time (SRT), was used in the determination of the volume required for the digester [33]. The amount of methane-forming volatile solids synthesized per day was determined using the complete-mix high-rate digester equation, followed by the calculation of the volume of methane gas using kinetic equations [33,40]. The calculations were performed taking into account the volume of methane gas at the operating temperature of 35 °C. An egg-shaped digester was used in the design to provide a higher mixing efficiency, improved homogeneous biomass, and most importantly, a smaller real estate area in the WRP [33,47].

The anaerobic digestion process produces methane gas that can be used for energy generation; however, digestion itself consumes energy. Energy consumption for the anaerobic digester is driven by the mixers providing a homogeneous biomass mixture, by the heat-exchanger providing heating for the sludge, and heat losses through the digester walls. Mixer energy requirements were determined based on the volume of the digester, using an average energy consumption of 6.5 W/m^3 [47].

The energy requirement to heat the sludge was determined using [33,40,47]:

$$q = Ms \times Cs \times (T - Ti) \tag{1}$$

where q = heat required, J/day; Ms = mass flow of sludge, kg/day; Cs = specific heat of sludge, J/kg °C; T = digestion temperature, °C; and Ti = influent sludge temperature, °C. For this study, Cs = 4200 J/kg °C [33] (Metcalf & Eddy, 2003).

The energy required to compensate for the loss of heat through the walls of the digester were determined as [33,40,47] (Metcalf & Eddy, 2003; Davis, 2010; WEF, 2010b):

$$q = U \times A \times \Delta T \tag{2}$$

where q = heat loss, J/sec; U = overall coefficient of heat transfer, $J/m^2 \cdot s \cdot °C$; A = cross-sectional area perpendicular to heat flow, m^2; and ΔT = change in temperature between digestion and surface in question. The coefficients of heat transfer used in the research are 0.68, 0.85, and 0.91 $W/m^2 \cdot °C$ for the walls, floor, and roof, respectively [33,40,47] (Metcalf & Eddy, 2003; Davis, 2010; WEF, 2010b).

Energy production from the combustion of digester gas was determined using:

$$E = H \times V \times e \tag{3}$$

where E = energy generated, kJ/day; H = heat of combustion, kJ/m^3; V = volume of gas produced per day, m^3/day; and e = electrical efficiency. In this study, H = 37,000 kJ/m^3 and e = 33% (for an internal combustion engine) [47].

2.3.2. Photovoltaic Solar System

Parameters used in the design of the PV solar system can be found in Table 3. Real estate area available for the PV system was determined based off basin and membrane/clarifier area in the form of a shaded structure with single-axis panels. For weather data, Typical Meteorological Year (TMY) data, which is site-specific weather information was used. TMY2 (dataset spans 1961–1990) and TMY3 (dataset spans 1976–2005) weather information could be utilized. The PV system size was determined using the following equation [43]:

$$Ps = Ap \times Ip \times ep \tag{4}$$

Energy generated by the PV system can be determined using the following equation [44]:

$$E = Ap \times ep \times Is \times PR \tag{5}$$

where E = energy generated, kWh/day; Ps = PV system size, kW; Ap = Total panel Area (m^2), ep = panel efficiency = 20%, PR = performance ratio = 0.8 [18]. I_s is the average daily solar insolation on tilted panels, also called peak sun hours in kWh/m^2 per day. It represents long-term typical year solar resource data. The standard test condition for irradiance, I_p, is 1 kW/m^2, which is equal to one peak sun.

2.4. Greenhouse Gas Emissions

To compute the GHG emissions, equivalent carbon dioxide generation potential was used. Carbon dioxide equivalent (CO_{2e}) is the conversion of all GHG (most contributing:

carbon dioxide, methane, nitrous oxide, and fluorinated gases) into a common unit for ease of computing and reporting. The carbon emissions rate of various fuel types was obtained from [48,49], which determined the values as an average of emission rates obtained by literature review of about eleven studies. The emissions rates were determined for natural gas (605.9 g CO_{2e}/kWh), coal (1022.9 g CO_{2e}/kWh); hydroelectric (25.4 g CO_{2e}/kWh); geothermal (66.7 g CO_{2e}/kWh); and solar (70.8 g CO_{2e}/kWh) [48,49]. An energy fuel mix found in the southwestern United States was used, which includes 60% natural gas, 25% coal, 7% hydroelectric, 7% geothermal, and 1% solar [50]. The GHG emission rate used in this study for electrical energy was computed by taking the average of the product of energy fuel mix percentage and the GHG emission rates of various fuel types (626.4 g CO_{2e}/kWh consumed).

2.5. Economics

The economics of using anaerobic digesters and PV solar systems was analyzed using payback period. For capital costs of PV systems, the range varies widely based on the size and type of the system, and installation location. The National Renewable Energy Laboratory (NREL) publishes yearly benchmark costs for residential, commercial, and utility-scale PV systems [51–53]. In this research, [51], was referred to choose the economic parameters for commercial PV systems; for example, the capital cost for PV system located in Texas was $\$1.69/W_{dc}$, while for one located in Hawaii, it was $\$1.92/W_{dc}$. For this study, the average value of $\$1.8/W_{dc}$ was assumed [51].

A wide range in capital costs was also found for anaerobic digesters ($2570–$7000/kW) [54–56]. An average value of $5000/kW was assumed in this research. The estimates determined through literature review were based on the data collection from actual plants. The economic analysis in this study was conducted by estimating and comparing the payback period for both the anaerobic digester and the solar photovoltaics. An average commercial retail electricity price of $0.11/kWh [57] was used. A low, medium, and high energy price value was used for sensitivity analysis by changing the price by 20%.

3. Results and Discussion

Energy consumption estimates of the main energy driving and producing units for the anaerobic digester and PV solar system for varying flow rates in the WRP are presented in Table 4. Overall, net totals of the energy consumption and generation are also provided. For flow rates between 2.6 and 28.9 m^3/min (1 and 11 million gallons per day (MGD)), the heat-exchanger consumed on average 87.8% of the total energy consumed by the anaerobic digester for both MBR and CAS facilities. The mixers used inside the digester only utilized about 12.2% of the total operational energy consumption. Assuming a specific gravity of 1.01 for primary sludge, an average of 0.72 kWh/kg of sludge digested is generated by the anaerobic digester for both MBR and CAS facilities across all flows. Energy consumption in the anaerobic digestion process was found to be higher than values found in [47,58]. The energy consumption for an anaerobic digester of a 28.9 m^3/min (11 MGD) facility was reported as 1850 [47] and 236.35 [58] kWh/day, compared to 2687.02 kWh/day found in this research. This difference may be due to the combination of primary and secondary sludge [47]. For 28.9 m^3/min (11 MGD) flow rate, [47] reported a value of 3850 kWh/day for energy generation by the digester, which is 13.5% less than the value reported in this study (4451.8 kWh/day). This difference may be due to the type of energy generator used, as different generators have different efficiencies. If micro-turbines with an efficiency of 27% were used, the energy generated would be 3642.4 kWh/day for this study, thus only 5.4% less comparing to [47]. In addition, a pattern was seen in the anaerobic digester, as flow increases, the fraction of energy generated over energy consumed by the digester increased by an average of 3.1% across all flows.

Table 4. Estimated energy consumption and generation of anaerobic digester and photovoltaic solar system in a water reuse plant (kWh/day).

Renewables	Energy Driving & Producing Equipment	2.6 m^3/min (1 MGD)	5.3 m^3/min (2 MGD)	10.5 m^3/min (4 MGD)	15.8 m^3/min (6 MGD)	23.1 m^3/min (8.8 MGD)	28.9 m^3/min (11 MGD)
Anaerobic Digester	Mixers	32.67	64.69	96.63	188.19	277.88	343.06
	Heat-Exchanger	252.09	478.34	708.41	1345.50	1944.15	2343.96
	Total Consumption	284.76	543.04	805.04	1533.69	2222.03	2687.02
	ICE—Generation	404.71	809.42	1214.13	2428.25	3561.44	4451.8
	Net Total	119.95	266.38	409.09	894.56	1339.41	1764.78
Solar Photovoltaic System	Panel Generation—MBR Plant	155.28	313.58	627.26	940.95	1371.44	1714.3
	Panel Generation—CAS Plant	463.41	840.59	1681.29	2521.98	3767.83	4709.78

For flow rates between 2.6 and 28.9 m^3/min (1 and 11 MGD), energy generation of the PV solar system in CAS facilities was proven to be on average 2.75 times higher than that of MBR facilities due to the requirements of large real estate size. The real estate sizes and their corresponding PV system sizes can be found in Table 5. Future improvements in PV panel efficiency will make this energy generation even greater. Since 1954, PV solar cells have increased from a two percent panel efficiency to percentages of forty-seven plus in laboratory settings [46,59,60]. A value of 20% panel efficiency was used in this research.

Table 5. Estimated areas and system size for PV installation in reuse facilities with advanced and conventional treatment units.

Facility Type	Parameter	2.6 m^3/min (1 MGD)	5.3 m^3/min (2 MGD)	10.5 m^3/min (4 MGD)	15.8 m^3/min (6 MGD)	23.1 m^3/min (8.8 MGD)	28.9 m^3/min (11 MGD)
MBR Facility	Area (m^2)	153.8	310.6	621.3	932	1358.4	1698
	System size (kW)	30.76	62.12	124.26	186.4	271.68	339.6
CAS Facility	Area (m^2)	459	832.6	1665.3	2498	3732	4665
	System size (kW)	91.8	166.52	333.06	499.6	746.4	933

Table 6 summarizes energy generation from advanced and traditional treatment facilities, incorporating anaerobic digestion and solar PV individually and in conjunction per unit flow. These values were derived by dividing the energy consumption/generation per day by the unit flow per day, resulting in energy consumption/generation per million cubic meters (kWh/m^3). Energy consumption patterns were as expected, with the consumption of energy per unit volume decreasing as treatment capacity increased [47]. In addition, energy production patterns were also similar to [47] as energy recovery in anaerobic digestion stayed constant on a per unit volume basis. This is the result of primary sludge increasing proportionally as flow increased. For both MBR and CAS facilities, using flow rates between 2.6 and 28.9 m^3/min (1 and 11 MGD), an average net total of 102.6 kWh/1000 m^3 is generated by the anaerobic digester. This correlates to an average of 14.7% of the MBR and 28% for the CAS facility's total energy consumption. Assuming an average commercial electrical energy rate of $0.11 USD/kWh, the savings in energy costs by the anaerobic digester is $11.29/1000 m^3 treated. On average, PV solar energy however only generates 41.3 kWh/1000 m^3 for MBR facilities and 113.6 kWh/1000 m^3 for CAS facilities. This produces on average of 5.9% of the total energy consumption for MBR facilities and 31.1% for CAS facilities; resulting in a savings of $4.5/1000 m^3 treated at MBR facilities and $12.5/1000 m^3 treated at CAS facilities, not including the capital costs of the anaerobic digester.

Table 6. Energy consumption and generation per unit flow of the anaerobic digester and photovoltaic solar system.

Facility Type	**Unit Process**	**Energy Consumption Per Unit Flow (kWh/1000 m^3)**						
		2.6 m^3/min (1 MGD)	**5.3 m^3/min (2 MGD)**	**10.5 m^3/min (4 MGD)**	**15.8 m^3/min (6 MGD)**	**23.1 m^3/min (8.8 MGD)**	**28.9 m^3/min (11 MGD)**	**Average**
MBR Facility	Wastewater Treatment Total	723.4	709.1	700.9	696.7	680.1	680.1	698.4
	Anaerobic Digester	75.2	71.7	53.2	67.5	66.7	64.5	66.5
	Anaerobic Digester Generation	107.0	107.0	80.3	107.0	107.0	107.0	102.6
	Net Total w/Digester	691.7	674.0	674.0	657.3	639.9	637.5	662.4
	Photovoltaic System Generation	41.03	41.42	41.43	41.43	41.17	41.17	41.28
	Net Total w/PV	682.37	667.68	659.47	655.27	638.93	638.93	657.12
	Net Total w/Digester and PV	650.67	632.58	632.57	615.87	598.77	596.33	621.12
CAS Facility	Wastewater Treatment Total	390.0	368.6	360.1	358.0	358.8	356.4	365.3
	Anaerobic Digester	75.2	71.7	53.2	67.5	66.7	64.5	66.5
	Anaerobic Digester Generation	107.0	107.0	80.3	107.0	107.0	107.0	102.6
	Net Total w/Digester	358.3	333.4	333.2	318.6	318.6	313.9	329.3
	Photovoltaic System Generation	122.43	111.04	111.05	111.05	113.12	113.12	113.64
	Net Total w/PV	267.57	257.56	249.05	246.95	245.68	243.28	251.66
	Net Total w/Digester and PV	235.87	222.36	222.15	207.55	205.48	200.78	215.66

The low energy generation observed with solar energy is due to panels being incorporated over the basin and membrane/clarifier area only. The solar energy generation can be greatly increased if panels were to be placed on top of building structures, parking shade structures, or around the facility itself. Further, the size of the PV systems at WWTPs is not an indicator of the treatment capacity of the facility. For instance, an 819 kW PV system was installed at a 11 m^3/min (4.2 MGD) facility [61] while 1000 kW PV systems were installed at 65.7 to 84 m^3/min (25 and 32 MGD) facilities [23]. In this research, however, incorporating solar energy on structures was not evaluated because facility layout and design was not developed in this research. A sensitivity analysis was performed on solar panel efficiency. If a low panel efficiency value of 15% was used [26,30,31], this would result in a reduction of 25.0% of the energy generated by the panels. If a high panel efficiency of 23% was used [62], an increase in energy generation of 15.0% would result.

The temporal aspects of the PV production are to be in-sync with the electric demands and are important considerations in PV design. The energy consumption of the WRPs, estimated in this study, is the electric load input for the PV sizing, and is representative of the worst-case scenario for the digester. In this study, the PV system was sized for the WRP using acreage available from basin and membrane/clarifier area, thus land area availability was the limiting factor for PV sizing. The meteorological data used for PV sizing represents the long-term typical year solar resource data. Hence, the PV production estimates, computed by using this data, are also long-term typical year values. The solar PV's total monthly and yearly production can differ from the long-term typical value, by about ±30% and ±10%, respectively [43]. This is a simplistic study to evaluate the renewable energy generation potential of a water reuse plant by incorporating and comparing the use of solar PVs with an anaerobic digester. Approach of using simplistic PV design is acceptable since PVs is only being used as an auxiliary power supply, to offset a relatively small portion of the overall energy consumption of the WRP. Further, solar PVs can only be used during the daytime to offset the energy consumption. The WRP is still connected to the electric grid for the 24-h supply of electricity. The intermittency of the PV system generation can be overcome using grid-connected electricity.

For CAS and MBR facilities, an average energy saving of 33.2% and 9.6%, respectively, was accomplished when both anaerobic digestion and solar energy were incorporated in the WRP. Using an average commercial retail electricity price of \$0.11/kWh [57], total savings of \$8.5/1000 m^3 (77.3 kWh/1000 m^3) for MBR facilities and \$16.5/1000 m^3 (149.6 kWh/1000 m^3) for CAS facilities were achieved, not including the capital costs of both the anaerobic digester and solar system. If 100% of the energy consumption were to be offset at each facility by solar generation, a 16.9 times increase of available real estate area on average would be required at the MBR facilities and a 3.2 times increase at the CAS facilities. If 50% of the energy consumption were to be offset, an 8.5 times increase in available real estate area is required at MBR facilities and a 1.6 times increase at CAS facilities. However, these options will require either storage or a net metering arrangement with utility.

Table 7 shows the payback period in years, for both the energy generating systems for a low, medium, and high energy price. For all cases in the table, PV solar systems will take approximately 30% longer to pay back compared to anaerobic digesters. However, in recent decades due to the growth in technologies, capitals costs for PV systems have declined rapidly. Reference [51] reported that the cost of residential, commercial, and utility-scale PV systems was $2.7/Wdc, $1.8/Wdc, and $1/Wdc in 2018, respectively, compared to $7.3/Wdc, $5.4/Wdc, and $5.1/Wdc, in 2010, respectively. These benefits have resulted in about a 30% growth in PV systems per year and are estimated to be the largest renewable energy source providing a production of 25.1% of the total global power generation by 2040 [13].

Table 7. Cost evaluation of photovoltaic system and anaerobic digester.

Renewables	Energy Price ($/kWh)	Payback (years)
Photovoltaic System	0.09	11.1
	0.11	9.0
	0.13	7.6
Anaerobic Digester	0.09	8.2
	0.11	6.4
	0.13	5.2

Figure 2 visualizes the energy saving trends when comparing advanced and conventional treatment facilities, with and without incorporating energy generating units. The MBR WRP with energy generating units is on average 2.9 times more energy intensive than the CAS WRP. This is an even greater increase in energy consumption difference compared to MBR WRPs being 1.9 times more energy intensive than CAS WRPs without including energy generating units.

Table 8 summarizes the GHG emissions of each unit process per unit flow in terms of kg CO_2/1000 m^3. Totals are also provided for each scenario with energy generating units. As with energy consumption, GHG emissions with MBRs were 1.9 and 2.9 times more intensive without and with energy generating units at the facilities, respectively, compared to emissions at CAS facilities. In MBR WRPs, an average decrease of 11.1% in emissions was observed when energy-generating units were used; and 41% for CAS WRPs. Even with energy generating units at advanced and conventional treatment WRPs, GHG emissions were still relatively large. For instance, at the 23.1 m^3/min (8.8 MGD) MBR WRP, GHG emissions without energy generating units were 14,190 kg CO_2e/day and with energy-generating units the emissions were 12,490 kg CO_{2e}/day (Figure 3). This however is a reduction of 1700 kg CO_2e/day, which is equivalent to the burning of 3.9 barrels of oil a day, the use of 134 passenger vehicles a day, or the electricity use of about 72 single-family homes a day [63].

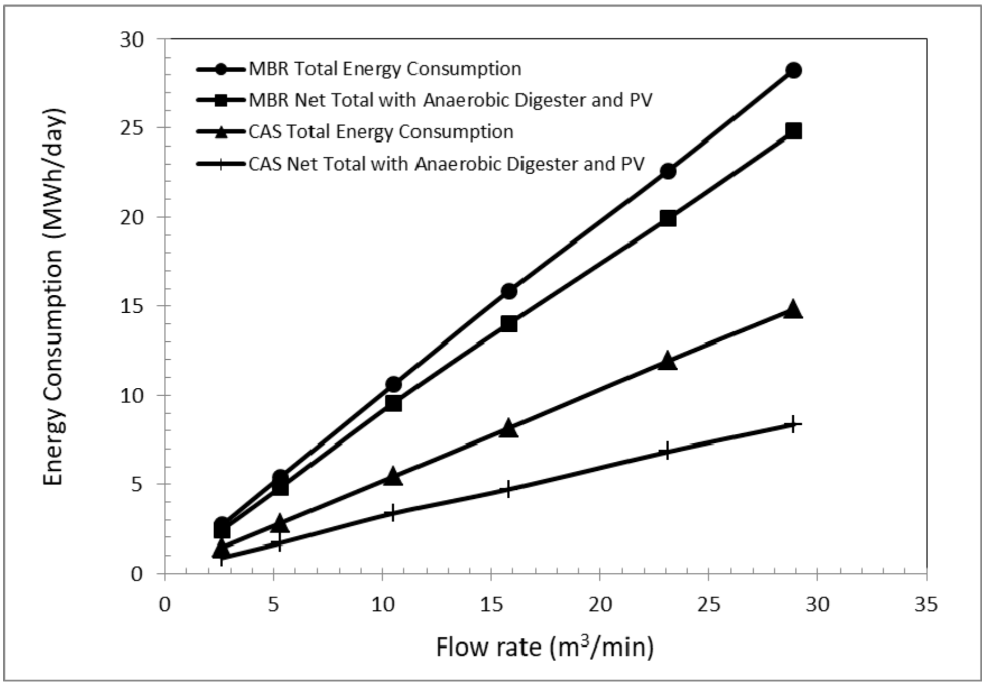

Figure 2. Energy comparison of advanced and conventional treatment facilities with and without incorporating energy generating units.

Table 8. Greenhouse gas (GHG) emissions of each unit process per unit flow.

Facility Type	**Unit Process**	**GHG Emissions Per Unit Flow (kg CO_{2e}/1000 m^3)**						
		2.6 m^3/min (1 MGD)	**5.3 m^3/min (2 MGD)**	**10.5 m^3/min (4 MGD)**	**15.8 m^3/min (6 MGD)**	**23.1 m^3/min (8.8 MGD)**	**28.9 m^3/min (11 MGD)**	**Average**
MBR Facility	Coarse Screens	0.19	0.10	0.05	0.03	0.02	0.03	0.07
	Grit Chamber	17.8	10.4	7.4	5.9	4.7	4.0	8.4
	Fine Screens	5.9	3.0	1.5	1.0	0.7	0.8	2.2
	Bioreactor	263.4	263.8	263.8	263.8	266.0	266.0	264.5
	Membranes	149.6	149.6	149.6	149.6	138.9	138.9	146.0
	UV Disinfection	16.2	17.4	16.7	16.1	15.8	16.2	16.4
	Total	453.2	444.2	439.1	436.5	426.0	425.9	437.5
	Anaerobic Digester	47.1	44.9	33.3	42.3	41.8	40.4	41.6
	Anaerobic Digester GHG Savings	67.0	67.0	50.2	67.0	67.0	67.0	64.2
	Net Total w/Digester	433.3	422.2	422.1	411.8	400.8	399.4	414.9
	Photovoltaic System GHG Savings	25.70	25.95	25.95	25.95	25.79	25.79	25.86
	Net Total w/PV	427.44	418.23	413.09	410.46	400.23	400.23	411.62
	Net Total w/Digester and PV	407.58	396.25	396.24	385.78	375.07	373.54	389.07
CAS Facility	Coarse Screens	0.19	0.10	0.05	0.03	0.02	0.03	0.07
	Grit Chamber	17.8	10.4	7.4	5.9	4.7	4.0	8.4
	Fine Screens	5.9	3.0	1.5	1.0	0.7	0.8	2.2
	CAS	195.3	192.7	192.7	192.7	194.6	194.6	193.8
	Secondary Clarifier	1.5	1.1	1.1	1.1	1.0	1.0	1.1
	Dual Media Filters	0.8	0.8	0.6	0.6	0.5	0.5	0.6
	UV Disinfection	22.8	22.8	22.3	23.0	23.1	22.2	22.7
	Total	244.3	230.9	225.6	224.2	224.7	223.2	228.8
	Anaerobic Digester	47.1	44.9	33.3	42.3	41.8	40.4	41.6
	Anaerobic Digester GHG Savings	67.0	67.0	50.2	67.0	67.0	67.0	64.2
	Net Total w/Digester	224.4	208.8	208.7	199.5	199.5	196.7	206.3
	Photovoltaic System GHG Savings	76.69	69.56	69.56	69.56	70.86	70.86	71.18
	Net Total w/PV	167.61	161.34	156.0	154.69	153.89	152.39	157.64
	Net Total w/Digester and PV	147.75	139.29	139.15	130.01	128.71	125.77	135.09

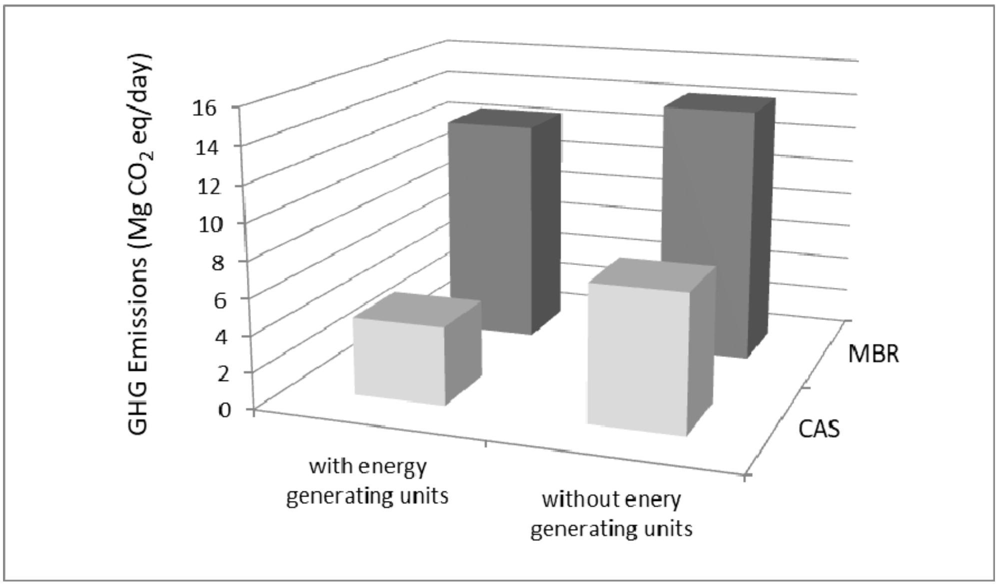

Figure 3. Greenhouse gas emissions due to electrical energy consumption with and without incorporating energy generating units at 23.1 3 m^3/min (8.8 MGD) flow rate.

4. Conclusions

This research evaluated the renewable energy generation potential of a satellite WRP with the addition of a PV solar system and anaerobic digestion. This was performed for two types of facilities: conventional (CAS bioreactor with secondary clarifiers and dual media filtration) and advanced (bioreactor with membrane filtration) treatment satellite WRPs. In addition, the associated GHG emissions for both conventional and advanced treatment processes were evaluated. For conventional treatment, it was found that 28% and 31.1% of the facility's total energy consumption could be generated by anaerobic digestion and solar energy, respectively. For advanced treatment, 14.7% and 5.9% of the facility's total energy consumption could be generated by anaerobic digestion and solar energy, respectively. It was observed that energy recovery generation for both anaerobic digestion and PV systems was constant on unit volume basis. When both energy-generating units were incorporated in satellite WRPs, an average energy savings of 33.2% was accomplished in a CAS facility and 9.6% in a MBR facility, resulting in MBR WRPs being on average 1.86 times more energy intensive than CAS WRPs. This translates to a cost savings in electricity of \$7.4/1000 m^3 treated for MBR facilities and \$13.3/1000 m^3 treated at CAS facilities, using an average commercial energy rate of \$0.110/kWh. The payback periods for both anaerobic digestion and solar energy were investigated, and it was found that solar energy requires on average 30% longer to pay back compared to anaerobic digestion.

Furthermore, the results of this research showed that in terms of GHG emissions, MBR WRPs without incorporating energy-generating units were 1.9 times more intensive than CAS WRPs and 2.9 times more intensive with energy generating units. With or without energy generating units, GHG emissions were still very large at WRPs. On average for MBR WRPs, 437.5 and 389.1 kg CO_2e/1000 m^3 treated were emitted without and with energy generating units at the facilities, respectively. For CAS WRPs, 228.8 kg and 135.1 CO_{2e}/1000 m^3 treated were emitted at facilities without and with energy generating units, respectively.

Energy consumption estimates in this study were determined by using industry-accepted design criteria. This research has shown that with the addition of energy generating units the energy consumption of the WRP can be greatly decreased. The generated numbers can be used to determine and compare the energy consumption estimates of other WRPs at other locations. Performing such energy analysis can assist researchers, design engineers, and operators in the decision-making process regarding the sustainability of utilizing advanced or conventional treatment technologies at a reuse facility. These kinds of studies assist in expanding on the efforts of water reuse, as well as incorporating sustainability initiatives into the design of water reuse infrastructure. Using renewables for energy generation for water reuse assists in improving environmental and public health because of reduction in GHG emissions. The term “energy hog” is often used for satellite WRPs. With time, as more energy offset measures are implemented, satellite WRPs will have the prospective to be termed “energy neutral” facilities.

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References

1. Dow, C.; Ahmad, S.; Stave, K.; Gerrity, D. Evaluating the Sustainability of IPR and DPR: A Southern Nevada Case Study. *AWWA Water Sci.* **2019**. [CrossRef] [PubMed]
2. Venkatesan, A.K.; Ahmad, S.; Johnson, W.; Batista, J.R. Salinity Reduction and Energy Conservation in Direct and Indirect Potable Water Reuse. *Desalination* **2011**, *272*, 120–127. [CrossRef]
3. Bailey, J.R. *Investigating the Impacts of Conventional and Advanced Treatment Technologies on Energy Consumption at Satellite Water reuse Plants*; University of Nevada: Las Vegas, NV, USA, 2012.
4. Shoushtarian, F.; Negahban-Azar, M. Worldwide Regulations and Guidelines for Agricultural Water Reuse: A Critical Review. *Water* **2020**, *12*, 971. [CrossRef]
5. U.S. Environmental Protection Agency (USEPA). 2019. Available online: https://www.epa.gov/waterreuse (accessed on 25 December 2019).
6. Amoueyan, E.; Ahmad, S.; Eisenberg, J.N.S.; Pecson, B.; Gerrity, D. Quantifying pathogen risks associated with potable reuse: A risk assessment case study for Cryptosporidium. *Water Res.* **2017**. [CrossRef]
7. Amoueyan, E.; Ahmad, S.; Eisenberg, J.N.S.; Gerrity, D. Equivalency of Indirect and Direct Potable Reuse Paradigms based on a Quantitative Microbial Risk Assessment Framework. *Microb. Risk Anal.* **2019**. [CrossRef]
8. Amoueyan, E.; Ahmad, S.; Eisenberg, J.; Gerrity, D. A Dynamic Quantitative Microbial Risk Assessment for Norovirus in Potable Reuse Systems. *Microb. Risk Anal.* **2019**. [CrossRef]
9. Bukhary, S.; Batista, J.; Ahmad, S. Sustainable Desalination of Brackish Groundwater for the Las Vegas Valley. In *World Environmental and Water Resources Congress*; American Society of Civil Engineers: Reston, VA, USA, 2018; pp. 311–322.
10. Water Environment Federation (WEF). *Design of Municipal Wastewater Treatment Plants: WEF Manual of Practice No. 8*; McGraw-Hill: New York, NY, USA, 2010.
11. Bailey, J.R.; Ahmad, S.; Batista, J.R. The Impact of Advanced Treatment Technologies on the Energy Use in Satellite Water Reuse Plants. *Water* **2020**, *12*, 366. [CrossRef]
12. Conti, J.; Holtberg, P.; Diefenderfer, J.; LaRose, A.; Turnure, J.T.; Westfall, L. *International Energy Outlook 2016 with Projections to 2040 (No. DOE/EIA-0484 (2016)*; USDOE, Energy Information Administration (EIA), Office of Energy Analysis: Washington, DC, USA, 2016.
13. Demirbas, A. Global renewable energy projections. *Energy Sources Part B* **2009**, *4*, 212–224. [CrossRef]
14. Chen, C.; Kalra, A.; Ahmad, S. Hydrologic responses to climate change using downscaled GCM data on a watershed scale. *J. Water Clim. Chang.* **2019**, *10*, 63–77. [CrossRef]
15. Tamaddun, K.A.; Kalra, A.; Ahmad, S. Spatiotemporal Variation in the Continental US Streamflow in Association with Large-Scale Climate Signals Across Multiple Spectral Bands. *Water Resour. Manag.* **2019**. [CrossRef]
16. Saher, R.; Stephen, H.; Ahmad, S. Urban evapotranspiration of Green Spaces in Arid Regions through Two Established Approaches: A Review of Key Drivers, Advancements, Limitations, and Potential Opportunities. *Urban Water J.* **2021**. [CrossRef]

17. Boden, T.A.; Marland, G.; Andres, R.J. *National CO2 Emissions from Fossil-Fuel Burning, Cement Manufacture, and Gas Flaring: 1751–2014*; Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, US Department of Energy: Oak Ridge, TN, USA, 2017.
18. Bukhary, S.; Ahmad, S.; Batista, J. Analyzing land and water requirements for solar deployment in the Southwestern United States. *Renew. Sustain. Energy Rev.* **2018**, *82*, 3288–3305. [CrossRef]
19. Gormus, N.A.; Soytas, U.; Diltz, J.D. Oil prices, fossil-fuel stocks and alternative energy stocks. *Int. J. Econ. Financ.* **2015**, *7*, 43–55. [CrossRef]
20. United Nations Educational, Scientific and Cultural Organization (UNESCO). The United Nations World Water Development Report 2020: Water and Climate Change. 2020. Available online: https://unesdoc.unesco.org/ark:/48223/pf0000372985.locale=en (accessed on 30 June 2002).
21. US Environmental Protection Agency (USEPA). 2019. Available online: https://www.epa.gov/sustainablewater-infrastructure/energy-efficiency-water-utilities (accessed on 25 December 2019).
22. Meng, F.; Liu, G.; Liang, S.; Su, M.; Yang, Z. Critical review of the energy-water-carbon nexus in cities. *Energy* **2019**, *171*, 1017–1032. [CrossRef]
23. Seeta, V.; Thakral, S.; Sun, L.; Meyer, Z. "Free" Solar Power—A Big Leap Towards Energy Self-Sufficiency at WWTPs. *Proc. Water Environ. Fed.* **2011**, *2011*, 5588–5598. [CrossRef]
24. Di Maria, F.; Micale, C. Energetic potential of the co-digestion of sludge with bio-waste in existing wastewater treatment plant digesters: A case study of an Italian province. *Energy* **2017**, *136*, 110–116. [CrossRef]
25. Strazzabosco, A.; Kenway, S.J.; Lant, P.A. Solar PV adoption in wastewater treatment plants: A review of practice in California. *J. Environ. Manag.* **2019**, *248*, 109337. [CrossRef] [PubMed]
26. Bukhary, S.; Batista, J.; Ahmad, S. Design Aspects, Energy Consumption Evaluation, and Offset for Drinking Water Treatment Operation. *Water* **2020**, *12*, 1772. [CrossRef]
27. Bukhary, S.; Batista, J.; Ahmad, S. Evaluating the Feasibility of Photovoltaic-Based Plant for Potable Water Treatment. In *World Environmental and Water Resources Congress*; American Society of Civil Engineers: Sacramento, CA, USA, 2017; pp. 256–263.
28. U.S. Energy Information Administration (USEIA). 2020. Available online: https://www.eia.gov/todayinenergy/detail.php?id=43895 (accessed on 30 June 2020).
29. U.S. Energy Information Administration (USEIA). 2020. Available online: https://www.eia.gov/energyexplained/electricity/electricity-in-the-us.php (accessed on 30 June 2020).
30. Bukhary, S.; Batista, J.; Ahmad, S. Water-energy-carbon nexus approach for sustainable large-scale drinking water treatment operation. *J. Hydrol.* **2020**, *587*, 124953. [CrossRef]
31. Bukhary, S.; Batista, J.; Ahmad, S. An Analysis of Energy Consumption and the Use of Renewables for a Small Drinking Water Treatment Plant. *Water* **2020**, *12*, 28. [CrossRef]
32. Bukhary, S.; Weidhaas, J.; Ansari, K.; Mahar, R.B.; Pomeroy, C.; VanDerslice, J.A.; Burian, S.; Ahmad, S. Using Distributed Solar for Treatment of Drinking Water in Developing Countries. In *World Environmental and Water Resources Congress*; American Society of Civil Engineers: Sacramento, CA, USA, 2017; pp. 264–276.
33. Metcalf, L.; Eddy, H.P.; Tchobanoglus, G.; Burton, F.; Stensel, H.D. *Wastewater Engineering: Treatment and Reuse*; McGraw Hill: New York, NY, USA, 2003.
34. Horstmeyer, N.; Weibbach, M.; Koch, K.; Drewes, J.E. A novel concept to integrate energy recovery into potable water reuse treatment schemes. *J. Water Reuse Desalin.* **2018**, *8*, 455–467. [CrossRef]
35. Kavvada, O.; Horvath, A.; Stokes-Draut, J.R.; Hendrickson, T.P.; Eisenstein, W.A.; Nelson, K.L. Assessing location and scale of urban nonpotable water reuse systems for life-cycle energy consumption and greenhouse gas emissions. *Environ. Sci. Technol.* **2016**, *50*, 13184–13194. [CrossRef]
36. Malinowski, P.A.; Stillwell, A.S.; Wu, J.S.; Schwarz, P.M. Energy-water nexus: Potential energy savings and implications for sustainable integrated water management in urban areas from rainwater harvesting and gray-water reuse. *J. Water Resour. Plan. Manag.* **2015**, *141*, A4015003. [CrossRef]
37. Water Environment Federation (WEF). *Membrane Bioreactors: WEF Manual of Practice No. 36*; McGraw-Hill: New York, NY, USA, 2012.
38. Water Environment Federation (WEF). *Nutrient Removal: WEF Manual of Practice No. 34*; McGraw-Hill: New York, NY, USA, 2011.
39. Qasim, S.R. *Wastewater Treatment Plants: Planning, Design, and Operation*; CRC Press: Boca Raton, FL, USA, 1999; ISBN 1-56676-688-5.
40. Davis, M.L. *Water and Wastewater Engineering: Design Principles and Practice*; McGraw Hill: New York, NY, USA, 2010; ISBN 978-0-07-171384-9.
41. Lin, S.D. *Water and Wastewater Calculations Manual*, 2nd ed.; McGraw Hill: New York, NY, USA, 2007; ISBN 0-07-147624-5.
42. National Renewable Energy Laboratory (NREL). Solar Resource Data, Tools, and Maps. 2018. Available online: https://www.nrel.gov/gis/solar.html (accessed on 1 July 2020).
43. National Renewable Energy Laboratory (NREL). *PVWatts®Calculator*; PVWatts®: Golden, CO, USA, 2020. Available online: http://pvwatts.nrel.gov (accessed on 1 October 2020).
44. U.S. Environmental Protection Agency (USEPA). 2020. Available online: https://www.epa.gov/greenpower/green-power-equivalency-calculator-calculations-and-references (accessed on 26 October 2020).

45. Khalid, A.M.; Mitra, I.; Warmuth, W.; Schacht, V. Performance ratio–Crucial parameter for grid connected PV plants. *Renew. Sustain. Energy Rev.* **2016**, *65*, 1139–1158. [CrossRef]
46. Green, M.A. Silicon photovoltaic modules: A brief history of the first 50 years. *Prog. Photovolt. Res. Appl.* **2005**, *13*, 447–455. [CrossRef]
47. Water Environment Federation (WEF). *Energy Conservation in Water and Wastewater Facilities: WEF Manual of Practice No. 32*; McGraw-Hill: New York, NY, USA, 2010.
48. Shrestha, E.; Ahmad, S.; Johnson, W.; Shrestha, P.; Batista, J.R. Carbon footprint of water conveyance verses desalination as alternatives to expand water supply. *Desalination* **2011**, *280*, 33–43. [CrossRef]
49. Shrestha, E.; Ahmad, S.; Johnson, W.; Batista, J.R. The carbon footprint of water management policy options. *Energy Policy* **2012**, *42*, 201–212. [CrossRef]
50. U.S. Energy Information Administration (USEIA). 2010. Available online: http://www.eia.gov/electricity/annual/ (accessed on 20 July 2012).
51. Fu, R.; Feldman, D.J.; Margolis, R.M. *US Solar Photovoltaic System Cost Benchmark: Q1 2018 (No. NREL/TP-6A20-72399)*; National Renewable Energy Lab (NREL): Golden, CO, USA, 2018.
52. Fu, R.; Feldman, D.; Margolis, R.; Woodhouse, M.; Ardani, K. *US Solar Photovoltaic System Cost Benchmark: Q1 2017 (No. NREL/TP-6A20-68925)*; National Renewable Energy Lab (NREL): Golden, CO, USA, 2017.
53. Fu, R.; Chung, D.; Lowder, T.; Feldman, D.; Ardani, K.; Margolis, R. *US Solar Photovoltaic System Cost Benchmark: Q1 2016 (No. NREL/TP-6A20-66532)*; National Renewable Energy Lab (NREL): Golden, CO, USA, 2016.
54. Navaratnasamy, M.; Edeogu, I.; Papworth, L. *Economic Feasibility of Anaerobic Digesters*; Alberta Agriculture and Rural Development: Edmonton, AB, Canada, 2008.
55. Gielen, D. *Biomass for Power Generation, Renewable Energy Technologies: Cost Analysis Series*; International Renewable Energy Agency: Bonn, Germany, 2012.
56. Steele, L.; Sampsel, Z.N. *Final Report for Clean, Reliable, Affordable Energy that Reflects the Values of the Pinoleville Pomo Nation (No. DOE-PPN-0002518)*; US Department of Energy (USDOE), Office of Energy Efficiency and Renewable Energy (EERE): Washington, DC, USA, 2014.
57. U.S. Energy Information Administration (USEIA). 2018. Available online: https://www.eia.gov/electricity/data/browser/#/topic/7?agg=0,1&geo=g&endsec=4&linechart=~{}&freq=A&start=2005&end=2013&chartindexed=1&ctype=linechart&ltype=pin&rtype=s&maptype=0&rse=0&pin= (accessed on 30 October 2020).
58. Pirnie, M. *Wastewater Treatment and Sludge Management: Energy Reference Guide*; New York State Energy Research and Development Authority: Buffalo, NY, USA, 1995.
59. Spanggaard, H.; Krebs, F.C. A brief history of the development of organic and polymeric photovoltaics. *Sol. Energy Mater. Sol. Cells* **2004**, *83*, 125–146. [CrossRef]
60. National Renewable Energy Laboratory (NREL). Best Research-Cell Efficiency Chart. 2019. Available online: https://www.nrel.gov/pv/cell-efficiency.html (accessed on 1 July 2020).
61. Drainville, M.; Rudenko, A.; Saad, D.; Doyle, P.S. Reducing the Carbon Footprint of the Hyannis WPCF Through Renewable Energy Production and Energy Efficiency Measures. *Proc. Water Environ. Fed.* **2011**, *2011*, 1493–1509. [CrossRef]
62. Stanislawski, B.; Margairaz, F.; Cal, R.B.; Calaf, M. Potential of module arrangements to enhance convective cooling in solar photovoltaic arrays. *Renew. Energy* **2020**, *157*, 851–858. [CrossRef]
63. U.S. Environmental Protection Agency (USEPA). 2012. Available online: http://www.epa.gov/cleanenergy/energy-resources/refs.html (accessed on 18 September 2012).