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Review

A Review of Renewable Energy Technologies in Municipal Wastewater Treatment Plants (WWTPs)

Derick Lima [1], Li Li [1,*] and Gregory Appleby [2]

[1] School of Electrical and Data Engineering, University of Technology Sydney, Sydney, NSW 2007, Australia; 13699638@student.uts.edu.au
[2] Sydney Water Corporation, Sydney, NSW 2124, Australia; gregappleby70@gmail.com
* Correspondence: li.li@uts.edu.au

Abstract: The global trend towards sustainable development has included the implementation of renewable energy recovery technologies in municipal wastewater treatment plants (WWTPs). WWTPs are energy-intensive consumers with high operational costs and often are dependent from the electricity supplied by the main grid. In this context, the integration of renewable energy recovery technologies into WWTPs emerges as an environment-friendly strategy that enhances energy efficiency, sustainability and reduces energy operating costs. Renewable energy recovery technologies, such as anaerobic digestion, microbial fuel cells, and sludge gasification, can offer multiple benefits for a WWTP. Anaerobic digestion is the most widely adopted technology due to its efficiency in treating sewage sludge and its ability to generate biogas—a valuable renewable energy source. The use of biogas can offset the energy demands of the wastewater treatment process, potentially leading to energy self-sufficiency for the WWTP and a reduction in reliance from the electricity supply from the main grid. Similarly, microbial fuel cells harness the electrochemical activity of bacteria to produce electricity directly from wastewater, presenting a promising alternative for low-energy processes for sustainable power generation. Gasification of sewage sludge is a promising technology for managing municipal sewage sludge, offering key advantages, especially by generating a renewable energy production (sludge is converted into syngas), which further decreases the sludge volume and operating costs with sludge management, helps to eliminate odour associated with sewage sludge, and effectively destroys the pathogens. Adoption of renewable energy sources in WWTPs can be a great alternative to overcome issues of high operating costs and high dependency of electricity from the main grid, but their successful integration requires addressing challenges such as technological maturity, economic feasibility, and regulatory frameworks. This study aims to comprehensively explore the significance of different renewable energy technologies in municipal WWTPs, including site-specific and non-site-specific sources, evaluating their impact on sustainability, energy efficiency, and overall operational effectiveness. This review also highlights some studies in which different strategies were adopted to generate extra revenue and/or reduce operating costs. Through a comprehensive review of current practices and emerging technologies, this study underscores the transformative potential of these innovations in advancing low-emission wastewater management.

Keywords: wastewater treatment plants (WWTP); renewable energy resources; sewage sludge

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1. Introduction

Wastewater treatment plants (WWTPs) are an essential component of a municipal system. These facilities receive raw municipal wastewater, treat it and send the treated effluent back to the environment [1]. WWTPs are large energy consumers, requiring a significant amount of electricity for their operation. Treating municipal wastewater is a complex and costly process; for example, the energy costs can range from 2% to 60% of the total operating costs, depending on the level of treatment used [2]. On average, the energy required to treat 1 million liters of sewage is between 150 to 1400 kWh. The reason for this energy range may be associated with several factors, such as treatment levels, facility capacity, energy efficiency, operational processes, and regulatory requirements [3]. In addition, due to more stringent effluent standards and the increase in the volume of wastewater generated globally, energy demand for WWTPs has been increasing [4].

With rising electricity costs, sustainability targets, and efficiency goals, more and more plants are looking for alternatives to minimise their operating costs and reduce carbon emissions while increasing their energy efficiency [1]. A commonly used technology for treating wastewater in WWTPs is anaerobic digestion (AD), and through this process, biogas is generated from the sludge treatment. Although energy recovery from AD is a very mature and common alternative, other emerging renewable energy technologies are arising as complementary sources to improve the potential of energy production in WWTPs [3]. Renewable energy technologies can significantly decrease a plant's overall energy demand and, in some cases, help energy-intensive consumers move toward energy self-sufficiency or even energy positivity. For example, several WWTPs in the USA (i.e., East Bay Municipal Utility District, Gresham, Gloversville-Johnstown Joint, Point Loma, and Sheboygan Regional) and Europe (Aquaviva, Greves-muhlen, Strassim, Wolfgangsee-Ischl, and Zillertal) have implemented different strategies to reach self-sufficiency, including the adoption of renewable energy technologies and co-digestion [5]. Another possibility to reduce energy costs is to participate in demand-response programs and demand-side management [6].

A large number of studies have been conducted on this topic of renewable energy generation in WWTPs. Some studies have focused on a particular technology, including anaerobic digestion [7], fuel cells [8], combined heat and power (CHP) technologies [9], supercritical water gasification [10], hydrothermal liquefaction [11], thermochemical conversion processes [12], and hybrid systems [13]. Some reviews explored new technologies not widely implemented in large-scale plants, including dark fermentation (DF), photocatalysis, photo-fermentation (PF), microbial photoelectrochemical cells (MPEC) [14], Microbial Electrolysis Cells (MECs) [15], microbial fuel cells (MFCs) [16], and biodiesel [17]. Other studies explored different strategies and market opportunities for WWTPs, including demand-response and demand-side management [6] and energy spot markets [18]. Although review papers covering different types of renewable energy technologies adopted in WWTPs have been conducted, few articles have considered and summarised multiple technologies in one comprehensive review. In this context, this review paper aims to comprehensively review the different types of energy technologies that can be used in WWTPs, including site-specific and non-site-specific sources. These technologies can lead WWTPs to be less dependent on importing electricity from the main grid, become more energy-sustainable and reduce operating costs. In addition, this review also included some alternatives that these facilities can explore to generate extra revenue and/or reduce operating costs, including providing grid services. The main contribution of this paper is to summarise the several types of renewable energy technologies that can be used in WWTPs in one review paper which can provide a comprehensive, balanced, and forward-thinking overview on this topic.

This literature review was conducted by searching related works in the academic literature and government and industry reports. To conduct this study, two research questions were included: Which types of site-specific and non-site-specific renewable energy technologies can be used in WWTPs? Which strategies and opportunities can be explored by WWTPs to increase revenues and benefits? Based on the research questions, the following research objectives were developed: (1) review different renewable energy technologies, including site-specific and non-site-specific that can be adopted by WWTPs, and (2) investigate strategies and opportunities WWTPs can consider to increase revenues and/or reduce operating costs. As the first step, the literature search was conducted primarily using three online databases—Scopus, IEEE Xplore, and ScienceDirect—for academic papers published in journals and conference proceedings. Despite limitations, this work aims to provide a rigorous and comprehensive review of energy generation in WWTPs. Therefore, it is expected that the insights and results from this study will be useful in generating a clear, structured, and comprehensive understanding of the current state-of-the-art of renewable energy generation opportunities in WWTPs.

This paper is organised as follows. Section 2 presents a short WWTP overview. Section 3 explores different energy technologies that can be adopted in WWTPs for energy recovery and power generation. Section 4 explores some market strategies that were used by WWTPs to generate revenues, including providing grid services, demand-response participation, and exposure to the spot electricity market. Challenges and opportunities for WWTPs in adopting renewable energy sources (RES) and providing grid services Section 4. This review is concluded in Section 5.

2. WWTP Overview

The main objective of a WWTP is to accelerate the natural process of purifying wastewater and return it back to the environment. The wastewater treated by WWTPs, also known as effluent, must meet quality standards and regulatory requirements (i.e., solids, carbon, phosphorus and nitrogen limits). The effluent's discharge standards can be defined by the state, territory, or on a national level. They can also vary from plant to plant depending on different factors, such as age, impact on waterways, and treatment capacity. WWTPs may differ in size, capacity, efficiency, effluent quality requirements, and type of treatment processes. In terms of treatment process, wastewater plants can be composed of one (primary), two (secondary), or three (tertiary) stages. Figure 1 shows a schematic diagram of a facility with two stages, primary and secondary [19].

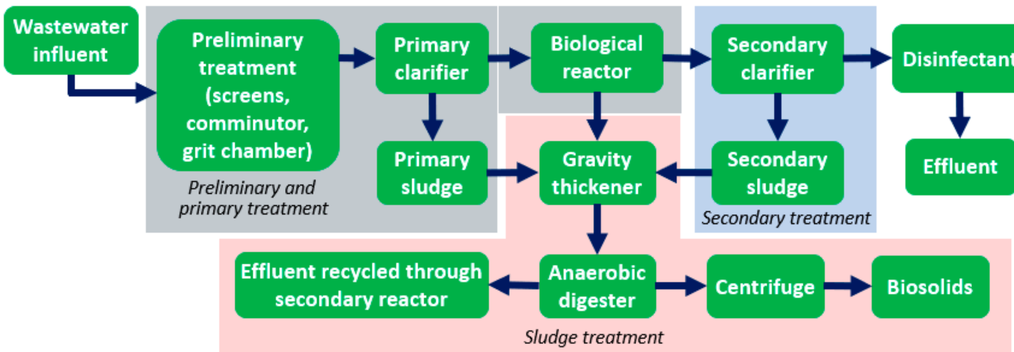

Figure 1. Basic schematic of a WWTP that provides primary and secondary treatments [19].

Preliminary and primary treatments are associated with the physical processes that are used to clean the wastewater. The objective of this stage is to remove solids from wastewater. In the preliminary stage, pollutants and large particles (i.e., rags, twigs, and stones), which can cause operational damage in treatment processes, especially to pumps, are removed from the wastewater. This stage usually uses screens, grit chambers, comminutors, and flotation. Primary treatment, also known as sedimentation, is where the scum, suspended, and settled solids are removed by sedimentation on the primary clarifiers. In most facilities, the preliminary stage is considered as a component of the primary treatment [19]. Secondary treatment consumes the organic matter that was not removed during the primary treatment. In this stage, biological mechanisms are able to remove up to 85% of the organic material contained in the wastewater. Usually, secondary treatment relies on biological reactors followed by a second clarifier with an activated sludge process. Some WWTPs are required to remove nutrients (i.e., nitrogen and phosphorus), and, in this case, additional tanks may be needed to accomplish the effluent quality standards in a process called nitrification–denitrification. Nutrient removal can be achieved by chemical or biological methods or a combination of both. Tertiary treatment aims to remove specific pollutants that were not removed from the previous treatment stages. It usually relies on chemical processes and filtration to provide the required polishing before the effluent is disposed. Additional treatment can be provided to extract nutrients and remove pathogens if required [19,20]. Choosing the most appropriate effluent treatment technology for a WWTP involves considering various technical factors (i.e., effluent volume, water demand, and plant size), and some commercial software tools, such as Winflows, IMSDesign, and WAVE, can support the planning and design processes of a WWTP.

Sewage Sludge

Sewage sludge is the solid material (organic and inorganic) removed from the raw wastewater during the treatment process. The amount of sludge produced in a WWTP is proportional to the quantity of wastewater treated by the plant, and can be expressed in mass or volume. On average, the total sludge produced may range from 0.2 to 0.3 kg/m^3 of wastewater treated [19]. It contains a mixture of organic and inorganic matter and a high concentration of several pathogenic organisms that have to be treated before disposal. Sewage sludge disposal is costly, and most WWTPs must follow regulatory requirements for waste management [21]. The energy recovery potential from sludge is directly related to three main components: (i) water content, (ii) organic (volatile) and (iii) inorganic (inert) matter. Several methods can be found on both literature and industry to treat sewage sludge, including anaerobic digestion (most common), co-digestion, composting, incineration, disposal in landfills, or being used in agriculture as a soil conditioner. However, due to the high costs of conventional treatment methods and the aim to improve sustainability targets and reduce operating costs of sludge disposal, WWTPs can recover energy from utilise sewage sludge using different methods [12], as shown in Figure 2. The energy content of dried sewage sludge, with 21–48% volatile matter, can range between 11.1 and 22.1 MJ/kg, and the calorific values for primary, secondary, and digested sludges were reported to be 16.2 MJ/kg, 12.2 MJ/kg, and 11.4 MJ/kg, respectively [22].

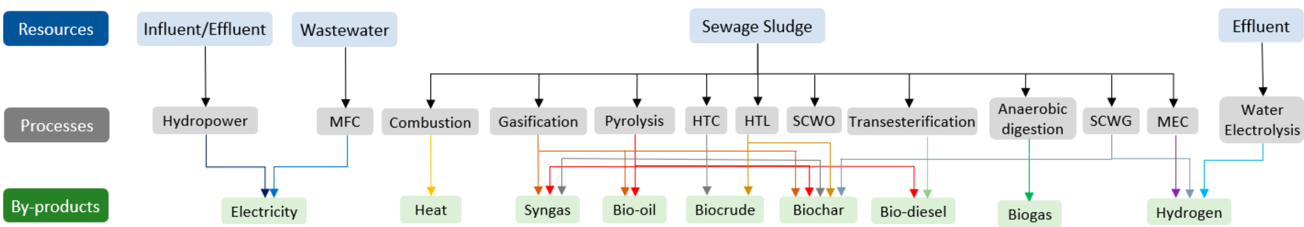

Figure 2. Site-specific sources of renewable energy in a WWTP.

3. Energy Resources in WWTP

Renewable energy technologies have become an essential component of the energy transition and one of the most effective solutions for reducing costs and emissions from WWTPs. Several types of renewable energy sources can be adopted by a WWTP. Some options can take advantage of the specific plant's sources, including energy recovery from wastewater and sewage sludge, an influent/effluent flow, and treated water. In contrast, others can be non-site-specific, such as solar and wind. Although many technologies can be implemented in WWTPs, some are still in the research and development stages and have not been widely used in large-scale facilities [23].

3.1. Site-Specific Sources

Site-specific sources refer to the energy recovery embedded in the WWTP's resources, including wastewater, sewage sludge, an influent/effluent flow, and treated water. In theory, the energy contained in a municipal wastewater and sewage sludge can be about five to ten times more than the energy required for their treatment processes, and this energy is mainly found in three forms: chemical, hydraulic/kinetic, and thermal. Based on this huge potential, according to the Water Environment Federation, WWTPs have the potential to become energy-neutral facilities or even net-energy producers [24]. Although many energy recovery methods can be used in WWTPs, each technology has its advantages, disadvantages, limitations, and potential benefits. Some of them are very widely used in large-scale plants (i.e., anaerobic digestion), and others are not as common (i.e., water electrolysis, MFC and MEC). Figure 2 illustrates the energy resources that can be recovered from a WWTP and the conversion processes associated.

3.1.1. Anaerobic Digestion

Anaerobic digestion (AD) is the most common technology used to treat sewage sludge in WWTPs (48% of the total wastewater is treated through AD in the USA). In this process, microorganisms consume the organic matter in the sludge and generate biogas as a by-product of the digested sludge. This process occurs in the absence of oxygen and is divided in four stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Biogas is a renewable gas that contains mostly methane and carbon dioxide, which can be used on-site to generate both electricity and heating or can be upgraded and injected into gas networks [25]. Several factors can influence the AD process, such as feedstock characteristics (i.e., total solids, suspended solids, volatile solids, chemical oxygen demand, and the carbon/nitrogen ratio) and operational parameters (i.e., temperature, retention time, organic load rate, pH, alkalinity, and reactor volume) [7].

Sewage sludge is known for its low degradability and low carbon/nitrogen ratio (two main parameters for anaerobic digestion efficiency). An effective alternative to overcome these challenges is to use co-digestion. It combines two or more organic feedstocks aiming to enhance the overall efficiency and performance of the digestion process, including biogas production and methane concentration. The average biogas generation from sewage sludge only can vary around 0.9–1.1 m^3/day.m^3 digester volume, whereas using co-digestion, it can reach up to 2.5–4.0 m^3/day.m^3 digester volume. Depending on the feedstock type, biogas production with co-digestion may increase by 25 to 400% compared to single-feedstock. Examples of feedstocks that can be mixed with sewage sludge include agricultural residues, beverage/dairy/food processing waste fats, food waste/scraps, oils, and grease (FOG), microalgae, an organic fraction of municipal solid waste (OFMSW), and high-strength waste (HSW). Some full-scale WWTPs have successfully adopted co-digestion of sewage sludge and other feedstocks to increase biogas production, such as Grevesmuhlen WWTP and Köhlbrandhöft WWTP, both in Germany [26] and East Bay Municipal Utility District WWTP and Des Moines Metropolitan Wastewater Reclamation Authority WWTP, both in the USA [25].

Pre-treatment techniques can also be used to improve biogas production and AD process; however, its main objective is to enhance sewage sludge digestibility and dewaterability, reduce sludge volume, and minimise environmental impacts. Improving sludge biodegradability and solubility may allow higher load ratings and shorter retention times, which can result in a higher processing efficiency [7]. Table 1 summarises some methods used in sewage sludge treatment, whereas Tables 2 and 3 show some studies found in the literature related to co-digestion and pre-treatment techniques.

Other methods, such as lime and alkaline stabilisation, are primarily used to reduce pathogens in the SS as a pre-treatment for land applications and aerobic digestion. Although the several benefits which can be provided by co-digestion and pre-treatment methods, the successful implementation of these processes in large-scale facilities may be challenging, especially in terms of re-designing the operation process and physical upgrades/updates. Additionally, new operating costs can be added when adopting these new alternatives [7].

Table 1. Pre-treatment methods that can be used to treat sewage sludge.

Type	Process	Advantages	Disadvantages	Applications
Th	SS heated (150–200 °C) under pressure, breaking down complex OC and making SS more digestible.	- Enhance biodegradability - Reduce pathogens and OC - Increase biogas production	- High CAPEX and OPEX - High energy consumption	- Used before AD - Improve biogas yield
M	SS is exposed to microwave radiation to rupture cell structures of the solid particles within SS and disrupt OM, improving digestion.	- Increases CH_4 production - Reduces pathogens - Improves biogas yield - Enhances dewaterability	- High CAPEX and OPEX - High energy consumption - Require controlled temperature to avoid OM degradation	- Used before AD - SS with high OC - Co-digestion processes
Uc	High-frequency sound waves (ultrasonication) are used to disrupt SS particles, improving degradability.	- Improve dewaterability - Increase CH_4 production - Reduce need for chemicals	- High CAPEX and OPEX - Energy-intensive process - Need of special equipment	- Increase biogas yield - SS with high MC - Co-digestion processes
Ud	High-frequency sound waves (20 kHz–1 MHz) to disrupt SS particles to cause cavitation, improving digestibility.	- Enhance digestibility - Increase dewaterability - Reduce pathogens	- High energy consumption - Expensive equipment - Need special setup and O&M	- SS dewatering - SS with high OC - Co-digestion processes
O	Ozone gas is bubbled through SS, breaking down OC and killing pathogens.	- Strong pathogen control - Effective in reducing odors - Increases biodegradability	- High operational cost - Requires energy-intensive ozone generation	- Odor control - Enhance degradability - Before AD
FA	Apply high pressure and high temperature to SS in the presence of water or organic additives.	- Enhance biodegradability - Increase CH_4 production - Reduce need for chemicals	- High CAPEX and OPEX - High energy consumption	- Enhance AD efficiency - Improve biogas yield - SS with high OC

Th: Thermal, M: Microwave, Uc: Ultrasonic; Ud: Ultrasound; O: Ozonation; FA: Free ammonia; SS: Sewage sludge: OC: Organic content; MC: Moisture content; O&M: Operation and maintenance.

Table 2. Co-digestion of sewage sludge with different feedstocks.

Ref.	Substrate	Parameters and System Design	OLR (gVS/L.d)	VS Removal (%)	Methane Production (L/kgVS)		Methane Concentration (%)	
[27]	SS and FW	6 × 5 L reactor, 37 °C, 22 days HRT, 10–50% FW:SS ratios	Min: 2.8 ǀ Max: 4.2	Min: 66 ǀ Max: 76	SS: 230–280 ǀ FW: 290–330	Co-d: 318–385	SS: 45–57 ǀ FW: 49–57	Co-d: 53–55.7
[28]	SS and FW	2 L reactor, 30–38 °C, 22 days HRT, ratios (1:1, 1:2 and 1:3)	NI	Min: 51.47 ǀ Max: 60.36	SS: 356–478 ǀ FW: 511	Co-d: 453–609	SS: 53 ǀ FW: 50.4	Co-d: 52–70.3
[29]	SS and FW	5 L reactor, 30–38 °C, 22 days HRT, different mixing ratios (1:1, 1.5:1, 2:1, 1:1.5 and 1:2)	0.5–7 g VS/L	Min: 82.8 Max: 87.7	SS: 625.4 FW: 385.9–507.5	Co-d: 384.6–492	SS: 55.9–58.6 FW: 58.8	Co-d: 53–60.4
[30]	SS and FW	6 L reactor volume, 35 °C, 8–30 days HRT and three different SS:FW mixing ratio (2.4:1, 0.9:1, 0.4:1)	Min: 4.6 Max: 18.5	Min: 39.7 Max: 70	SS: 157–237 FW: 377–465	Co-d: 215–400	SS: 63–65 FW: 50–54	Co-d: 53–61

Table 2. *Cont.*

Ref.	Substrate	Parameters and System Design	OLR (gVS/L.d)	VS Removal (%)	Methane Production (L/kgVS)		Methane Concentration (%)	
[31]	SS and FVW	100 L reactor, 35 °C, 11–14 days HRT	Min: 1.46 Max: 2.8	Min: 35 Max: 43	VW: 335 SS: 84	Co-d: 90–430	NI	NI
[32]	SS, GTS, OFMSW	2 × 6 L reactor, 38 °C, 20 days HRT and 5–30% mixing ratio	Min: 1.15 Max: 2.17	Min: 52 Max: 65	SS: 300 | GTS: NI OFMSW: NI	Co-d: 456–547	SS: 66 | GTS: NI OFMSW: NI	Co-d: 66–69
[33]	TWAS and RS	0.25 L reactor, 37 °C, 50 days HRT, mixing ratio of 1:1 and 1:3 on volume basis	5% TS	Min: 34.5 Max: 69.1	RS: 216.3 TWAS: 184.6	Co-d: 304	NI	NI
[34]	SS and RS	1.2 L reactor, 35 °C and 55 °C, between 25 (55 °C) and 75 days (35 °C) HRT, 4:1 (weight basis) mixing ratio	20% TS	Min: 61 (35 °C) Min: 70.2 (55 °C)	RS: 222 (35 °C), 248 (55 °C) SS: 308 (35 °C), 344 (55 °C)	Co-d: 518 (35 °C), 602 (55 °C)	NI	Co-d: 36–60
[35]	SS and WS	0.5 L reactor, 37 °C, 30 days, 1.15:1.94 (VS basis) ratio	7.73	Min: 56.38 | Max: 63.59	SS: 136.8 | WS: 243	Co-d: 176.7–333.9	NI	NI
[36]	WAS, WS, and RS	0.15 L reactor, 30 days HRT, 1:1 mixing ratio	4 g VS/L	NI	RS: 95 | WS: 103 WAS: 87	Co-d: 36–223	RS: 50 | WS: 48 WAS: 50	Co-d: 30–58
[37]	SS and GTW	0.25 L reactor, 35 °C, 10–31 days HRT, 4 mixing ratios (14%, 24%, 43% and 39% GTW)	NI	Min: 31 Max: 35	SS: 223 GTW: 606	Co-d: 214–517	NI	NI
[38]	SS and GTW	6 L reactor, 35 °C, 15 days HRT, 1:1 mixing ration (PS and WAS) + GTW 5% VS.	2.93	Min: 47 Max: 59	SS: 384 GTW: NI	Co-d: 641	SS: 61 GTW: NI	Co-d: 69
[39]	SS and FOG	For 55 °C: 10 L reactor, 20 days HRT. For 70 °C: 2 L reactor, and 2 days HRT. Mixing ratios: 20, 40, 60 and 80% FOG	NI	Min: 46.8 Max: 82	SS: 138.3 FOG: NI	Co-d: 102–673	SS: 61.6–62.8 FOG: NI	Co-d: 49.7–67.3
[40]	SS and FOG	1 L reactor, 35 °C, 15 days HRT, 4 mixing ratios (14%, 24%, 43% and 39% GTW)	4 g COD/L.d	Min: 43.1 Max: 54.6	SS: 114–128 FOG: 143–290	Co-d: 453–609	SS: 62.8–71.2 FOG: 63.3	Co-d: 66.1–68.4
[41]	SS, FW and G	0.25 L reactor, 37 °C, 20 days HRT, 1:1 mixing ratio (SS:FW) with 1% and 3% glycerol.	0.66–1.1	Min: 8.6 Max: 17.4	SS: 138.3 FW: NI | G: NI	Co-d: 236–526	SS: 85.9% FW: NI | G: NI	Co-d: 77.4–79.4
[42]	SS and G	5.5 L reactor, 35 and 55 °C, 20 days HRT, 2 SS:G mixing ratios (99:1, 98.8:1.2 *v*/*v*%)	1.2–1.6 (35 °C); 1.1–1.3 (55 °C)	Min: 36 (35 °C), 45 (55 °C) Max: 64 (35 °C), 73 (55 °C)	SS: 296 (35 °C), 354 (55 °C) G: 277–475 (35 °C), 349–490 (55 °C)	Co-d: 250–660 (35 °C) 230–530 (55 °C)	NI	Co-d: 63–72 (35 °C) 57–66 (55 °C)
[43]	SS and PM	0.16 L reactor, 35 °C, 47 days HRT, different SS:PM mixing ratios (21:1, 14:1, 7:1 VS)	0.54 (average)	Min: 56.3 Max: 71.4	SS: 182 PM: 239	Co-d: 190–200	SS: 52–58 PM: 52–58	Co-d: 52–58
[44]	SS, SM PoM	1 L (b) and 3 L (s-c) reactor, 35 °C, 15–30 days HRT, different mixing ratios	1.27–2.86 (s-c)	37.9–45.8 (b) 23.9–38 (s-c)	SS: 184 (b) PoM: NI | SM: NI	Co-d: 198–290 (b); 186–273 (s-c)	SS: 67–68 PoM: NI | SM: NI	Co-d: 67–68
[45]	SS, WV PoM	5 L reactor, 35 °C, 6–20 days HRT, 50:50 *w*/*w*% SS:WV mixing ratio plus 10 g/L of PoM	NI	Min: 38 Max: 58	SS: 130 (10 days HRT) PM: NI | WV: NI	Co-d: 210–261	NI	NI

Table 2. *Cont.*

Ref.	Substrate	Parameters and System Design	OLR (gVS/L.d)	VS Removal (%)	Methane Production (L/kgVS)		Methane Concentration (%)	
[46]	SS and CM	1 L reactor, 37 °C, 20 days HRT, 3 CM:SS mixing ratio (30:70, 50:50, 70:30 *w*/*w*%)	NI	Min: 78.4 Max: 97.3	NI	Co-d: 335–511	NI	NI
[47]	SS and M	70 L reactor, 35–37 °C, 30 days, SS:M ratio of 0.2–1.8% VS	NI	Min: 4 ∣ Max: 35	NI	Co-d: 226	NI	Co-d: 79–85.5
[48]	WAS and M	0.13 L reactor, 35 °C, 25–30 days HRT, 4 WAS:M mixing ratio (3:1, 1:1, 1:3)	NI	NI	WAS: 362 M: 318	Co-d: 354–442	NI	NI

Co-d: Co-digestion; NI: Not informed; FVW: Fruit and Vegetable waste; RS: Rice straw; WS: Wheat straw; GTW: Grease trap waste; G: Glycerol; PM: Pig manure; PoM: Poultry manure; SM: Swine manure; WV: Wine vinasse; CM: Cow manure; M: Microalgae; b: batch mode; s-c: semi-continuous mode; FW: Food waste; OLR: Organic loading rate; SS: Sewage sludge.

Table 3. Pre-treatment techniques applied to sewage sludge.

Ref.	Type	Sludge Collection	Operating Parameters	Biogas Production/Methane Yield
[49]	Th	WWTP in Valladolid, Spain	System include steam boiler, 1.5 L hydrolysis reactor connected to a 5 L flash tank. Reactor loaded with 0.75 L sludge, under 110–200 °C, and 10–50 min.	CH_4 yield increased up to 50% (thermal) under 30 min under 180–200 °C. CH_4 production improve up to 45% using thermal compared to conventional process.
[50]	Th	WWTP, in Korea.	The hydrolysis thermal plant had the capacity to treat 1 ton SS/cycle. SS was dewatered before the treatment and the thermal hydrolysis process operated at 75–225 °C and 15–105 min reaction time.	Optimal parameters included 76 min reaction and 180 °C. At 150 °C and 1 h reaction, the maximum CH_4 yield was 273.2 mL/g COD (40% increase compared to control). The minimum CH_4 yield was 221.7 mL/g COD under 30 min and 200 °C.
[51]	Th and FA	WAS obtained from a WWTP in Changsha, China.	Three temperatures (35, 50 and 70 °C) were used. Reactors fed with 0.4 L of WAS, and different concentrations of ammonium stock solution was used (220–450 mg). FA concentrations between 79.7 and 163.1 mg $NH_3 - N$/L and operate at 25 °C.	Without any treatment (control), the biochemical methane potential (BMP) was 183.4–200.6 mL/g VSS. With FA only and thermal only, the BMP was 188.1–201.8 mL/g VSS, and 184.1–196.9 mL/g VSS, respectively. With combined methods, BMP varied between 195.7 and 229.4 mL/g VSS.
[52]	Th and Uc	Ulu Pandan municipal WWTP, in Singapore.	Batch mode and operating temperature of 35 °C. Sewage sludge treated with ultrasonic at 5 MJ/kg TS and optimal temperature of 65 °C for thermal treatment.	Combining thermal and ultrasonic (30 s, 5000 kJ/kg TS) resulted in high COD solubilisation (760–10,200 mg/L), proteins (115–2900 mg/L) and carbohydrates (60–660 mg/L) than a single treatment. Biogas production improved by 20%.
[53]	Th, M, and Uc	Copero urban WWTP in Seville, Spain.	Batch mode and operating temperature of 35 °C. Thermal parameters included 75 L volume autoclave, 120 °C, 2 atm for 15 min. Microwave parameters included 100–900 W at 80 °C for 1.4 min. Ultrasonic parameters: 6 L volume 25 °C, atm pressure, 150 W power generator for 45 min.	CH_4 production improved by 20%, 29%, and 95% based on microwave, thermal and sonication, respectively. The specific energy applied for the thermal, sonication and microwave was 36, 102 and 20 kJ/g TS, respectively. Sludge solubility increased by 19.2% using thermal and 83.4% using microwave.
[54]	M	WWTP located in the city of Leon, Spain.	Microwave oven (2450 MHz frequency) was used. SS samples were irradiated with a power output of 650–900 W. Reaction was carried out at 34 °C in 2 × 3 L reactors with mechanical stirrers. A 30:70 mixing ratio of PS:WAS was used. SS samples irradiated at energy values of 975 kJ/L.	CH_4 yield without treatment was 166, 209, 213, and 226 mL/g VS considering 5, 10, 20, and 25 days, respectively. With microwave treatment, the CH_4 yield increased to 214, 295, 308, and 324 mL/g VS for a 5, 10, 20, and 25 days of retention times respectively. CH_4 yield increased between 29% and 43%.
[55]	M	Copero urban WWTP in Spain.	Pre-treatment applied (400 W and 700 W), and the specific energy used was up to 30 kJ/g TS and maximum temperature of 100 °C.	CH_4 yield for raw SS was 111 mL/g VS. Using microwave pre-treatment, CH_4 yield increased to 118–130 mL/g VS.

Table 3. *Cont.*

Ref.	Type	Sludge Collection	Operating Parameters	Biogas Production/Methane Yield
[56]	M	Qinghe WWTP in Beijing, China	2 L lab-scale reactors with 112 rpm and 20 days HRT. OLR of 2.92 g VS/L.d at 37 °C. Microwave-H_2O_2 pre-treatment was used. A 2-stage reactor was set up with a 0.65 L bottle (the first stage reactor) in series with a 2 L reactor.	CH_4 production improved from 215.5 mL/g VS (control) to 258.4 mL/g VS (microwaved) for a 1-stage reactor. For 2-stage, CH_4 yield increased from 258.4 mL/g VS (control) to 288.3 mL/g VS (microwaved). The 2-stage was 11.6% higher than 1-stage.
[57]	Uc	Full-scale WWTP located in Antwerp-South, Belgium.	Ultrasound reactor at 10 L/min fixed flow rate and 25 kHz frequency applied. Power up to 1 kW was used. The AD happened at 37 °C and retention time of 3 weeks in a 1 L reactor filled with 0.5 L WAS.	CH_4 production increased up to 20% using the pre-treatment. For a 23 day reaction, CH_4 production was 126 mL/g DS, and 1.014 kWh/kg DS energy value. Energetic content of the surplus biogas by ultrasonic was 0.195 kWh/kg DS.
[58]	Th and Ud	Biobío WWTP, in Concepción, Chile.	Ud and low-thermal (55 °C) pre-treatment were conducted. Ud using specific energies of 0.5, 15.5 and 30.5 MJ/kg TS. Th treatment with retention times of 3, 8 and 13 h were also performed.	CH_4 production ranged between 472 and 611 mL/g V based on 0.5–30.5 MJ/kg TS (Ultrasound) at for 3–13 h reaction, The CH_4 yield increased between 16% and 50% using the methods.
[59]	M and Uc	WWTP in of Mechelen-Noord, Belgium.	0.6 L reactor used with 500 g SS. Applied 100 W power for 8 min, and 800 W power for 1 min. Total energy of 96 kJ/kg SS to both treatments.	Biogas production increased to 0.26–0.28 L/g VS compared to 0.22 L/g VS (control case). Biogas improved by 27% and 20% based on Uc and M treatments, respectively. Both methods were considered not cost feasible.
[60]	U and O	Municipal WWTP, in Singapore.	130 W and 20 kHz (ultrasound) and 180 W (ozonation) applied to a 0.2 L of sewage sludge.	Biogas production improved by 11–15.4%. The maximum CH_4 production rate increased from 3.53 (control) to 4.32–4.54 mL CH_4/d.

Th: Thermal, M: Microwave, Uc: Ultrasonic; Ud: Ultrasound; O: Ozonation; FA: Free ammonia; WAS: Waste activated sludge; PS: Primary sludge; DS: Dry solids; OLR: Organic Loading Rate; SS: Sewage sludge.

Biogas can be used to generate electricity from different CHP technologies, including fuel cells (FCs), gas turbines (GTs), and Internal Combustion Engines (ICEs). Traditionally, an ICE is the most widely technology used in WWTPs due to its low capital and operational costs, technology maturity, flexibility, robustness, and simple maintenance. GTs are versatile due to their multi-fuel capabilities, relative low maintenance costs, and high-power density, but compared to ICEs, they are still a more complex technology, requiring more maintenance and higher investment costs [9]. FCs have grown rapidly worldwide, especially because of their flexibility, which can be widely used in cogeneration applications. Different from ICEs and GTs, FC generates electricity directly from chemical energy without the need for an intermediate mechanical conversion.

Multiple criteria can be considered for selecting the most suitable technology, such as quantity of biogas available, biogas purity, system capacity, and investment/operation costs [7]. Table 4 shows the main characteristics of FCs, GTs, and ICEs.

Table 4. Characteristics of fuel cell, gas turbines, and CHP systems.

	FC	Micro GT	GT	ICE
Technology status	Emerging	Mature	Mature	Mature
Capacity (kW)	200–1200	30–250	1200–4700	110–3700
Electrical Efficiency (%)	36–45	26–30	26–37	30–42
Thermal Efficiency (%)	30–40	30–37	30–52	35–49
CH_4 minimum level (%)	85	40	30	60
Emissions	Extremely low	Very low	Low	Medium/High
Capital costs (USD/kW)	3800~5280	800~1650	1100~2000	465~1600
O&M costs (USD/kWh)	0.004~0.019	0.012~0.025	0.008~0.014	0.01~0.025

The biogas generated from WWTPs can also be upgraded into biomethane and used as renewable natural gas (RNG). For example, the Janesville WWTP used the biomethane generated on-site to power eight biogas-based fuel vehicles in 2012, with a goal to refuel up to 40 vehicles in the future. The plant has a treatment capacity of over 68,000 m^3/d and a maximum fuel capacity of up to 33,357 MJ/d. From the total biogas generated (225 m^3/h), about 35.7% (80.4 m^3/h) was used in the biogas upgrade to refuel the vehicles, and the remaining part was used in the CHP system [61]. Point Loma WWTP secured a long-term clean biogas power purchase agreement (PPA) with two customers: University of California (2.8 MW) and San Diego South Bay Water Reclamation Plant (1.4 MW). The project cost USD 45 mi, and 75% of the project was subsidised. The plant has capacity to generate around 45,300 m^3/d, and it was the first project in California (USA) to inject biomethane into the natural gas network [62]. San Antonio WWTP, located in Texas, USA, partnered with Ameresco under a PPA to develop a biogas project. The system treats and upgrades the biogas generated during the sewage treatment process and injects it into a commercial gas pipeline. The system has the capacity to process more than 42,475 m^3/d of biogas, and about 60% is injected into the gas network, providing an annual reduction of over 19.700 tons of CO_2 [63]. Newtown Creek WWTP, located in New York (USA), aims to provide enough RNG to supply 5200 homes, saving up to 90,000 metric tons of GHG emissions [64]. Many studies have been conducted on the use of biogas-fuelled gas turbine cogeneration systems in WWTPs. Table 5 summarises some studies that investigated the energy generation potential using FCs, GTs, and ICEs in WWTPs.

Table 5. Studies found in the literature based on different generation technologies, including GT, FC and ICE, in WWTPs.

Ref.	Type	Study Aim	Operating Parameters
[5]	FC	Study the Castiglione WWTP in Italy to achieve self-sufficiency based on co-digestion and SOFC system.	• Castiglione WWTP (5th largest WWTP in Europe) serves 25 million PE, and the co-digestion of SS:OFMSW ratio of 76:24, in terms of mass. • The biogas yield increased from 402 to 500 L/kg VS and biogas production increased from 18.800 to 47,100 m^3/d after co-digestion. • With SOFC and co-digestion, thermal and electrical load coverage was 95.4% and 155.8% (the current system supplies about 49–54.6% of the loads).
[65]	FC	Assess the economic benefits of using SOFC in a WWTP.	• The investment cost of a SOFC system was found to be 7000 EUR/kW, which is currently competitive against CHP technology. • SOFC system can be a feasible option if the cost is around 5600 EUR/kW (with subsidies) or between 2900 and 3400 EUR/kW (without subsidies).
[66]	FC	Study a SOFC system in a WWTP in the UK. WWTP serves 750,000 PE and 105,000 m^3/day inflow.	• WWTP's electricity demand and generation were 60 and 40 MWh/day. Thermal and biomethane production was 48 MWh/day, and 8230 kg/day. • 159 kg/h of H_2 could be generated from biomethane using the SMR system. • For a 120 kW system, the WWTP could generate up to 58 MWh/day (increase by 45%), and the WWTP could achieve 100% electricity self-sufficiency.
[67]	FC	Integration of a SOFC in Parand WWTP to eva-luate economic benefits. Two objective functions were optimised.	• For the single-objective optimisation (payback period), the SOFC electrical power output was 51.56 GWh/year, the investment cost was USD 36.9 mi, the annual benefit was about USD 5.6 mi, the payback period was 1.68 years, and overall exergy efficiency of 19.47%. • For the two-objective optimisation (payback period and exergy efficiency), the SOFC electrical power output was 55.6 GWh/year (29.2% was sold to the grid), the investment cost was USD 39.3 mi and the annual benefit about USD 6.6 mi, payback period was 1.74 years, and overall exergy efficiency of 20.94%.
[68]	GT	Investigate the optimum size of a gas turbine system in a sewage Wastewater plant which serves about 100,000 people.	• The WWTP average monthly wastewater treated volume, biogas production and electricity demand are 1564 mL, 130,000 m^3 and 638 kW, respectively. • Three GT sizes (30, 65 and 200 kW), and three ambient temperatures (continental, temperate, and tropical) were considered. • The annual average power generation for the 30, 65 and 200 kW GT systems were around 1.4–2.4 GWh, 1.5–2.6 GWh, and 1.5–3 GWh, respectively. • The NPV of the 30, 65 and 200 kW GT systems were around USD 2.64–4.73 mi/year, USD 2.96–5.51 mi/year, and 3.1–6.74 mi/year, respectively.
[69]	GT	Study the feasibility of a GT system to supply energy in a real WWTP, in Iran, which treats around 74.2 mL of sewage daily.	• Two scenarios were considered: scenario 1 (local energy prices with no tax on emissions) and scenario 2(international prices with tax on emissions) • For scenario 1, the LCOE, annual electricity generation and the payback period was USD 0.1373/kWh, 10.34 GWh and 14.8 years, respectively, whereas when the total cost is minimised, it was USD 0.0395/kWh, 10.73 GWh and 18.24 years, respectively. For scenario 2, the LCOE, annual electricity generation and payback period were USD 0.3166/kWh, 11.73 GWh and 2.38 years, and when the total cost is optimised, it was USD 0.067/kWh, 2.17 GWh and 2.52 years.
[70]	GT	Study a GT system in the Bali WWTP in Taiwan that has a daily treatment capacity of 1320 mL.	• Daily biogas production is around 4424 m^3/d; around 25.8% is used to supply heating, and the remaining can be used for electricity generation. • The GT's model (30 kW) selected was the CR-30 from Capstone Turbine, and the yearly net electricity generation for the system is about 172 MWh. • The actual power generated from the system is 629 kWh/d based on the system's efficiency of 23.4% and the available biogas of 433 m^3/d.

Table 5. *Cont.*

Ref.	Type	Study Aim	Operating Parameters
[71]	GT	Investigates the injection of hydrogen into biogas to generate electricity in a WWTP.	• Generation system included a 10,000 m^2 PV system to power PEM electrolysers, and 2 × GTs (C65 and C200 Capstone turbines) to generate electricity. • Yearly electrical power and thermal energy varied between 70–400 kW and 120–500 kW, respectively, and available biogas is around 94 m^3/h. • The LCOH can vary between 8.3 and 27.5 USD/kg with a payback period of 6.5–11.6 years.
[72]	ICE	Investigate the combined utilisation of syngas and biogas to power a CHP system in a WWTP.	• Two CHP systems considered: compression ignition (CI) and natural gas (NG) engines. Biogas production estimated at 25 m^3/h, and syngas production for undigested and digested sludges were 0.05 m^3/s and 0.02 m^3/s. Total investment costs for the CI and NG systems were around EUR 1.60–1.66 mi and EUR 0.63–0.99 mi, respectively. The total annual cost savings for the CI and NG systems were around EUR 171,000–235,000 and EUR 110,000–174,000, respectively.
[73]	ICE	Study the potential of a biogas-fuelled system to supply electricity to 5 WWTPs, in Spain.	• Five WWTPs which supply 121,500–451,250 PE and flow between 20 and 30 mL/d. • CHP systems selected based on biogas production: 300 kW (plant 1), 500 kW (plant 2), 500 kW (plant 3), 700 kW (plant 4) and 800 kW (plant 5). • The payback period for all 5 plants was between 2 and 3 years. The CHP systems could supply electricity between 39 and 76%, and 100% thermal energy.
[74]	ICE	Investigated the biogas energy potential in 4 WWTPs in Brazil.	• The 4 WWTPs serve between 41,000 and 133,000 PE. The theoretical net power estimated was 71–329 kW, total investment costs were USD 205,000–315,000, and total generation potential for all plants could be up to 23.6 GWh/year. • The NPV for a 15 years lifetime could vary from USD 1.31–4.74 mi.
[75]	FC and GT	Investigate a system of SOFC and GT in Collegno WWTP, in Italy, which serves around 270,000 PE.	• A 180 kW system generates 1.58 GWh/y with an 11.6-year payback time. The LCOE was 0.134 EUR/kWh. • A 390 kW SOFC-GT generates 2.54 GWh/y with a 7.7-year payback time, and the LCOE was 0.116 EUR/kWh. • For a 275 kW SOFC-GT system, the system could generate 2.2–2.4 GWh/y with an 8–8.5-year payback time and LCOE of 0.118–0.125 EUR/kWh, whereas for a 310 kW SOFC-GT system, the system could generate 2.3–2.7 GWh/y with a 7.9–8.3 years payback period and almost the same LCOE.
[76]	GT, ORC, chiller	Investigate the benefits of a CHP system in WWTPs.	• For 70,000 PE and 400,000 PE plants, the total investment cost was USD 0.25–0.4 mi, and USD 0.75–1.27 mi, respectively. For a 70,000 PE, the payback period for the GT, ORC and chiller were 2.6–3.3, 10–15, and 21–25 years, respectively. For a 400,000 PE, it could be reduced to 1.6–2.1, 5.5–7, and 16–18 years.
[77]	FC, ICE and GT	Study the opportunities and challenges of using FC, ICE and GT on 6 WWTPs.	• 2 WWTPs used: 100,000 PE (12.35 mL/d flow and 62.5 m^3/h biogas production) and 500,000 PE (61.5 mL/d flow and 312.5 m^3/h biogas production). • For the 100,000 PE plant, the system consisted of 143 kW ICE, 2 × 60 kW GT, 300 kW MCFC and 150 kW SOFC. For a 500,000 PE plant, it was 844 kW ICE and 1.2 MW MCFC. The LCOE for the ICE, GT, MCFC and SOFC systems were 4.6–10.4, 6.7–11.5, 16.6–19.9, and 15.2–19.4 EUR/kWh, respectively.
[78]	SCWG and CC	Study an integrated system for H_2 production and power generation.	• Syngas yield was between 1.48 kg/kg_{feed} (500 °C) and 1.78 kg/kg_{feed} (700 °C), and H_2 was 0.02 kg/kg_{feed} (500 °C) and 0.09 kg/kg_{feed} (700 °C). • At 500 °C, total net power was 62.1–90.7 kW with 23.3% efficiency. At 700 °C, the net power and system efficiency were 56.6–88.4 kW, and 63.48%.

3.1.2. Thermochemical Processes

Thermochemical Processes aim to recover the sludge energy content by changing its composition, including biological, chemical, and physical characteristics, based on thermal treatment to produce a valuable fuel, which can be solid, liquid, and/or gas renewable fuels. Additionally, it can reduce the operating costs related to sludge disposal and its negative impacts on the environment. These processes have been receiving significant attention over the last few decades, and they can be classified into incineration (also known as combustion), gasification, pyrolysis, and hydrothermal treatments [79]. Figure 3 illustrates different thermochemical methods that can used to treat sewage sludge, producing valuable by-products, including hydrogen-rich gas, syngas, bio-oil, and biochar.

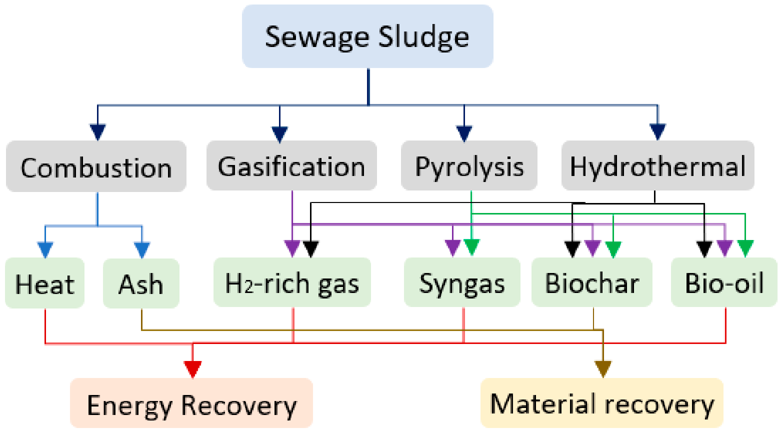

Figure 3. Thermochemical processes applied to sewage sludge for energy recovery.

(a) Combustion

Also known as incineration, it occurs under high temperatures (between 800 °C and 1000 °C) and an excess of air. It is a very mature technology and one of the most traditional methods to convert biomass into energy. Its applications on sewage sludge have been widely studied, and the main benefits of using combustion includes achieve complete oxidation of the organic elements in the biosolids, reduce the sludge volume, and ensure pathogen destruction. In this process, heat and electricity can be recovered, and other co-products, such as ash (inert material), flue gas, and water, are generated [80]. Its main advantages include the ability to significantly reduce the sludge volume (up to 90%), destroy pathogens and toxic elements, mature technology, lower costs compared to other methods, odour control, and potential for energy recovery. However, this method also results in low energy efficiency, emission of toxic compounds, low economic viability, and usually requires additional fuel. Due to its high ash and water content, sewage sludge is typically mixed with other feedstocks (i.e., wood pallets) to achieve a better performance (process known as co-combustion) [81]. Some commercial sludge treatment facilities have been reported in the literature, including plants in Belgium, China, Germany, Japan, the USA, the UK, and the Netherlands, which have used incineration to treat municipal sewage sludge [80]. For instance, a sludge treatment facility (STF) was constructed and started its operation in 2015 in Hong Kong, China, to process 2000 tons/day of sewage sludge from the Stonecutter's Island WWTP. The STF is supplied by two generators capable of producing all the electricity needed to operate the plant. The STF is not only energy self-sufficient but also exports the electricity surplus (up to 2 MW) to the main grid [82].

(b) Gasification

Gasification is a method where the biomass (i.e., dried sludge) is exposed to a high temperature (about 1000 °C) in a reduced air environment, generating syngas, heat, and ash. The syngas (synthetic gas) composition may include CH_4, CO, CO_2, H_2, O_2, and N_2, which can be cleaned to produce a higher quality fuel, whereas the heat can be further recovered to generate electricity. The high heating value (HHV) of syngas from sewage sludge gasification depends on different parameters, including gasification technology, operating conditions (i.e., temperature, pressure, and air-to-fuel ratio), and sewage sludge characteristics. On average, it may vary from 5.8 to 18 MJ/m^3. The benefits of gasification are related to the ability to deal with the inorganic elements, generation of syngas and heat, low energy needs, mature technology, and combined feedstocks without quality/efficiency problems. However, issues related to low energy efficiency, emissions, economic viability, and additional fuel requirements are the main drawbacks [83].

(c) Pyrolysis

Sludge pyrolysis (also known as liquefaction) operates under a temperature between 350 and 500 °C in a restricted oxygen environment. Some parameters, including temperature, heating rate, residence time, pressure, sludge characteristics, reactor type, and process design, can influence pyrolysis efficiency [79]. The main co-product generated from this process, which can be used as a renewable energy source, is bio-oil, which has a calorific value of 30–37 MJ/kg [84]. Syngas and biochar are also other co-products generated that can be used for electricity generation and carbon sequestration or soil amendments, respectively [85]. Different types of pyrolysis can be found in the literature, and the most common are listed in Table 6.

Table 6. Types of pyrolysis and their characteristics.

<table>
<tr><th>Pyrolysis Type</th><th>Residence Time</th><th>Temperature</th><th>Heating Rate</th><th>Pressure</th></tr>
<tr><td>Slow</td><td>>60 min</td><td>300–700 °C</td><td>0.1–1 °C/s</td><td rowspan="4">0.1 MPa</td></tr>
<tr><td>Intermediate</td><td>~10 min</td><td>500–650 °C</td><td>1–10 °C/s</td></tr>
<tr><td>Fast</td><td>0.5–20 s</td><td>550–1250 °C</td><td>10–300 °C/s</td></tr>
<tr><td>Flash</td><td><0.5 s</td><td>800–1300 °C</td><td>>1000 °C/s</td></tr>
<tr><td>Microwave</td><td>30 min</td><td>500–1000 °C</td><td><5 °C/s</td><td>-</td></tr>
<tr><td>Vacuum</td><td>30–120 min</td><td>300–600 °C</td><td>0.1–1 °C/s</td><td>0.01–0.02 MPa</td></tr>
<tr><td>Hydro</td><td>240 min</td><td>350–600 °C</td><td>10–300 °C/s</td><td>5–20 MPa</td></tr>
</table>

Reactor type is a very important parameter in the pyrolysis that directly impacts the conversion efficiency of organic matter into useful energy (i.e., solid, liquid or gas fuels). Examples of pyrolysis reactors include fixed bed, fluidised bed, rotary kiln, auger (screw), microwave, vacuum, conical spouted bed, bubbling fluidised, circulating fluidised, plasma, and solar, as illustrated in Table 7. Among them, the most common are the fixed and fluidised bed reactors due to their low cost, simplicity, efficiency, flexibility, heat uniformity, and controllability [85].

Table 7. Types of reactors used in pyrolysis.

Type	Details	Efficiency	Op. Costs	Scale	Benefits	Limitations
FiBR	Stationary bed, batch or continuous operation	Low to moderate (15–25%)	Moderate (USD 30~80/ ton SS)	Small	- Simple design - Low capital cost - Easy to operate - Well-established	- Lower throughput - Low heat transfer - Energy efficiency
FBR	Granular material, heated by upward gas flow, continuous operation	Moderate to high (25–40%)	Moderate (USD 50~120/ ton SS)	Large	- High heat transfer efficiency - High throughput - Uniform heating - Well-established	- Complex design - Requires filtration - Higher capital cost
RKR	Rotating drum, externally heated, continuous operation	Moderate (20–35%)	High (USD 70~150/ ton SS)	Large	- High throughput - Suitable for high moisture content - Well-established	- High energy consumption - Expensive maintenance

Table 7. *Cont.*

Type	Details	Efficiency	Op. Costs	Scale	Benefits	Limitations
AR	Screw conveyor moves SS through a heated zone continuously	Moderate to high (20–35%)	Moderate (USD 40~90/ ton SS)	Small/ Medium	- Continuous operation - Easy to control - Low maintenance	- Limited scalability - Needs specialized equipment - Less mature
MR	Direct heating using microwave radiation	High (50–70%)	High (USD 90~150/ ton SS)	Small	- Fast heating - High energy efficiency - Smaller footprint - Uniform heating	- Limited scalability - High capital cost - Complex control systems - Emerging (pilot-scale)
VR	Pyrolysis under reduced pressure, improving bio-oil quality and volatile product yields.	Moderate to high (30–50%)	High (USD 70~130/ ton of SS)	Small/ Medium	- High-quality bio-oil - Improved energy recovery - Better volatile product yields	- Requires vacuum pumps - High capital cost - Complex design - Emerging (limited use)
CSR	Conical reactor with particles suspended by gas flow. SS is fed in from the top and heated through gas flow.	Moderate (25–35%)	Moderate (USD 50~100/ ton of SS)	Medium/ Large	- Efficient heat transfer - Can handle particles of varying sizes - Uniform heating	- Complex design - Requires precise flow control - Less scalable than fluidized beds - Less mature
BFBR	Reactor with a bubbling action caused by gas flow and typically used for lower-density feedstocks.	Moderate (20–35%)	Moderate (USD 50~120/ ton of SS)	Small/ Medium	- Simple design - Moderate heat transfer - Suitable for moderate-sized sludge feedstocks	- Lower efficient heat transfer - Requires gas–solid separation - Mature (widely used)
CFBR	Fluidised bed with a continuous loop of particles in motion and continuous operation	High (30–50%)	High (USD 60~150/ ton of SS)	Large	- High heat transfer efficiency - Suitable for large-scale use - Uniform heating - Well-established	- Complex design - High energy consumption - Expensive maintenance
PR	Pyrolysis using high-temperature plasma arc	Very high (60–80%)	Very high (USD 150~300/ ton of SS)	Small/ Medium	- Very high temperatures (up to 10,000 °C) - Capable of decomposing almost all feedstocks	- Extremely high capital and operating cost - Need of special equipment - High energy use - Emerging (high-tech)
SR	Uses concentrated solar energy to heat the sludge for pyrolysis.	Moderate to high (20–40%)	Low (USD 80~150/ ton of SS)	Small/ Medium	- Renewable energy source - Sustainable	- Dependent on sunlight - Requires large infrastructure - Expensive setup

SS: Sewage sludge; FiBR: Fixed-bed reactor; FBR: Fluidized-bed reactor; RKR: Rotary kiln reactor; AR: Auger reactor; MR: Microwave reactor; VR: Vacuum reactor; CSR: Conical spouted bed reactor; BFBR: Bubbling fluidized bed reactor; CFBR: Circulating fluidized bed reactor; PR: Plasma reactor; SR: Solar reactor.

(d) Hydrothermal treatment

Hydrothermal treatment applies high pressure and a high temperature the sewage sludge in the presence of water in order to generate useful products, including biogas, biofuels, and solid biochar. Hydrothermal treatment methods (see Table 8) can classified in three groups: Hydrothermal Carbonisation (HTC), Hydrothermal Liquefaction (HTL), and Hydrothermal Gasification (HTG).

Table 8. Characteristics of HTC, HTL and HTG.

Type	Temperature (°C)	Pressure (MPa)	Water State	Generated Products	Advantages
HTC	150–280	0.1–11	Subcritical	Solid (char), small amount of liquid (biocrude) and gas	Sludge stabilisation, volume reduction, fertiliser
HTL	280–375	8–22	Sub/near critical	Liquid (biocrude), small amount of solid (char), water-soluble fractions	Use wet sludge without the need for drying
HTG	>375	>22.1	Super-critical	Gas (Syngas), small solid amount (char), and water-soluble fractions	Produce high concentrations of H_2

HTC focuses on producing carbon-rich solids (hydrochar) and offers benefits in carbon sequestration and soil enhancement. However, it has lower energy recovery compared to other processes. HTL generates bio-crude oil with high energy density. It requires further upgrading, and involves complex operating conditions. HTG efficiently converts organic materials into syngas, and it is highly effective for waste-to-energy conversion, but there is high operational costs and material challenges [79]. Gasification of sewage sludge has been reported in different studies, as illustrated in Table 9. Some researchers have investigated the energy potential from thermochemical processes applied to sewage sludge, as shown in Table 10. Table 11 highlights studies that investigate the generated products and the potential for applying HTC and HTL on sewage sludge.

(e) Supercritical water

There are two main methods to treat sewage sludge via supercritical water technologies: supercritical water gasification (SCWG) and supercritical water oxidation (SCWO). SCWO and SCWG (also known as HTG) are considered promising technologies to treat organic wastes, including sewage sludge, because this technology not only generates fuel gases (including hydrogen), but also has low environmental and social impact. In supercritical water processes, the feedstock (i.e., sewage sludge) is subjected to a supercritical water environment (temperature and pressure higher than 374 °C and 22.1 MPa), and the organic compounds in the feedstock are dissolved. The by-products of SCWO are typically water vapour, carbon dioxide, and hydrogen (can be generated as a secondary product depending on the composition of the feedstock and reactor operation conditions), whereas the SCWG method generates syngas, which is mostly composed primarily of hydrogen but also smaller amount of carbon dioxide and methane. The composition of the gases generated from SCWO and SCWG may vary depending on different factors, including the feedstock composition, temperature, pressure, residence time, and the presence of catalysts [10,86,87]. Some companies, such as General Atomics, EcoWaste Technologies, Chematur, and Supercritical Fluids International, have been developing both small and large-scale SCWO systems that can be applied to a range of areas, including wastewater treatment [86].

Ref. [87] studied different SCWO systems (small and large scale systems), which were implemented in different locations across several years and based on different feedstocks, including sewage sludge. The authors summarised the main information of different systems, highlighting their location, year of construction, company name, system capacity, and feedstock type. They also highlighted the common operation challenges, which include (i) corrosion due to both a high temperature and pressure, (ii) corrosion due to acid formation, (iii) salt precipitation or plugging, and (iv) high energy consumption and operating costs. Some of the plants stopped operations due to technical and/or economic reasons.

Table 9. Studies focused on sewage sludge gasification from small-scale and commercial plants.

Ref.	Sewage Sludge	Feedstock Characteristics	Operation Parameters	Generated Products
[88]	DSS	HHV 13.5 MJ/kg dry, 8.6% MC, 51.8% VM, 43.1% ash. UA: 51% C, 7.3% H, 7.9% N, 2.05% S, and 31.8% O.	100 kW_{th} FBR, DSS feeding rate of 9–16 kg/h, temperature 790–815 °C, air flow 11–15 m^3/h,	Syngas LHV 3.6–4.5 MJ/m^3 dry, gas composition includes 4.6–6.6% CH_4, 8.4–10.2% H_2, 7.3–9.9% CO, 15.2–16.5% CO and other gases.
[89]	DSS + sp (mix ST)	HHV 13.2 MJ/kg dry, 29.9% MC, 67.7% VM, 9.8% ash. UA: 45.2% C, 5.8% H, 1.2% N, 0.4% S, and 37.4% O.	100 kW_{th} LTCFB reactor, 45 kg of dry SS gasified for 28 h, temperature 500–750 °C, Air eq. ratio of 0.2–0.3	Syngas LHV and HHV as 1.76 and 1.88 MJ/m^3 dry. Gas composition includes 2.5% CH_4, 1.6% H_2, 8% CO, 18% CO_2 and other gases.
	Dry SS + sp (BJ)	HHV 14.8 MJ/kg dry, 12.5% MC, 66.5% VM, 13.3% ash. UA: 43.5% C, 4.2% H, 1.2% N, 0.4% S, and 35.7% O.	6 MW_{th} LTCFB reactor, 7.5 ton of dry SS gasified for 30 h under 500–750 °C, Air eq. ratio of 0.3	Syngas LHV and HHV as 3.84 and 4.2 MJ/m^3 dry. Gas composition includes 4.2% CH_4, 9% H_2, 11.8% CO, 19.4% CO_2 and other gases.
	Dry SS (SLU BJ)	HHV 11.4 MJ/kg dry, 12.5% MC, 42.7% VM, 43.1% ash. UA: 27.6% C, 4.3% H, 3.9% N, 0.8% S, and 19.8% O.	100 kW_{th} LTCFB reactor, 240 kg of dry SS gasified for 14 h, temperature 500–750 °C, Air eq. ratio of 0.2–0.3	Syngas LHV and HHV as 1.88 and 2.05 MJ/m^3 dry. Gas composition includes 2.6% CH_4, 5% of H_2, 4.5% CO, 18.5% CO_2 and other gases.
	Dry SS (SLU RA)	HHV 12.2 MJ/kg dry, 4.6% MC, 43.1% VM, 43.8% ash. UA: 28.7% C, 4.2% H, 3.9% N, 1.3% S, and 18.1% O.	100 kW_{th} LTCFB reactor, 800 kg of dry SS gasified for 40 h under 600–750 °C, Air eq. ratio of 0.2–0.3	Syngas LHV and HHV as 1.96 and 2.16 MJ/m^3 dry. Gas composition includes 2.4% CH_4, 6.6% H_2, 4.2% CO, 17% CO_2 and other gases.
[90]	SS	SS: HHV 2.84 MJ/kg dry, 80.1% MC, 9.78% VM, 8.3% ash. UA: 6.27% C, 1.1% H, 0.77% N, 0.3% S, 3.2% O.	Fluidised-bed gasifier, temperature of 784–822 °C with 0.3 air:fuel ratio. SS feeding rate of 25 kg/min,	Syngas LHV 2.2–2.6 MJ/m^3. Gas composition: 2.9–3.4% CH_4, 3.3–3.5% H_2, 5.6–6.9% CO, 23.2–27.8% CO_2. Gas yield: 28.5 m^3/min, 46.6–53% CGE.
	SS and PMS	PMS characteristics: HHV 4.25 MJ/kg dry, 51.4% MC, 29.9% VM, 18.33% ash. UA: 13.9% C, 2.03% H, 0.42% N, 0.15% S, and 13.8% O.	Fluidized-bed gasifier, 1:1/1:2 SS:PMS mix ratios at 816–858 °C and 0.3 air:fuel ratio. SS feeding rate of 8.3–12.5 kg/min, and 16.7–12.5 kg/min for PMS.	Syngas LHV 1.7–2.42 MJ/m^3 dry. Gas composition: 2.6–3.65% of CH_4, 2.6–4.13% of H_2, 3.95–4.7% of CO, 17.4–25.42% of CO_2 and other gases. Gas yield of 29.4 m^3/min and CGE around 45.6–61.6%.
[91]	Dry SS	6.5% MC, 48.1% VM, 47.6% ash, 4.3% fc. UA: 51% C, 6.9% H, 7.5% N, 2.4% S, and 32% O.	20 kW bubbling fluidised bed reactor, temperature of 850 °C, air ratio of 0.25, fuel mass flow of 7 kg/h.	Syngas yield of 1.3 m^3/kg. Gas composition in fraction mole: 6% of CH_4, 40% of H_2, 20% of CO, 32% of CO_2 and other gases.
[92]	Dry SS	6.8% MC, 38% VM, 50% ash, 12% fc. UA: 29.7% C, 4.3% H, 4.6% N, 1.4% S, 59.9% O. 11.73 MJ/kg HHV.	20 kW reactor operating for 12 h/day at 20 kg/h feeding rate (max of 240 kg/day) at 1000–1150 °C.	Gas composition in fraction mole: 1.2% CH_4, 23.3% H_2, 18.5% CO, 13.4% CO_2 and 43.6% N_2. 1.2 kg SS could produce up to 1 kWh
[93]	Dry SS	LHV 9.2 MJ/kg dry, 7.8% MC, 47.8% VM, 47.5% ash. UA: 48.8% C, 7.4% H, 7.1% N, 2.3% S, and 34.2% O.	20 kW fluidised bed reactor at 800 °C. Parameters: 2.7 kg/h steam, 3.6–5.4 kg/h fuel, 1.5 mol/mol steam:carbon.	Gas yield: 0.85 m^3/kg (800 °C), 0.4 m^3/kg (710 °C). CGE: 60% (800 °C), 45% (710 °C). Gas composition in m^3/m^3: 0.1 CH_4, 0.46 H_2, 0.12 CO, 0.3 CO_2.
[94]	Dry SS	Raw SS: HHV 10.98 MJ/kg dry, 3.2% fc, 55% VM, 41.8% ash. UA: 21.86% C, 3.4% H, 3.8% N, 0.64% S, 28.5% O.	Reactor at 700–900 °C and 1–60 min reaction. SS:SD mix ratios of 1:0, 1:3, 1:1, 3:1, and 0:1. SS upgraded via HTC.	At 900 °C, syngas yield was 0.93 m^3/kg, LHV 5.62 MJ/kg dry and 67% efficiency. Gas composition: 2% CH_4, 5% H_2, 35% CO and 58% CO_2.
	Dry SS and SD	SD-SS: HHV 12–17 MJ/kg, 13–21% fc, 46–65% VM, 13–41% ash. A total of 33–49% C, 3–5% H, 2.5% N, 0.5% S, 19–30% O.	130 W and 20 kHz (ultrasound) and 180 W (ozonation) applied to a 0.2 L of sewage sludge.	At 900 °C and 3:1 SS:SD ratio, syngas yield was 1.04 m^3/kg, LHV 8.15 MJ/kg dry and 77.7% efficiency. Gas content: 7% CH_4, 8% H_2, 45% CO, 40% CO_2.
[95]	SS	64.2% VM. UA: 41.2% C, 5.2% H, 3.2% N, 20.7% O, and calorific value of 14.1 MJ/kg.	Temperature around 750–850 °C, SS mass rate around 170–260 g/h.	Gas yield was 0.45–1.13 m^3/kg (20–23% H_2 and 4–13% CH_4), LHV was 6.5–9.7 MJ/m^3. Biochar HHV up to 15 MJ/kg
[96]	Dry SS	LHV 13.2 MJ/kg, 7.1% MC, 51.53% VM, 4% fc, 37.4% ash. UA: 31.3% C, 4.56% H, 4.72% N, 1.3% S, 20.7% O.	Fluidized bed reactor at 813–817 °C, 60–260 min reaction time, and usage of additives (AC, Ni, Fe)	Syngas LHV 5.04–6.52 MJ/m^3 dry, 67.5–88.87% CGE. Gas content: 4–6.5% CH_4, 13.4–28.13% H_2, 10–13.4% CO, 9.4–14.5% CO_2, 44–51.7% N_2 and others.

Table 9. *Cont.*

Ref.	Sewage Sludge	Feedstock Characteristics	Operation Parameters	Generated Products
[97]	Dry SS	LHV 13.1 MJ/kg dry, 8.7% MC, 51.3% OM, 41.7% ash. UA: 29.5% C, 4.9% H, 4.1% N, 1.6% S, and 15.0% O.	Fluidised bed gasified with 0.3 air: fuel ratio and 800 °C operating temperature. A total of 1.2–3.7 g/min SS feeding rate, and use Do as catalyst (10% mix with sludge)	Without De: Syngas LHV 2.9–3.6 MJ/m^3, 35.7–43.2% CGE of, gas yield 2.7–3 m^3/kg. Gas content: 2.3–3.3% CH_4, 8.5–10.3% H_2, 6.1–9% CO, 13.2–13.9% CO_2. With De: Syngas LHV 2.9–3.9 MJ/m^3, 35–49% CGE, gas yield 2.8–3.2 m^3/kg. Gas content: 2.2–3.2% CH_4, 9.6–14% H_2, 5.3–9.7% CO, 12.6–15% CO_2.
[98]	Dry SS	LHV 17 MJ/kg dry, 5.3% MC, 61.56% VM, 26.14% ash, 7% fc. UA: 39.5% C, 5.8% H, 5.3% N, 0.9% S, 24.4% O.	2-stage gasifier in series. A total of 2 kg/h feeding rate of, and use additives (AC, CaO). A 0.25 eq. ratio and 785–820 °C.	52.5–66% syngas, 19.2–23% char, 14.3–20.3% condensate liquid and tar. Syngas LHV was 9.2–11.7 MJ/m^3 dry and 51.7–80.1% CGE. Gas content: 7.2–8.5% CH_4, 28–52.2% H_2, 15.9–19.3% CO, 20–32.4% CO_2 and 3.8–8.9% N_2.
[99]	DSS	SS Characteristics: LHV 14.26 MJ/kg dry, 18.75% MC, 33.4% VM, 11.6% ash, 36.3% fc. UA: 45.55% C, 6.6% H, 1.1% N, 1.2% S, and 33.9% O.	2-stage gasifier (fluidized bed and tar-cracking reactors) connected in series. Operating temperature of 800 °C, air flow rate 13–17 L/min, operating time 60 min.	65.5–75.3% syngas, 15–22.4% char, 9% condensate liquid and tar. Syngas LHV of 5.35–6.1 MJ/m^3 dry and 67–92.4% CGE. Gas composition: 4.5–5.4% CH_4, 14.6–22.6% H_2, 9.7–12.4% CO, 10.64–10.9 CO_2 and 51.6–54.5% N_2.
	DSS and coal	Coal Characteristics: 1% MC, 22.5% VM, 17.8% ash, 64.95% fc. UA: 78.5% C, 0.6% H, 0.43% N, 0.4% S, and 2.32% O. Coal:DSS mix ratio of 70:30, 50:50, and 30:70.		74% syngas, 12.5–13.7% char, 11.8–13.3% condensate liquid and tar. Syngas LHV of 5.1–5.4 MJ/m^3 dry, 80.6–84.3% CGE. Gas composition: 3.8–4% CH_4, 24–26.6% H_2, 9.46–10.4% CO, 11.12–12.5% CO_2 and 46.2–50.8% N_2.
[100]	Dry SS	LHV 15.1 MJ/kg dry, 8.2% MC, 56.9% VM, 30.3% ash, 4.6% fc. UA: 39.8% C, 6.4% H, 5.6% N, 1.2% S, and 24.7% O.	2-stage gasifier (fluidized bed and tar-cracking reactors) connected in series, 760–815 °C temperature, 90–100 min reaction, and use of AC as additive.	68.6–76.9% syngas, 12–19.5% char, 6.2–20% condensate liquid and tar. Syngas LHV of 5.4–7.5 MJ/m^3 dry. Gas composition: 2.7–7% CH_4, 9.6–34.1% H_2, 9.2–17.2% CO, 6.5–14.6 CO_2, 38.4–64.4% N_2 and other elements.
[101]	Dry SS	LHV 14.1 MJ/kg dry, 4.7% MC, 51.3% VM, 24.1% ash. UA: 39.46% C, 5.8% H, 5.35% N, 0.9% S, and 24.4% O.	2-stage gasifier, 13 L/min ratio, and 785–810 °C. A 10.4–16.6 g/min feeding rate for 75–220 min, and used additives.	Syngas LHV was 5.65–7.1 MJ/m^3 dry. Gas content: 3.2–5.8% CH_4, 11.8–31.3% H_2, 9.1–18.4% CO, 7.6–14.7% of CO_2, 39.5–54.4% of N_2 and other elements.

SS: Sewage sludge; DSS: Dewatered sewage sludge; PMS: Paper-mill sludge; SD: Sawdust; LTCFB: Low Temperature Circulating Fluidised Bed; De: Dolomite, CGE: Cold gas efficiency; HHV: Higher heating value, LHV: Lower hearing value; AC: Active carbon; OM: Organic matter; MC: Moisture content; UA: Ultimate analysis; fc: Fixed carbon; sp: Straw pellets; FBR: Fluidized-bed reactor.

Table 10. Studies focused on sewage sludge pyrolysis.

Ref.	Sludge Collection	Feedstock Characteristics	Operation Parameters	Generated Products
[102]	WWTP in Medellin, Colombia	6.56 MJ/kg dry HHV, 6.1% MC, 27.24% VM, 3.3% fc, 63.4% ash. UA: 12.8% C, 1.74% H, 1.2% N, 0.55% S, 16.22% O.	Fluidised bed reactor operated at an atm pressure. Operating temperature between 300 °C and 800 °C.	At 500 °C and 600 °C, the biochar, bio-oil and gas yields were 14–27%, 28–39%, and 45–47%, respectively. At 800 °C, gas content included 50% H_2, 20% CO_2, 20% CO, and 10% CH_4. At 600 °C, it was 43% H_2, 37% CO_2, 12% CO, and 8% CH_4.
[103]	Municipal WWTP in Dalian, China	13.6 MJ/kg dry HHV, 76.6% MC, 27.24% VM, 3.3% fc, 63.4% ash. UA: 12.8% C, 1.74% H, 1.2% N, 0.55% S, and 16.22% O.	Quartz cylindrical reactor. Sludge pyrolised for 4 h with heating rate of 3 °C/min at temperatures ranging from 500 °C to 800 °C.	The char, bio-oil and gas yields were around 17.5–25%, 38–43.5%, and 37–42%, respectively. Highest yields for char, bio-oil and gas were at 800 °C, 600 °C, and 500 °C. The lowest value was at 600 °C, 500 °C/800 °C, and 800 °C, respectively.

Table 10. *Cont.*

Ref.	Sludge Collection	Feedstock Characteristics	Operation Parameters	Generated Products
[104]	Carter's Creek WWTP in Texas, USA	18.5 MJ/kg dry HHV, 1.9% MC, 68.1% VM, 14.1% fc, 17.8% ash. UA: 39.4% C, 5.6% H, 7.8% N, 0.8% S, and 28.6% O.	Fast pyrolysis using a bench-scale bubbling fluidized bed reactor. Temperature between 425 °C and 550 °C.	Highest bio-oil yield was 35.7%, biochar was 28.7% and biogas 23.5%, and 11.8% losses. The bio-oil HHV ranged between 24.3 MJ/kg (at 425 °C) and 37.6 MJ/kg (at 550 °C). The generated biochar HHV was 7.4 MJ/kg.
[105]	Urban WWTP in Barcelona, Spain.	11.1 MJ/kg dry HHV, 5.6% MC, 54.2% VM, 8.6% fc, 37.2% ash. UA: 25.5% C, 4.5% H, 4.9% N, 2.1% S, and 25.8% O.	Flash pyrolysis using a conical spouted bed reactor (CSBR) at between 450 °C and 600 °C.	Char and bio-oil yields at 450 °C, 500 °C, 550 °C, 600 °C were 51%, 46%, 44%, 43%, and 45%, 48.5%, 48.5%, 46%, respectively. Gas yield of 4–11%.
[106]			Fast co-pyrolysis with SS and lignocellulosic biomass in a conical spouted bed reactor.	At 500 °C, the gas, bio-oil and biochar yields were 12%, 55%, and 33%, respectively,
[107]	WWTP in Minnesota, USA.	4.5% MC, 68.6% VM, 0.3% fc, 16.4% ash. UA: 53.24% C, 7.4% H, 6.12% N, and 33.25% O. A total of 24.42 MJ/kg HHV.	A cfMAP with 1 kW power and 2450 MHz was used. Temperature of 450–600 °C. Used ZSM-5 as catalyst (activated at 550 °C for 4 h)	The energy value for bio-oil, biochar and gas varied between 2.2 and 7.7 MJ/kg, 2.14 and 5.4 MJ/kg, and 5.6 and 9.4 MJ/kg, respectively. The char, bio-oil and gas yields were between 33 and 62.5%, 16 and 40%, and 21.5 and 40%, respectively.
[108]	WWTP in Shaanxi, China	4.57% MC, 63.13% VM, 5.47% fc, 26.83% ash. UA: 29.12% C, 5.98%, 3.98% N, 1.64% S, 21% O. A total of 16.7 MJ/kg HHV.	Fast pyrolysis using a fixed bed quartz tube reactor at operating temperature between 500 °C and 900 °C.	Char, bio-oil and gas yields ranged between 14 and 35%, 37.5 and 71%, and 15 and 27.5%, respectively. The generated gas included 8–36% H_2 and below 7% CH_4. CO content was 35%, at 900 °C, and below 10% for the other temperatures
[109]	urban WWTP in Madrid, Spain.	7% MC, 50% VM, 3% fc, 40% ash. UA: 27.9% C, 4.7% H, 4.5% N, 1.4% S, and 34.6% O. A total of 12.5 MJ/kg HHV.	Bench-scale stirred batch reactor at 525 °C under N_2 atmosphere.	At 525 °C, the biochar, bio-oil and gas yields were approx. 50%, 41%, and 9%, respectively. LHV of the pyrolised SS was 10 MJ/kg.
[110]	WWTP in Beijing, China.	SS: 2.25% MC, 61.52% VM, 6.7% fc, 29.5% ash. UA: 53.2% C, 7.5% H, 6.4% N, 2% S, and 30.9% O. Cb: 4.6% MC, 78.1% VM, 15.64% fc, 1.7% ash. UA: 49.2% C, 6.3% H, 0.5% N, 0.3% S, and 43.7% O.	Tube furnace reactor under 400–800 °C. Pyrolysis rate of 20 °C/min under N_2 protection (99.99%, flow rate = 25 mL/min). Mix ratio of SS:Corncob of 1:1	The yields of char, bio-oil and gas varied from 30.4% (800 °C) to 75.1% (400 °C), 10.2% (400 °C) to 51.8% (800 °C), and 14.7% (400 °C) to 20% (700 °C), respectively. Gas content: CH_4 and CO below 10%, H_2 ranged from 22% to 59% and CO_2 from 35% to 59%.
[111]	Nanjing urban WWTP in Nanjing, Jiangsu province, China.	SS: 79% MC, 31.52% VM, 5.25% fc, 63.23% ash. UA: 20.9% C, 8.7% H, 3.5% N, 0.9% S, 2.8% O. HHV 12.5 MJ/kg. SD: 6.3% MC, 73.6% VM, 14.4% fc, 5.7% ash. UA: 49.5% C, 7% H, 0.3% N, 0.4% S, 42.7% O.	Co-pyrolysis conducted in a screw moving bed reactor. Operating parameters included 900 °C at 20 °C/min rate and kept for 30 min based on the 16 g/min feeding rate. SD content mixed with SS were 0, 20%, 40%, 60% and 80%.	Generated gas had an HHV of 14 MJ/kg, 13.4 MJ/kg, 13.45 MJ/kg, 13.41 MJ/kg and 13 MJ/kg for a mix of SD about 0, 20%, 40%, 60% and 80%, respectively. Dry gas yield for a mix of SD of 0, 20%, 40%, 60% and 80% was 0.24 m^3/kg, 0.36 m^3/kg, 0.55 m^3/kg, 0.66 m^3/kg, 0.74 m^3/kg, respectively. The H_2, CH_4, CO_2 and CO were 29.13–42.35%, 10.5–18.9%, 14.6–24.1%, and 26.8–31.4%, respectively.
[112]	WWTP in Australia.	Biosolids: 20–80% MC. UA: 35.7% C, 5.2% H, 3.5% N, 25.4% O, 0.7% S on wt%.	450–850 °C, 1 atm and feed rate of 265 kg/h. Costs included AUD 1000/kW (reactor and turbine), AUD 600/m^3 (N_2) plant, AUD 3/m^3 for water, and AUD 0.03/kW for electricity.	The biochar, bio-oil and gas composition was 43.2–53%, 37.7–40.4% and 9.3–17.2%, respectively. From 650 °C to 850 °C, the gas increases (HHV decreased from 23.2 to 20 MJ/kg) and oil decreases. For a 30-year plant operation, the NPV was AUD 2.3–2.6.

HHV: Higher heating value; LHV: Lower hearing value; VM: Volatile Matter; UA: Ultimate Analysis; MC: Moisture; fc: Fixed Carbon wt: wet basis; cfMAP: continuous fast microwave-assisted pyrolysis; SD: sawdust; SS: sewage sludge; Cb: Corncob.

Table 11. Studies that applied hydrothermal treatments using sewage sludge.

Ref.	Type	Sludge Collection	Feedstock Characteristics	Parameters	Generated Products
[113]	HTC	Jiangxinzhou WWTP in China.	82.5% MC. UA: 39.88% C, 6.20% H, 6.04% N, 20.5% O, 5.62% S. A total of 17.97 MJ/kg HHV.	1 L batch reactor with maximum pressure and temperature of 35 MPa and 500 °C.	Gas production of 1.59 L at 200 °C under 2 MPa and 2.86 L at 360 °C under 19.4 MPa. At 380 °C, H_2 and CH_4 yields were 0.14 and 0.24 mol/kg, respectively.
[114]		WWTP in Nanjing, China.	89.2% MC, 56.9% VM. UA: 25.6% C, 4.4% H, 4.6% N, 22% O, 0.2% S. 11 MJ/kg HHV.	5 reactors operation under 200–250 °C and 2–26 MPa.	H_2 yield reached 0.7 mol/kg at 450 °C, accounting for 11.2 v/v% of the syngas. At 400 °C, H_2 yield was below 0.15 mol/kg.
[115]		Il-San municipal WWTP, in Korea	66.9% VM. UA: 38.55% C, 6.46% H, 8.05% N, 46.50% O, 0.44% S. HHV of 16.5 MJ/kg.	1 L autoclave reactor under 180–280 °C and 30 min reaction time.	The HHV of the solid fuel was around 17.3–22.4 MJ/kg. Energy recovery efficiency decreased (from 92.2% to 89.6%) with the increase in temperature.
[116]		WWTP in Japan.	85.94% MC. UA: 51.20% C, 6.64% H, 8.85% N, 31.94% O, 1.37% S on db. 18.81 MJ/kg HHV	Operating temperature around 180–240 °C and 15–45 min reaction time.	Lowest HHV was 18.30 MJ/kg at 180 °C and 15 min. Highest value was 20.17 MJ/kg at 240 °C and 45 min. Recovery efficiency of 40% (>200 °C).
[117]		WWTP in Changsha, China.	89.3% MC, 47.5% VM. UA: 25% C, 4.2% H, 4.8% N, 15.3% O, 0.74% S, 11 MJ/kg HHV	0.5 L 316 stainless steel reactor (180–300 °C temperature and 30–480 min reaction time.	Maximum HVV was 12.06 MJ/kg at 260 °C and 1 h reaction. Lowest value (9.8 MJ/kg) was for 3 h reaction and 260 °C (high reaction time does not increase HHV).
[118]		WWTP in Ratmal-na, Sri Lanka	81% MC. UA: 34.41% C, 5.21% H, 4.75% N, 23.3% O, 1.73% S on db. 15.2 MJ/kg HHV	Temperature between 100 and 200 °C and reaction up to 1 h.	Maximum (89%) and minimum (73.7%) char yields. Highest HHV (16.17 MJ/kg) at 150 °C and lowest HHV (13.57 MJ/kg) at 100 °C.
[119]		WWTP in Kar-miel city, Israel.	81% MC. UA: 40.3% C, 5.8% H, 4.7% N, 19.4% O on db. A total of 18.0 MJ/kg HHV	0.5 L stainless steel stirred reactor, 200–300 °C and 0.5, 1, and 2 h retention times.	Hydrochar HHV ranged from 18.2 MJ/kg (200 °C, 0.5 h) to 21.5 MJ/kg (300 °C, 0.5 h). Highest and lowest BMP yield were 236.0 and 25.7 mL CH_4/gCOD.
[120]		WWTP in Shimodate, Japan	79% VM. UA: 48.94% C, 7.09% H, 2.51% N, 33.4% O, 0.65% S on db. 21.0 MJ/kg HHV	0.2 L reactor for 0.5 h and 180 °C, at 6:1, 4:1, 3:1 and 2:1 mixing ratios	SS hydrochar HHV was 21.59 MJ/kg (180 °C and 30 min) and HTC input energy was 115.96–117.7 MJ. Hydrochar HHV was about 23.46–25.34 MJ/kg.
[121]		WWTP in Gwangju, Korea.	72.33% VM. UA: 52.29% C, 7.89% H, 6.39% N, 32.62% O, 0.81% S on db. A total of 20.6 MJ/kg	1 L reactor operating under 180–270 °C and 30 reaction time.	Hydrochar HHV was around 18.66–23.44 MJ/kg. Maximum (93.13%) and minimum (40.78%) char yields were achieved at 180 °C and 270 °C.
[122]	HTL	Adelaide plant, Ontario, Canada.	62.2% VM, 96.1% MC. UA: 38.0% C, 5.23% H, 7.2% N, 25.2% O, 0.75% S. 16.0 MJ/kg HHV	0.1 L stirred reactor under 2 MPa, 200–350 °C, 10–60 min reaction.	Composition of oil, solid and WSP were 11.3–33.6 wt%, 9.9–61.2 wt%, and 27.3–62.3 wt%. From WSP, biogas was recovered (up to 0.8 L in 31 days).
[123]		WWTP at Viborg, Denmark.	Dry matter of 4 wt%. UA: 46.5% C, 6.1% H, 3.3% N, 31.2% O, 0.4% S. A total of 19.8 MJ/kg HHV	Reactor with 1.66 L/min feed capacity (20 L vol.), 350 °C temperature and 5 h reaction.	Bio-crude average yield of 24.5 wt%, chemical energy recovery of about 33.6%, and an average of HHV of around 26.9 MJ/kg.
[124]		Marselisborg WWTP, Denmark	Not informed	HTC batch reactor (20 mL) at 340 °C and 20 min reaction time.	With K_2CO_3 catalyst, the HHV and chemical energy recovery increased from 36.1 to 38 MJ/kg and 56 to 67%, respectively.
[125]		Daugavgriva plant in Riga, Latvia.	80.5% MC, 56.8% VM. UA: 52.0% C, 7.6% H, 7.5% N, 30.4% O, 2.6% S. A total of 15.3 MJ/kg HHV	Batch stainless steel autoclave reactor at 200–300 °C and 10–100 min reaction time.	Highest bio-oil yield (47.8%) and 70% recovery achieved under 5.0 MPa, 300 °C, and 40 min time. Lowest bio-oil yield (34.5%) with 36.2 MJ/kg HHV at 200 °C.
[126]		WWTP in Aalborg Forsyning, Denmark.	73.4% MC, 50.5% VM. UA: 50.9% C, 7.4% H, 6.9% N, 34.8% O, 0.8% S. A total of 22.15 MJ/kg HHV	0.1 L stainless steel reactor at 350–400 °C, 10 MPa, and 15 min reaction time.	At 350 °C and no catalyst, bio-crude HHV was 35.3 MJ/kg and 64% energy recovery. With catalyst, HHV was 36.6 MJ/kg and 74.6% energy recovery.

Table 11. *Cont.*

Ref.	Type	Sludge Collection	Feedstock Characteristics	Parameters	Generated Products
[127]	HTL	Beishiqiao plant in Xi'an, China	90% MC. UA: 33.9% C, 5.1% H, 5.8% N, 16.5% O, 3.2% S. A total of 16.1 MJ/kg HHV	4.4 mL mini-batch reactors at 18 MPa with temperature ranging 260–350 °C.	Highest biocrude yield (23 wt.%), 35.4 MJ/kg HHV and energy recovery (50.2%) at 340 °C. Lowest energy recovery (32.6%) with 34.84 MJ/kg HHV at 260 °C.
[128]		WWTP in State College, PA, USA.	97.8% MC. UA: 46.5% C, 7.0% H, 2.1% N, 33.3% O, 0.8% S. A total of 19.9 MJ/kg HHV	4.1 mL reactor at isothermal HTL (673 K, 1 h) and non-isothermal HTL (773 K, 1 min).	With 10 wt% and 50 wt% additives, biocrude yield ranged around 18.9–21.7% and 10.2–18.6% (isothermal), and 24.8–29.1% and 10.9–27.5% (non-isothermal).
[129]		Qinghe WWTP in Beijing, China	84.5% MC. UA: 46.7% C, 6.8% H, 8.1% N, 37.6% O, 0.8% S.	0.6 L batch stainless 316 reactor, at 210–330 °C, 30 MPa and 0.5 h.	At 210 °C, biocrude yield was 39.9% and 86.3% HTL conversion. At 270 °C, it increased to 47.5% and 97.7%, and at 330 °C, it decreased to 41% and 90.1%.
[130]		Municipal WWTP in Changsha, China.	UA: 28.9% C, 4.5% H, 4.2% N, 13.9% O, 0.6% S.	0.5 L autoclave reactor (316 stainless steel) at 350–400 °C, 35 MPa (max), and 0.5 h.	Bio-crude HHV about 37.8–39 MJ/kg at 350 °C and 0.5 h reaction time. For SS with no pyrolysis, bio-crude HHV was 37.35 MJ/kg at 350 °C and 30 min reaction.
[131]		WWTP in Doha, Qatar.	83.6% MC. UA: 30.5% C, 6.2% H, 5.5% N. A total of 16.9 MJ/kg HHV	0.1 L reactor under 275–400 °C and 30–120 min reaction time.	For a 0.5h reaction time and 350 °C, maximum biocrude yield was 44.8%, whereas at 275 °C, the lowest biocrude yield was reached (less than 20%).
[132]		H.C. Morgan Water Facility, in Alabama, USA.	82.4% MC, 52.9% VM. UA: 33.1% C, 5.5% H, 5.0% N, 25.9% O, 0.7% S. A total of 14.1 MJ/kg HHV	1.8 L reactor at 350 °C, and 1 h. Used red mud (RM) catalyst: calcined RM, reduced RM at 500 °C, and reduced RM at 700 °C	At 25 wt% of CRM ethylene, RM at 500 °C ethylene and RM at 700 °C ethylene, the biocrude yield reached 27.1%, 31.3% and 38.3%, respectively, and HHV was 30.43 MJ/kg, 28.29 MJ/kg and 28.44 MJ/kg, respectively.
[133]		WWTP in Shenyang, China	84.9% MC. UA: 40.6% C, 4.7% H, 3.7% N, 49.6% O, 1.2% S. A total of 14.3 MJ/kg HHV	Batch-type 0.5 L reactor at 340 °C and 40 min reaction time.	Bio-oil HHV was 32.2 MJ/kg. After using treatment methods, it increased to 33.5–35.3 MJ/kg, and maximum HHV was reached (37.2 MJ/kg).
[134]		Qinghe WWTP, in Beijing, China.	53.5% OM. UA: 44.7% C, 7.6% H, 7.2% N, 39.6% O, 1.0% S. A total of 21.3 MJ/kg HHV	1 L stainless 316 steel reactor with 400 °C and 20 MPa.	Bio-oil HHV was 29.05 MJ/k (control). With treatment, Bio-oil HHV was 25.3–41.5 MJ/kg. Bio-oil HHV treated with HCl reached up to 45.2 MJ/kg.

BMP: Biomethane Potential; MC: Moisture; UA: Ultimate Analysis; OM: Organic Matter; db: dry weight basis; WSP: water-soluble products.

Ref. [135] reviewed supercritical technologies exploring their influences on the hydrogen production based on different parameters (i.e., sludge properties, moisture, and temperature). They presented some real-world projects, including small and large-scale plants, including the pilot-scale systems developed by Duke University, University of Missouri, University of Valladolid, and Xi'an Jiaotong University). Commercial projects were also highlighted as follows:

- HydroProcessing: An SCWO system implemented in the Harlingen WWTP in Texas, USA, in 2001. Some operating parameters of this system included a 150 ton/day capacity, 592 °C temperature, 24.5 MPa pressure, 20–90 s reaction time, and 6–9% solid content. The consumption of heater, oxygen, and pumps were 4.1 MWh/dry ton sludge, 1.5 ton/dry ton sludge, and 0.55 MWh/dry ton sludge, respectively. The capital and operating costs of the project were about 3 million USD and 100 USD/dry ton of sludge, respectively.
- Chematur AB: Two SCWO systems were developed: (i) first system included a 250 kg/h capacity for demonstration purposes, and (ii) second had a capacity of 1.1 ton/h, built with a plan to treat the sewage sludge of Kobe, Japan. The operational parameters of the second system included a 25 MPa pressure, 30–90 s reaction time, 400–600 °C, and operation at 15% dry solids. The consumption of natural gas, oxygen, cooling water, and electricity was around 21.9 Nm^3/dry ton sludge, 1.05 ton/dry ton sludge, 100 m^3/dry ton sludge, and 228.6 kWh/dry ton sludge, respectively. The capital and operating cost of the project were about 5 million GBP and 70 GBP/dry ton sludge, respectively.
- SuperWater solution: It was implemented in the Iron Bridge Regional Water Reclamation facility in Orlando, USA. Tested between 2009 and 2011, the SCWO system had a capacity of 5 t/d. The capital and operating costs were around 268 USD/dry ton sludge and 33.7 million USD, respectively. System's parameters included 35 dry ton sludge/d capacity, a 600 °C operating temperature, 26 MPa pressure, a 30–60 s reaction time, and 10% dry sludge.

Table 12 presents some studies that used supercritical water technologies to investigate the potential of hydrogen production using sewage sludge as feedstock.

3.1.3. Transesterification

The transesterification of sewage sludge is a chemical process in which the triglycerides/lipids (i.e., fats, oils, and greases) present in the feedstock are converted into biodiesel and glycerol by reacting them with an alcohol (usually methanol or ethanol) in the presence of a catalyst (typically an alkaline). This reaction produces methyl esters (biodiesel) and glycerol as by-products. The biodiesel produced is a fatty acid methyl ester (FAME) that can be used as a renewable fuel in diesel engines. It has properties similar to conventional diesel fuel but is derived from biological sources [136]. Two main techniques, lipid extraction and esterification/transesterification or direct in situ esterification/transesterification, are used to produce biodiesel from sewage sludge. Biodiesel production from sewage sludge can be divided into five main steps: (i) sludge pre-treatment (improve lipid extraction), (ii) lipid extraction from sewage sludge, (iii) use of extracted lipids to generate biodiesel, (iv) use of catalysts (optimise process), and (v) extraction of valuable by-products. This process provides a great alternative to managing sewage sludge by reducing its volume and converting waste into a useful product [17].

Pyrolysis also generates biodiesel from sewage sludge, but not directly. The by-products of pyrolysis include gaseous products, solid char and bio-oil. The bio-oil can be further processed and refined to be converted into biodiesel. Pyrolysis can be adjusted to increase the desired bio-oil fraction and, consequently, biodiesel production [137]. Table 13 summarises some works based on converting sewage sludge into biodiesel using transesterification and pyrolysis.

Table 12. Studies related to utilising supercritical water gasification on sewage sludge for hydrogen production.

Ref.	Sludge Collection	Sewage Sludge Properties	Parameters	Gas Production
[138]	WWTP in Jiangsu, China.	73.5–88.5 wt% MC. UA: 7.6–31% C, 2.3–6.2% H, 0.4–3.5% N, 20.2–34.1% O, 0.9–3.3% S. Up to 13.7 MJ/kg HHV	316 L batch reactor under 400 °C, 1 h reaction time.	Total gas production ranged from 10.7 to 43.3 mol/kg (mean gas production of 18.9 mol/kg).
[139]	WWTP in Shaanxi, China.	84 wt% MC. UA: 38.2% C, 2.4% H, 4.7% N, 23.7% O, 1% S. A total of 14.6 MJ/kg LHV	Heating rate reactor (70 °C/min) under 550–750 °C and 30 MPa	H_2 production up 18.9 mol/kg under 750 °C and 20 min
[140]	Municipal WWTP in Zhengzhou, China.	79 wt% MC, 65 wt% OM. UA: 7.4% C, 15.5% H, 1.3% N, 55.7% O, 3.8% P, TOC of 0.88 g/L	0.6 L reactor, 27 MPa, 6 min retention time and 380–460 °C temperature	H_2 production ranged from 2.5 mol/kg (380 °C) to 19.9 mol/kg (460 °C), and CH_4 production ranged from 1.8 mol/kg (380 °C) to 8.2 mol/kg (460 °C).
[141]	Municipal WWTP in Jiangsu, China.	77–88.5 wt% MC. UA: 7.6–27.5% C, 2.1–5.2% H, 0.4–3.8% N, 12.9–34.1% O, 0.9–2.5% S. Up to 12.6 MJ/kg HHV.	316 L batch reactor under 400 °C, 10 min reaction time and 24 Mpa.	H_2 yield was 1.06 mol/kg (control). With 5 wt% of NaOH and Ni, it was 2.7 and 3.6 mol/kg, respectively. For a mix of 3.3 wt% Ni and 1.67 wt% NaOH, 4.8 mol/kg,
[142]	Municipal WWTP in Nanjing, China.	83.2 wt% MC, organic matter of 45.1 wt%. UA: 19.5% C, 3.7% H, 3.2% N, 18.5% O, 0.2% S, 8.7 MJ/kg HHV	316 L batch reactor under 400 °C, 1 h reaction time and 22.1 MPa.	With Ni of 2–10 wt%, H_2 yield was 0.6–1.05 mol/kg. With H_2O_2, H_2 yield decreased from 0.31 mol/kg (2 wt% H_2O_2) to almost 0 mol/kg (10 wt% H_2O_2).
[143]	WWTP in Jiangsu, China.	73.9 wt% MC, 26.2 wt% OM. UA: 12.9% C, 2.1% H, 1.93% N, 4.24% O, 1.01% S. 4.8 MJ/kg HHV.	316 L batch reactor under 400 °C, 0.5 h reaction.	With no FA, H_2 yield was 0.16 mol/kg. With FA of 1, 2, 4 and 6 wt%, H_2 yield was 0.52, 1.2, 3.47 and 10.07 mol/kg, respectively.
[144]	WWTP in Higahashi-Hiroshima, Japan.	79.16 wt% MC. UA: 43.1% C, 6.6% H, 4.4% N, 25.9% O, 2.4% S on db.	316 L reactor under 500–600 °C, 25 MPa and 5–60 s reaction time.	At 550 °C and 600 °C, H_2 composition was about 38.5–39.4 vol%. At 500 °C, CO_2 composition was 49.5 vol%.
[145]	Domestic WWTP in Japan.	78.8 wt% VM. UA: 38.3% C, 5.9% H, 7.9% N, 33% O, 1% S on db.	Bench-scale reactor under 600 °C, 23 MPa and 1 h reaction time.	Total gas yield of 9.8 mol/kg with a composition of 60% of H_2.
[146]	WWTP in Nanjing, China.	75 wt% MC, 40.8 wt% OM. UA: 19.5% C, 3.7% H, 3.18% N, 14.25% O, 0.17% S on db. A total of 9.45 MJ/kg HHV.	Batch reactor under 23 MPa pressure, 400 °C for 10 min.	H_2 yield was 0.12 mol/kg without Ni catalyst, and 0.47 mol/kg with 1 cycle of Ni. H_2 yield decreased with more Ni cycles.
[147]	WWTP in Hangzhou, China.	35.14 wt% VM, 57.4 wt% OM. UA: 18.94% C, 2.21% H, 2.89% N, 12.79% O, 0.6% S on db. A total of 5.89 MJ/kg LHV.	0.5 L batch reactor under 26–28 MPa, 1 h reaction and 380–460 °C temperature.	H_2 yield was 6.44 mol/kg with 38.4% of H_2 composition.
[148]	Paşaköy WWTP in Istanbul, Turkey	57.4 wt% VM. UA: 29.4% C, 4.4% H, 17.9% O, 5.29% N, 0.47% S on db. pH of 5.84.	3.12 L reaction (20 L feed tank), operated with a 25 mL/min flow.	H_2 production increase from 3.4 L/h at 500 °C to almost 4.5 L/h at 650 °C.
[149]	Xi'an WWTP in Shaanxi, China.	87 wt% MC, 51.12 wt% VM. UA: 37.58% C, 4.4% H, 5.72% N, 24.44% O, 0.84% S. 9.64 MJ/kg HHV.	Batch reactor under 25 MPa pressure and 20 min reaction time.	The H_2 yield was 0.66, 1.93, 3.95, 7.44 and 11.81 mol/kg for 400 °C, 450 °C, 500 °C, 550 °C and 600 °C, respectively.

TOC: Total organic carbon; UA: Ultimate Analysis; OM: Organic Matter; MC: Moisture Content; db: dry weight basis.

Table 13. Studies on biodiesel production from sewage sludge.

Ref.	Type	Sludge Collection	Parameters	Gas Production
[136]	T	Municipal WWTP located in Tamil Nadu, India.	Lipid extraction performed for 6 h using 50 mL of chloroform methanol (2:1 ratio), diethyl ether, n-hexane and ethanol. Samples heated (50 °C for 0.5 h), and removed solvent	Total lipids extracted from PSS and SSS were between 3 and 6.5 g and 3.3 and 4.9 g using different solvents with concentration of 32.5% (PSS) and 24.5% (SSS). The generated biodiesel included: 89.2–91.2%, ester content, of 40.6–42.9 MJ/kg HHV, 65–72.6 cetane and saponification value of 131–162 mg of NaOH.
[150]	T	SS collected from two WWTPs in Beijing, China.	SS heated (45–75 °C), stirred at 300 rpm, added to methanol, H_2SO_4 and hexane solutions for 8 h. NaCl and hexane added, and the final mixture was centrifuged (3000 rpm) for 5 min, and filtrated.	Average biodiesel yield was 14.9% and 3.7% for A^2/O and MBR processes. Maximum biodiesel yield of 16.6% for A^2/O treatment was obtained using methanol:SS ratio of 10, 60 °C, and 5% H_2SO_4 con-centration. For the MBR process, the maximum value of 4.2% used ratio of 8, 50 °C, and 5% H_2SO_4.
[151]	T	WWTP at Universi-dad Rey Juan Car-los, Madrid, Spain.	Used methanol and n-hexane for extraction and reaction, and Zr-SBA-15 as catalyst. FAME producted in a 25 mL reactor at 209 °C, 2000 rpm, 50:1 methanol ratio and 12.5 wt% catalyst.	2 approaches used. (i) 1-step direct conversion: Overall weight FAME yield for PSS and SSS were about 15.5 wt% and 10 wt% (based on dried sludge mass), respectively. (ii) 2-step process: FAME yield was lower than 6% for PSS and almost negligible for SSS.
[152]	T	WWTP in Osong City, Korea.	1 L flask using a mixture of dewatered SS, methanol and n-hexane, and H_2SO_4 as catalyst, and stirred at 100 rpm. Reaction time varied from 1 to 8 h, and temperature of 55 °C (n-hexane) and 105 °C (xylene).	Maximum biodiesel yield generated from in situ transesterification were between 8.04% and 9.68% using n-hexane (solvent) and 10 mL/g methanol:SS ratio, and for a mix of PSS and SSS using 2 mL/g methanol:sludge ratio, it was 3.28% (n-hexane) and 8.12% (xylene)
[153]	T	WWTP in Villapérez-Oviedo (Asturias, Spain).	Hexane and methanol as solvents and extraction used 1:2 SS:hexane ratio. Solvent removed at 70 °C, and samples stored after 1 h drying at 105 °C. For solid liquid extraction, 1:10 SS:hexane ratio for 4 h.	Maximum production of 0.4 g FAME/100 g dry SS was achieved (26.8% of the total lipid extracted) for 24 h reaction. Total lipids extraction was 9% (1.75 g lipids/100 g dry SS) using hexane. For methanol (4% v/v), a 2.1% FAME content was achieved, whereas 0.4% was obtained for solid–liquid procedure.
[154]	T	Municipal WWTP in Oviedo, Spain	Reactor at 60 °C for 24 h, and methanol. NaOH (catalyst) at 4 ratios of methanol: 4%, 30%, 50% and 70%. SS:methanol ratio of 1:10. Used also H_2SO_4 in methanol (4% v/v) and mixed with SS in a 20:1 ratio. Microwave, sonication and particle sieving used for lipid extraction.	Maximum biodiesel yield of 14.3% (mass of FAME/lipid content). After 5 h reaction, biodiesel yield using 0.4% H_2SO_4 transesterification reached 22.2%, whereas the biodiesel yield using between 30% to 70% NaOH reached between 7 and 14.5%. Using microwave applied to dried SS for 4 min increased the FAMEs production by 110% (from 22.1 to 46.7%), whereas sonication improved by up to 42%.
[155]	T	PSS and SS from the Gangneung WWTP, in Korea.	Parameters used: 0.08% (w/w) alkaline/acidic catalysts with 40 mL/g-lipid methanol, 20 mL/g-lipid n-hexane at 50 °C for 24 h. Biodiesel extracted with n-hexane, centrifuged, separated, and dried for 24 h.	The contents of carbohydrate, crude lipid, ash, crude protein, and other elements were 8.9%, 14.5%, 17.8%, 42.8% and 16%, respectively. Lipid content organic solvents ranged from 2.9% to 5.7%, and using treatment methods (i.e., BDM, microwave, autoclave and ultrasonication), was about 10–14.5%.
[156]	T	WWTP in Beijing, China.	KOH, KOH/AC, and KOH/CaO as catalysts. Optimised reaction for KOH/AC used 1:10 SS:methanol ratio at 60 °C, 300 rpm, and 8 h extraction. For KOH and KOH/CaO, extraction time was 5 h.	The biodiesel yield was 1.2%, 6% and 6.8% using KOH, KOH/CaO and KOHAC as catalysts, respectively. The results showed that these are not good catalysts for biodiesel production from SS when compared with H_2SO_4.
[157]	T	WWTP in Beijing, China.	$SO_4^{2-}/Al_2O_3-SnO_2$ catalysts prepared by 79 wt% of H_2SO_4. Dry SS (10 g) added to n-hexane and ethanol (0.2 L each), and extraction at 80 °C for 10 h. Catalysts (0.4–1.2 g), n-hexane (50 mL) and methanol (128 mL) used to extract crude fat and reacted for 0.5–6 h, 130–170 °C.	Biodiesel yields of 57%, 50.3% and 50.5% were achieved for temperatures of 130 °C, 150 °C and 170 °C, respectively. The biodiesel yield increased from 33.7% to 73.3% from 0.5 h to 4 h reaction time, but for 6 h reaction time, the biodiesel yield was 72.1%. The highest FAME yield (73.3%) was achieved at 130 °C, 4 h reaction time, using 10 g of dry SS and 0.8 g catalyst.

Table 13. *Cont.*

Ref.	Type	Sludge Collection	Parameters	Gas Production
[137]	P	WWTP in Pavia, Italy.	Microwave system at different operating conditions, including temperature of 180–650 °C and reaction times of about 1–28 min.	Highest value of oil to sludge was about 25% under 280 °C and 8 min reaction time, and the lowest value (7%) was at 180 °C at 50 min reaction
[158]		WWTP in Texas, USA.	Bench-scale fluidized bed reactor, 150–300 °C, ethanol:bio-oil ratio (*w*/*w*) between 1 and 3, 2–4 hs reaction, and Ni/HZSM5 as catalyst.	Generated bio-oil upgraded to biodiesel. Bio-oil and biodiesel HHV were 36.43 MJ/kg and 39.97 MJ/kg. SS-derived biodiesel yield was 89.33% (max) at 150 °C, 3 h reaction time, and ethanol:oil ratio of 2.
[159]	T and P	Jungnang WWTP in Seongdong-Gu, Seoul city, Korea.	Dried SS (10 g) 0.2 L of solvent (hexane) used to extract the lipids at 80 °C for 24 h. To separate solvent, used an evaporator at 80 °C for 3 h. SSRB produced by pyrolysis. A total of 20 g of SSR used at 600 °C for 4 h.	Highest biodiesel yield (33.5 wt.%) at 305 °C via thermally induced transesterification in 1 min using the SS biochar. Biodiesel yield from (trans)esterification was less than 1% with 5 wt.% H_2SO_4. Kinetics (<1 min) of thermally induced transesterification was faster than normal transesterification (3–24 h).

P: Pyrolysis; T: Transesterification; SSRB: Solid residue biochar; BDM: Bligh and Dyer method.; PSS: Primary sludge; SSS: Secondary sludge; FAME: Fatty acid methyl esters.

3.1.4. Microbial Electrolysis Cell

A Microbial Electrolysis Cell (MEC) is an anaerobic process that converts organic matter contained in the wastewater into renewable fuel (mostly methane or hydrogen). MECs can utilise either wastewater or sludge as feedstocks, and this technology has the potential to reduce the costs associated with wastewater treatment and sewage sludge disposal, which are often the two main operating costs in a WWTP. In an MEC, the organic matter is oxidised through bacteria in the anode electrode, and hydrogen is produced as a by-product in the cathode by using a small electric voltage. An MEC's performance, can be measured in terms of organic removal and hydrogen production, is directly dependent on the electric voltage magnitude. Usually, when an MEC is fed with municipal wastewater, the electric current generated is low which is expected since municipal wastewater is known for its low organic matter content when compared to other feedstocks. This is one of the key challenges of applying this technology when used to treat municipal wastewater. The first commercial MEC reactor (Ecovolt) was developed by Cambrian Innovation to treat high-strength wastewater [160]. Small-scale experiments using MEC and domestic waste-water as feedstock have been reported in the literature, as shown in Table 14.

3.1.5. Microbial Fuel Cell

Microbial fuel cells (MFC) is similar to MEC, but it converts the organic matter contained in the municipal wastewater into electricity directly. In this process, the MFC converts chemical energy contained in the organic compounds to electrical energy under anaerobic conditions through the catalytic reactions of microorganisms. Bacteria oxidise the organic matter contained in the wastewater at the anode, and the reduction reaction occurs on the cathode. During the oxidation, electrons are released and transferred to the anode, generating the electrical current that drives the MFC. When the electrons reach the cathode, they are combined with electron acceptors (i.e., oxygen) and protons (i.e., hydrogen) to generate water and close the electrochemical circuit. The main parameters that influence the performance of MFCs include the pH, temperature, substrate characteristics, bacteria activity, electrodes material, and internal resistance. MFCs vary in design, size, and power density. For example, small-scale cells can have a high-power density (i.e., above 500 W/m^3), while large ones may have lower density (i.e., 30 W/m^3). The MFC scale up usually occurs via enlarging the single reactor or combining multiple reactors in one system. MFC technology has been receiving lots of attention in research, but it is still in the early stages of development [161,162].

The main drawbacks of MFCs include the process efficiency, power densitiy, longer start-up times, performance variability, and sensitivity. However, the main advantages of MFCs include energy savings (i.e., aeration and sludge treatment processes) and less sludge production. MFCs can operate in either batch or continuous mode, which usually depends on the wastewater characteristics, cell design, microorganisms group, and electrode materials [162]. Table 15 highlights some studies that have investigated the MFC technology applied to municipal and domestic wastewater treatment. As shown in Table 15, the coulombic efficiency may vary significantly due to several factors, including microbial metabolism, electrode material and configuration, system performance, substrate characteristics and concentration, and operating conditions. As these parameters are different across the different experiments, they lead to different values.

Table 14. Studies on MEC using wastewater from different WWTPs.

Ref.	Feedstock	Parameters	Gas Production
[163]	Wastewater collected prior to primary clarification from the Howdon WWTP, in Newcastle, UK.	100 L dual-chamber MEC with 6-cell cassettes (88 L working volume). Anode and cathode electrodes surface area of 16.4 and 3.4 m^2/m^3 (anode-to-cathode ratio of 5:1), respectively.	H_2 continuously generated for 1 year with average production rate of 7 L/m^3.d. Average energy recovery and coulombic efficient were 48.7% and 41.2%, respectively.
[164]	Different types of wastewater, including urban wastewater from Rubi WWTP, in Barcelona, Spain.	130 L dual-chamber MEC with 10-cell cassettes. Anode-to-cathode ratio volume of 3.5:1, and used an anionic exchange membrane (AEM) to separate the chambers.	The average H_2 production was 32 L/m^3.d with 95% of purity (5% was methane). The OM removal efficiency was around 25% for a 2-day retention time and OLR of 0.25 gCOD/L.d.
[165]	Wastewater obtained from a domestic WWTP in England.	175 L dual-chamber MEC with 13 m^2/m^3 cathode specific area and 34 m^2/m^3 anode surface area-to-volume ratio under 5 h HRT.	The average H_2 production was 5.2 L/m^3.d with 93% purity, and the COD removal was 63.5%.
[166]	Primary sludge collected from the Gold Bar WWTP in Alberta, Canada.	Dual-chamber MEC. Anode and cathode about 0.42 and 0.17 L, respectively. A 40 cm^2 membrane to separate the chambers. Semi- continuous fed mode (45 mL/d) and residence time of 8 days.	The H_2 production rate found was 145 L/m^3.d, and the COD removal efficiency was up to 73%.
[167]	Raw sludge obtained from a WWTP in Jinju, Republic of Korea.	2.5 L reactor with 16 mm anode-cathode electrode. Reactors under 30, 35 and 40 °C for 6 days and stirred at 100 rpm. Operated in fed-batch mode. Raw and seed sludge was mixed under 7:3 ratio.	Maximum CH_4 production was 111 L/m^3 under 35 °C, whereas under 30 °C and 40 °C, the CH_4 production was 85 L/m^3 and 98 L/m^3, respectively. The CH_4 yield at 30 °C and 40 °C was 82.1 L/kgCOD and 77.1 L/kgCOD, respectively.
[168]	Wastewater collected from the municipal WWTP of Leon, in Spain.	Single-chamber 3 L membrane less MEC operated under batch and continuous mode at 21 °C with 4 h, 8 h, 12 h and 24 h HRTs	At batch mode, CH_4 production rate was 1.3–1.4 L/m^3.d and 54% COD removal efficiency. The energy and net-energy consumptions were 2.92 and 2.14 kWh/kgCOD.

Table 15. Studies related to MFC technology using municipal or domestic wastewater.

Ref.	Feedstock	COD on Wastewater	MFC System	COD Removal Rate	Maximum Power Density	Max Energy Recovery	Coulombic Efficiency	Operation Time/HRT
[161]	Wastewater collected from the Pepper's Ferry Regional WWTP, in the USA.	155 mg/L.	96 tubular MFC modules (2 L liquid each)	76.8%	-	0.006 kWh/m^3	-	1 year and 18 h HRT.
[162]	Effluent from the primary clarifier of a WWTP, in Switzerland.	Up to 130 mg/L.	45 L (4 units with 11.2 L each) used in a full-scale WWTP.	13.5–67%	73 [4], 82 [5], 80 [6] mW/m^2	0.012 kWh/m^3	24.8%	9 months and 12–44 h HRT
[169]	Municipal wastewater from 2 WWTPs (Xiao Jiahe and Yong Feng), in China.	60–100 mg/L (Xiao Jiahe), 200–400 mg/L (Yong Feng).	1000 L system (50 stacked modules, 20 L each).	70–80%	60 W/m^3	0.033 kWh/m^3	41–75%	100 days to 1 year, 2 h HRT.

Table 15. *Cont.*

Ref.	Feedstock	COD on Wastewater	MFC System	COD Removal Rate	Maximum Power Density	Max Energy Recovery	Coulombic Efficiency	Operation Time/HRT
[170]	Primary effluent wastewater from Pennsylvania State University WWTP, in US.	376–428 mg/L.	3 cell sizes: 0.028 [2] L, 0.22 [3] L and 85 [1] L. CSA: 15 m^2/m^3 (small) and 7.3 m^2/m^3 (big)	75–80%	83 [1] W/m^3/ 304[2] W/m^3	-	13–27%	-
[171]	Primary effluent wastewater from the Pennsylvania State University WWTP, in US.	480–1010 mg/L	2 L reactor (1.4 L liquid vol.). A total of 0.86 L anode volume and CSA of 29 m^2/m^3.	57%	22 W/m^3	-	4.4% (min) and 42% (max)	8 h HRT
[172]	Effluent from the primary clarifier from the Haeundae domestic WWTP, in Korea.	144 mg/L.	5 MFC units (150 mL each) in series. CSA: 400 m^2/m^3	34%	16.7 W/m^3	-	12%	8 months 2.5 h HRT
[173]	Wastewater from primary clarifier from a municipal WWTP, in Switzerland.	200–450 mg/L	1000 L system (64 MFC × 16.25 L each) into 4-quadruple stacks.	34.4–95.4%	-	0.015–0.060 kWh/m^3	4.7–14.9% (25% max)	18 months
[174]	Effluent from the primary clarifier of the Mumbai municipal WWTP, in India.	1650 mg/L	0.7 L system.	68%	621 mW/m^2	-	47–48%.	-
[175]	Wastewater collected from Al Gabal Al Asfar WWTP, in Egypt.	92–350 mg/L	Double chamber MFC with 2 × 0.3 L (anode and cathode)	Up to 72.85%.	209 [7] mW/m^2/ 117 [8] mW/m^2	-	-	24 h HRT
[176]	Effluent from primary clarifier from the Taiping municipal WWTP, in China	200–350 mg/L	1.5 m^3 system	63% (92% max)	406 mW/m^3	0.0034 kWh/m^3	-	5 h HRT

[1]—large MFC; [2]—small MFC; [3]—medium MFC; [4]—44 h HRT; [5]—22 h HRT; [6]—12 h HRT; [7]—in summer; [8]—in winter; CSA: Cathode surface area.

3.1.6. Hydropower

Hydroelectric power is known as one of the most economical and popular energy resources. Hydropower is an affordable source of electricity, and compared to other sources, it has a relatively low cost during the project lifespan in terms of maintenance and operations costs. It is a flexible type of renewable energy resource that can be widely applied in WWTPs by using the water flow potential to generate renewable energy [177]. In a WWTP, the possible locations for installing a hydropower system typically include the upstream (raw/untreated wastewater) or downstream (treated effluent). Usually, it is classified based on size, including micro (1–100 kW), mini (0.1–1 MW), small (1–10 MW), and large (above 10 MW). The power output from a hydropower turbine is directly dependent on the water flow rate and available head. There are different types of hydropower turbines available on the industry, including an Archimedes screw, Crossflow, Francis, Kaplan, Pelton, and Propeller [178]. Some researchers have studied the application of hydropower in WWTPs, and some works are summarised in Table 16.

Ref. [178] listed 46 WWTPs that had installed hydropower systems (17 micro, 22 mini, and 7 small). Among them, 12 plants used Pelton turbines, 10 used Kaplan, 2 used Propeller type, 2 used Francis, 2 used pumps working as turbines (PATs), and the remaining were not specified. The authors noticed that the adoption of hydropower technology was not very high when compared to other types of renewable energy technologies. Some real hydropower plants which were installed at different WWTPs are listed in Table 17.

3.1.7. Water Electrolysis

Water electrolysis is a technology where an electric current is passed through water, splitting it into hydrogen and oxygen. This method is valued for its potential to generate clean hydrogen fuel (also known as green hydrogen), when the electricity used in the process comes from a renewable source. In WWTPs, hydrogen can be used to power CHP technologies, including FC, GT, or even modified ICEs, or can be injected into the gas network following the standards regarding the hydrogen-blending constraints. The oxygen part is a valuable element and can also be used in the wastewater treatment process. Oxygen in a WWTP can be used is in the aeration process, which is vital for the biological treatment of wastewater. In the activated sludge process, oxygen is supplied to the aeration tanks to support the growth of aerobic microorganisms that break down organic pollutants. Additionally, in advanced treatment stages such as membrane bioreactors (MBRs) or in systems focusing on nutrient removal, controlled oxygen levels can improve the performance of both nitrification and denitrification processes. Water electrolysis is a promising technology, and the possibility of using treated effluents from municipal WWTPs as the source of water for electrolysis can potentially enhance sustainable hydrogen production in these facilities. However, to utilise the treated effluent from a WWTP as a water supply, it must meet specific requirements, including being purified and demineralised and exhibiting a conductivity lower than 5 μS/cm [179,180].

Additionally, depending on the quality of the treated effluent, some further tertiary treatments may be required, including chemical treatments, accelerated filtration, ultrafiltration, nanofiltration, coagulation, reverse osmosis, ion exchange, and electrodeionization. Water electrolysis can be a competitive technology in terms of costs. For example, hydrogen production via water electrolysis can range between USD 2.05 and 10.5/kg H_2, whereas the costs for sewage sludge pyrolysis can be around USD 1.2–2.2/kg H_2, and the steam methane reform method is about USD 1.14/kg H_2 [180].

Table 16. Studies that considered hydropower technologies applied in WWTPs.

Ref.	Study Aims	Main Findings
[177]	Investigate the hydro potential in a WWTP in Wisconsin, in the USA.	• WWTP parameters: 190 MGD effluent flow, 3 m head, 6.5–9 m^3/s flow rate. • Hydro turbine parameters: Kaplan design, 271 kW nominal capacity, output between 150 kW and 207 kW, 100–200 rpm and inlet mass flow between 5000 and 10,000 kg/s. Expected savings was estimated to be around 1.56 GWh/year
[178]	Assess the potential of hydropower technology in WWTPs	• Listed 49 real cases studies of hydro application in WWTPs in different countries. • Details of the hydro projects included installed capacity, potential energy generation, capacity, available head and water flow.
[181]	Investigate the benefits/feasibility of a hydropower system in Zeekoegat WW-TP, in South Africa (60 mL/d capacity).	• 3×6.7 kW siphon turbines were considered in the study based on head net and flow discharge of 3.6 and 0.37 m^3/s (each unit). • Economic analysis results included 30 years of design life, 9 years pp, total investment, maintenance and annual costs were USD 69,000, USD 691, and USD 7520, respectively. • System could produce 181.3 GWh/year and for a 20-year project, the potential cost savings would be approx. USD 437,500.
[182]	Evaluate the energy recovery potential and economic viability of different WWTPs in Ireland and UK.	• In the UK, 5 out of 11 plants were economically viable: (a) Beckton (4 years pp, 2.6 m head, 14 m^3/s flow, 234 kW, EUR 816,000 c.c., EUR 203,000 a.s.), (b) Knostrop (3.1 years pp, 8.5 m head, 4.3 m^3/s flow, 184 kW, EUR 623,200 c.c., EUR 202,800 a.s.), (c) Crosness (4 years pp, 4 m head, 7.2 m^3/s flow, 184 kW, EUR 633,000 c.c., EUR 159,600 a.s.), (d) Minworth (4.2 years pp, 4 m head, 6.3 m^3/s flow, 32.5 kW, EUR 249,000 c.c., EUR 28,000 a.s.), (e) Long Reach (8.8 years pp, 1.7 m head, 3 m^3/s flow, 25.5 kW, EUR 222,800 c.c., EUR 22,000 a.s.). • In Ireland, 3 out of 14 plants were economically viable (<10 years pp): 2 largest plants: Ringsend (5.1 years pp, 3.7 m head, 4.4 m^3/s flow, 103 kW, EUR 443,000 c.c., and EUR 87,000 a.s.) and Carrageenan (7.7 years pp, 4 m head, 1.2 m^3/s flow, 30 kW, EUR 195,000 c.c., EUR 25,400 of a.s.).
[183]	Study the hydro potential of treated wastewater discharged from the Torun WWTP, in Poland.	• WWTP maximum treatment capacity of 90,000 m^3/day and 0.5 m^3/s average wastewater flow. • The highest turbine power (24.8 kW) was based on maximum wastewater flow of 0.56 m^3/s and system efficiency of 66.35% and maximum hydraulic head of 7.5 m, whereas the lowest turbine power (14.8 kW) based on system efficiency of 53.7% and flow of 0.39 m^3/s.
[184]	Study the implementation of micro hydropower turbines in 4 different WWTPs, in Ireland.	• The WWTPs included Ringsend (1640,000 PE, 377,600 m^3/d flow rate, and 3.7 m head), Carrigrennan (413,000 PE, 102,000 m^3/d flow rate, and 4 m head), Navan (50,000 PE, 10,000 m^3/d flow rate, and 16.3 m head), and Greystones (40,000 PE, 8000 m^3/d flow rate, and 6 m head). • For Ringsend, the power output, annual savings, project cost and pp were 103 kW, EUR 87,000/year, EUR 442,000 and 5.1 years. For Carrigrennan, it was 30 kW, EUR 25,400/year, EUR 195,000 and 7.7 years. For Navan, it was 11.8 kW, EUR 10,000/year, EUR 77,200 and 7.8 years, and for Greystones, 3.5 kW, EUR 3000/year, EUR 50,000 and 16.9 years.

Table 16. *Cont.*

Ref.	Study Aims	Main Findings
[185]	Feasibility study of hydropower in Kiheung Respia WWTP, South Korea.	• WWTP parameters: 0.35 m^3/s flow rate, and 4.3 m available head. System efficiency and electrical power output were 83%, and 12.3 kW. • Up to 96% of the total effluent treated by the facility could be used to generate electricity (able to produce 68 MWh/year).
[186]	Hydro system a WWTP, in Pakistan.	• Plant's parameters: 1.5 m net head and 0.24 m^3/s flow rate. Archimedes screw turbine used for the study for low heads. • Hydro system of 1.96 kW.
[187]	Investigate the performance of propeller turbines in recovering energy in the aeration tank of a WWTP.	• Data collected from 13 WWTPs were analysed in the study. • The proposed microturbine system could generate around 3.8 GWh/year and provide a potential savings up to 15.7% and USD 260,500 on the plant's annual electricity consumption and annual cost savings, respectively. • The cost of system's implementation varied from USD 191,400 to USD 528,00, and the average p.p. was considered as 15 years.
[188]	Find the optimal design and best hydropower technology for Tatlar WWTP, in Turkey.	• Tatlar WWTP had the capacity to treats 765,000 m^3/d (plan to be 1377, 000 m^3/d by 2025). • Plant's parameters: 12.5 m^3/s average flow. • 2 turbines studied: (i) Archimedean turbine, the payback period, energy generation, investment, O&M, and average energy revenue were 2.4 years, 7.88 GWh/year, EUR 709,000/year, EUR 13,600/year and EUR 2172,000, respectively. (ii) Kaplan model, the payback period, energy generation, investment, O&M, and average energy revenue were 3.2 years, 8.6 GWh/year, EUR 773,500/year, EUR 57,000/year and EUR 2279,000, respectively. The Archimedean screw type was selected as a better option.
[189]	System at Clarkson WWTP (Canada).	• WWTP the capacity to treat 350 mL/d of wastewater. Up to 1.1 GWh/year of electricity could be generated on-site.

pp: Payback period; c.c.: capital costs; a.s.: annual savings.

Table 17. Hydropower plants installed in WWTPs [190].

WWTP	Location	Turbine Type	Total Installed Power (kW)	Flow (m^3/s)	H (m)
North Head, Sydney	Australia	Kaplan	4500	3.5	60
Emmerich	Germany	Archimedes	13	0.4	3.8
As Samra	Jordan	Pelton	1600	3.2	104
		Francis	1680		41
Aïre, Geneva	Switzerland	Kaplan	200	3.2	5
Engelberg		Pelton	50	0.16	54.4
Grächen			262	0.09	365
La Douve I, Leysin			430	0.08	545
La Douve II, Leysin			75	0.108	83
Morgental, St. Gallen			1350	0.84	190
Profay, Le Chable			350	0.1	449
La Asse, Nyon		Pump as turbine	220	0.293	94.3
Elsholt	UK	Archimedes	180	2.6	-
Deer Island, Boston	USA	Kaplan	2000	13.1	8.8
Point Loma, San Diego		Francis	1350	7.6	27
Hsinchu	Taiwan	-	11	-	-
Taichung		-	68	-	-

Following the stoichiometry balance, to generate 1 kg of H_2 and 8 kg of O_2 is required 9 kg of deionized water. However, in real-world applications, electrolyser manufacturers recommend using a higher quantity of water (between 10 and 22.4 kg), considering water losses (i.e., 10%) and water used for equipment cleaning (around 25%) [179]. Few studies have investigated the utilisation of water electrolysis technology in WWTPs, as illustrated in Table 18.

Table 18. Studies exploring the electrolysis technology utilisation in WWTPs.

Ref.	Plant	Study Aim	Parameters/Methods	Gas Production and Utilisation
[191]	The WWTP Mainz, in Germany. Wastewater inflow up to 55 mL/d (peaks of 6.300 mL/h.	Studied a 1.25 MW Electrolyser system in a WWTP. PV and CHP system to power the electrolyser. H_2 could be injected into the gas network or power FC buses. O_2 could generate ozone to be used in the advanced WW treatment	WWTP power consumption of 8200 MW/y, PV generation of 227 MWh/y, CHP generation (using biogas) of 6173 MWh/y and 1800 MWh/y power bought from the grid.	H_2 and O_2 production was about 2975 MWh/year and 600 ton/year, respectively. Assuming 2% vol of H_2 feed-in limit, 1240 MWh of H_2 could be fed into the gas network per year. The remaining 1735 MWh of H_2 could be used in fuel cell buses in public transport.
[192]	RWW, PE, SE, TE, and SW collected from a WWTP in Gyeongsan city, South Korea.	Generate H_2 from low-grade wastewater using alkaline water splitting technology. Based on this investigation, the potential applicability for achieving energy independence in municipal WWTP is planned	WW filtered through UF membrane to produce ATW. After treatment, COD, TN, TDS in the treated effluent were around 2.8–37.9 mg/L, 0.9–28.7 mg/L and 44–377 mg/L, respectively.	H_2 production based on low-grade water was between 19.2 and 22.8 mL/h.L, whereas based on a UF treatment, it was between 20.4 and 23.4 mL/h.L for the different WW samples. For a deionised and tap waters (control), H_2 production was 23.6–26.6 mL/h.L.

WW: wastewater; RWW: raw wastewater; PE: primary effluent; SE: secondary effluent; TE: tertiary effluent; SW: Surface water; ATW: Advanced treated water; UF: ultrafiltration; COD: Chemical oxygen demand; TN: Total nitrogen: TDS: total dissolved solids.

3.2. Non-Site-Specific Sources

Non-site-specific sources do not rely on a specific geographical location or environment to be used. This group include renewable energy technologies that are not tailored to the particular characteristics or location, such as solar energy and wind [23].

3.2.1. Solar Energy

Solar energy has the least environmental impact compared to other types of renewable energy resources. It can be used in multiple pathways in WWTPs, and some researchers have studied its application, including solar thermal and PV generation, in those facilities. Solar thermal energy can also be used in several applications, such as heating, heat pumps, and sludge drying. Sludge drying can be used to dewater digested sludge, which is a very important stage of sewage sludge management in a WWTP. It not only reduces the amount of waste to a minimum but also helps eliminate bad odour and pathogen problems. Traditional thermal drying systems are very complex and require high investment and operational costs [193]. Solar PV is the most widely used type, especially due to its scalability, flexibility and lower costs. For example, in [23], from 105 WWTPs investigated in the USA, 41 plants adopted a PV system. It was also identified that solar PV was primarily installed in hybrid configuration combined with AD. For plants with a flow rate above 19 mL/day, PV system could supply around 8–30% of the plant's energy demand.

3.2.2. Wind

Although wind generation is one of the most widely used technologies, it is not commonly used in water facilities, mainly due to its initial costs and the complexity of building a small-scale plant. Most studies consider hybrid configurations consisting of PVs, batteries, and biogas systems. Few researchers have investigated the use of wind turbines alone in WWTPs.

3.2.3. Hybrid System

Due to the intermittency and uncertainty of renewable energy resources, a single technology may be unreliable and add challenges in terms of the dynamic load demandingness of a WWTP. A hybrid system combines two or more power generation resources to improve the generation potential which can overcome the issues of a single technology, providing cost-effective system with flexible capacity [23]. Some studies have considered non-site-specific power generation technologies in WWTPs, including solar energy and wind alone, and also hybrid systems, as shown in Table 19.

Several large-scale renewable energy projects have been implemented or are under development in WWTPs worldwide, as shown in Table 20. In Australia, WWTPs have been focused on becoming more sustainable and energy-efficient in the last few years. Table 21 shows some examples of sustainable renewable energy projects and future systems planned to be installed in WWTPs in Australia.

4. Grid Services and Energy Market Participation of WWTPs

With rising electricity costs, sustainability targets, and efficiency goals, more and more WWTPs are looking for alternatives to minimise their operating costs and reduce carbon emissions while increasing energy efficiency. The adoption of renewable energy sources can be considered one the best alternative for WWTPs; however, due to some potential constraints, such as high upfront investment costs and site limitations, their adoption may create some challenges. Other potential alternative to overcome these issues can be participating in demand-response programs, energy markets, and grid services. Looking for opportunities to take advantage of better energy pricing and incentives, some WWTPs are starting to consider the possibility of exploring these areas [23].

Energy utilities incentivize customers to reduce their energy usage at particular time periods of the day, especially during peak periods. Some wastewater facilities have demonstrated capabilities to shift their loads to assist the grid, which can range from a slightly reduction on energy consumption for a short period to larger amounts during longer periods. One of the most common incentives given by energy utilities to consumers is based on demand-response (DR) programs. Its main objective is to adjust the customer's consumption under energy price signals or grid conditions. Customers are required to reduce energy consumption during peak periods when the energy price and demand are higher. By participating in DR programs, customers receive energy discounts that can help to reduce their energy costs. Before participating in DR schemes, WWTPs should conduct technical evaluations to understand if they are capable to maintain its wastewater treatment efficiency and effluent discharge quality while providing these services [194].

DR are mainly based on two methods: load shedding (electricity consumption reduction during peak period without a change in the overall consumption behaviour) or load shifting (shift the energy demand from peak to off-peak). DR programs can also be incentive-based or price-based. Based on incentives, the customer receives fixed payments based on the DR duration event and the total number of hours provided annually. The customers receive a demand reduction signal from the system operator, which can be mandatory or voluntary. Based on price, the customer is subjected to variable electricity prices over time. Clients are motivated to adjust consumption following the energy tariff at a specific time [6]. Some WWTPs were reported participating in energy markets and providing grid services. For example, an EMWD facility located in California, USA, started to participate in three DR programs: (i) Southern California Edison's (SCE's) EnerNOC DR Program, (ii) Base Interruptible Program, and (iii) Price-Based program for day-ahead pricing. EnerNOC is an aggregator that is responsible for the connection between the WWTP and the energy provider. Participating in those programs, the overall savings of the facility was USD 555,000 annually in 2012. EMWD also plans to partner with Honeywell to convert some of its manual controls to automatic controls to increase its DR portfolio [195].

Table 19. Solar, wind and hybrid system generation in WWTPs.

Ref.	Type	Study Objective	Main Findings
[196]	Solar thermal	Optimise a solar dryer in a WWTP in Morocco.	• Solar thermal system included a 2.5 m^2 solar collector, drying chamber, centrifugal fan and thermo-regulator. • Drying system based on 3 temperatures (50, 70 and 90 °C) and air flow rate of 0.083 m^3/s. System able to reduce up to 60% of the sludge volume.
[197]		Design a system for drying SS from Antalya Metropolitan Municipality WWTP, in Turkey.	• For the proposed system, the payback period, average collector efficiency, Levelised cost of heating (LCOH) and O&M costs were 2.9–3.5 years, 50.17%, 0.017–0.02 USD/kWh, and 6.41–7.86 USD/year. • Specific moisture extraction rate (SMER) and specific energy consumption (SEC) of about 0.77–1.34 kg/kWh and 1.77–2.86 kWh/kg, respectively.
[198]		Proposed a thin layer sandwich-like chamber for SS drying	• The best result was achieved for a 5 mm sludge thickness layer with average drying rate of 6.72 g/h under 0.5 kW/m^2 solar radiation. • In 11 h operation, the water content of the sludge decreased from 79% to 5%, and the heat utilisation efficiency was around 24.3%
[199]		Investigated the SS drying system for a WWTP in Beijing, China,	• Experiments conducted in a bench-scale convective dryer, SS exposed to temperatures around 100–200 °C and hot air speeds of 0.6, 1.4 and 2 m/s. • Average mass transfer and surface heat coefficients were between 1270–3460 m/s and 10.66–26.96 W m^2.K., respectively.
[200]		Studied the potential of a solar air heater for drying SS.	• The average system's efficiency and SEC were around 70.12–81.70%, and 2.36–5.40 kWh/kg, respectively. • The average minimum and maximum temperatures were 82.1 °C and 86.4 °C, respectively.
[23]	Solar PV	Assess the status of solar PV in 105 WWTPs in California, USA, to evaluate its usage in WWTPs.	• 41 out of 105 WWTPs had on-site PV system with an average capacity of 0.86 MW (12 kW min., 4.2 MW max.). • 34% of the plants had a 1 MW PV solar system, and the total PV solar capacity installed in the WWTPs was 35.5 MW. • Solar PV supplied 8–30% of WWTPs with flow above 5 MGD (biogas supplied 25–65%), and facilities below 5 MGD flow, the solar PV supplied between 30% and100% of the load demand. • For Sacramento WWTP, the 4.2 MW plant supplied 8% of the plant's energy needs.
[201]		Study the benefits of a PV system in a WWTP, in Romania.	• The flow rate of the WWTP was about 745 L/s and 322 L/s under peak and off-peak period, respectively. • Proposed PV system could reduce up to 40% of the total energy demand and 12% of the carbon WWTP emission.
[202]		Assess the SBBGR in a WWTP using a solar system.	• Propose a 5.1 kW solar PV system to supply heating/cooling and replace the need to buy energy from the grid. • The thermal energy extracted from the SBBGR system could reach up to 14.5 kWh and operated for 4 months.

Table 19. *Cont.*

Ref.	Type	Study Objective	Main Findings
[203]	PV-Battery system	Integration of PV-battery system for 2 small-scale decentralised WWTPs, in the Netherlands.	• The average energy consumption of the BEVER III and MBR DWWTPs were 1.08 and 2.3 MWh/month, respectively. • Proposed PV system for BEVER III: 15 kWp PV and 20 kWh battery to supply 75% (winter) and 100% (summer) of plant's electricity demand. • Proposed PV system for MBR: 30 kWp PV and 50 kWh battery to supply 65% (winter) and 100% (summer) of plant's electricity demand.
[204]	Wind	Assess the benefits of the 100 kW wind turbine to supply electricity for a WWTP located in Texas, US.	• The WWTP treated about 189.3 m^3/d of wastewater which required approximately 236,000 kWh/year. • Wind project cost about USD 610,900 (in 2012), and in 3 years, the plant saved almost USD 16,000/year in electricity costs, generating about 155,700 kWh. • To be a positive NPV, the system would need to generate about 557 MWh/y (or economic benefit of USD 49,000).
[205]	PV and Biogas	Study the potential of anaerobic co-digestion and solar PV in a WWTP in Loures, Portugal.	• Co-digestion of SS and FW (40–60% SS:FW mixing ratio) and co-digested under 37 °C, OLR of 1.12 g TVS/L.d, and 15 days HRT. • The proposed PV system had an installed capacity of 730 kWp which could generate approx. 1250 MWh/y, 12.2% PV self-sufficiency ratio, and 12 y payback period. The cost of co-digestion implementation was calculated as EUR 524,000.
[206]	Solar thermal/biomass	Propose a 20 MW solar/biomass system to supply a WWTP in Spain.	• Proposed hybrid system could generate up to 148.9 GWh under a 0.85 capacitor factor. Total system investment of EUR 211 million. • The LCOE was EUR 0.25/kWh. System's total exergetic efficiency was between 15% (solar) and 34% (biomass).
[207]	PV, battery and diesel generator	Analyse the potential of using a hybrid system to reduce consum-ption in a WWTP, in Romania.	• WWTP serves 23,000 PE with 315 kW total installed power and 537,180 kWh/y electricity consumption. • The proposed PV system was designed as 310.5 kWp (which could provide around 370,00 kWh), and 862 kWh battery capacity. • The LCOE for PV-battery and PV-only systems were 0.154 EUR/kWh and 0.01 EUR/kWh, respectively. PV-battery system costs of around EUR 1 million.
[208]	PV, heat pump, water electrolyser)	Investigate the economic benefits for implementing a hybrid generation in a WWTP.	• WWTP details: 8.7 MW thermal load, 4.1 MW electrical demand, 40 t/d oxygen demand and biogas supply of about 404,750 GJ/year. • Five configurations were proposed: (a) PV only (10 MW), (b) PV + HP (15 MW + 2.175 MW), (c) PV + HP + TES (15 MW + 5 MW + 43.5 MW), PV + HP + TES + grid (same as c), and (d) PV + electrolyser (15 MW + 2.175 MW).
[209]	MHP and MEC	Integration of MEC and MHP to assess potential benefits for a WWTP.	• MHP was used to power the MEC, based on 4 scenarios: (i) S1: water flow of 0.1–1.1 m^3/s, (ii) S2: water flow of 0.1–1.1 m^3/s and 10 m head, (iii) S3: water flow of 0.1–0.55 m^3/s and 10 m head, and (iv) S4: water flow of 0.0345–0.55 m^3/s and 20 m head. • Maximum power for S1, S2, S3 and S4 were 91.6, 32.6, 13.1, and 38.8 kW. It could power an MEC system of 2.8, 1.4, 0.7, and 0.5 GW. • The MHP-MEC integrated system required a capital cost of 453.77, 45.38, 56.87 and 45.57 USD million for S1, S2, S3 and S4 systems, respectively. • The payback period for S1, S2, S3 and S4 would be about 19.7, 2, 5.2 and 4.1 years, respectively.

Table 19. *Cont.*

Ref.	Type	Study Objective	Main Findings
[210]	FC and Solar thermal	Conduct an economic analysis for a hybrid system in Collegno WWTP, in Italy, which serves serves 270,000 PE and treats 38,500 m^3/day.	• LCOE for the SOFC only was EUR 0.144/kWh and a payback period of 20 years, considering a SOFC system generating 1 MW/year. • LCOE for the hybrid system for 3 different ST system sizes, including 300 m^2, 700 m^2 and 1000 m^2, was 0.141, 0.134 and 0.123 EUR/kWh, respectively. • System's payback period considered SOFC and ST systems sizes of 300 m^2, 700 m^2 and 1000 m^2 was 19, 13.5 and 9 years, respectively. • If the annual production of SOFC increases to 2, 5 or 10 MW/year, the payback period could reduce to 7.5, 3.5 or 3 years, respectively.
[211]	SOFC, solar thermal, and GT	Evaluate the potential benefits of a hybrid system in a WWTP, in Italy.	• 4 scenarios considered: (i) SOFC only, (ii) SOFC and ST, (iii) GT and SOFC, and (iv) Trigen (SOFC, RC, and absorption chiller). • The total investment costs, operating costs, electrical load coverage, total energy savings and payback period for the considered scenarios were around EUR 1.2–1.33 mi, EUR 113,000–134,000, 28–39.4%, EUR 220,000–380,000 and 2.95–5 years. The LCOE was calculated to be 0.069–0.087 EUR/kWh.

TES: Thermal energy storage, MHP: Micro-Hydropower; MEC: Microbial Electrolysis Cell; ST: Solar Thermal; GT: Gas turbine; SOFC: Solid Oxide Fuel Cell; RC: Rankine Cycle; MGD: Mega gallons per day; SS: Sewage sludge; SBBGR: Sequencing Batch Biofilter Granular Reactor; FW: Food waste.

Table 20. Large-scale renewable energy projects in WWTPs.

Ref.	WWTP	Location	Technology/ System	Findings
[212]	ACUA WWTP	New Jersey, US	7.5 MW Wind	• The 7.5 MW installed capacity wind farm started operation in 2006 • The plant can supply around 60% of the WWTP's electricity needs, and the surplus can supply the main grid. • The cost of the project was USD 12.5 mil, and in the first year of operation, the plant was able to save 20% of the investment cost.
[213]	Field's Point WWTP	Providence, US.	4.5 MW Wind	• WWTP treats up to 246 million litres per day of wastewater. It supplies around 25% of the facilities' annual demand. • Wind project cost was USD 14 mil, and reduced the electricity costs by 40% (from USD 2.5 mil to USD 1.5 mil) per year.

Table 20. *Cont.*

Ref.	WWTP	Location	Technology/System	Findings
[214]	JRDWRF	City of Pueblo, Colorado, US	309 kW solar PV	• The city received USD 1.5 mi to install a PV system. The system can cover around 40% of the facility's electricity demand. • Project was economically viable since it had support from deferral fund and tariff rebates from the local energy utility.
[195]	EMWD	California, US.	PV solar, FC, and turbines	• PV systems in 5 plants. Total PV system capacity of 21 MW (potential to produce 45 GWh/year and supply 30% of the electricity demand of each site, generating a revenue of USD 2 mi yearly). FC units installed in 2 facilities which can supply 25–40% of the energy needs for each site. • FC system uses biogas generated on-site and has the potential to save around USD 1 mi annually in electricity costs. • 8 micro-turbines of 60 kW capacity generate additional streams of USD 300,000 a year.
[215]	PLWWTP	San Diego, USA	Biogas upgrading	• Project cost USD 45 mi to implement of which the federal government provided 30% of rebates and USD 12 mi in tax-exempt bonds. • Plant generates more electricity than needed. It sells about 3.5 MW (plant produces 5.5 MW and consumes 2 MW) • The purified biogas powers 3 FC system (2.6–4.5 MW system). With the incentives, the 2.8 MW FC system received USD 7.65 mi in rebates.
[216]	Werdhölzli	Switzerland	Sludge incineration	• Plant uses the sludge from 70+ WWTPs to generate renewable energy. • The system can handle up to 100,000 metric tons of sludge yearly with a capacity of 875 kW of electrical power and 4450 kW of heat.
[217]	Deer Island WWTP	Boston, US	Solar PV, wind, and hydro	• WWTP treats 1300 MLD of wastewater. Hybrid system: 2 × 600 kW wind, 736 kW PV, and 2 MW hydro (up to 8.85 GWh/year generation). • Facilities' annual energy demand is 18 MW, costing USD 16 mi/year. After installing the hybrid system, electricity costs are reduced by 25%

EMWD: Eastern Municipal Water District; PLWWTP: Point Loma Wastewater Treatment Plant; JRDWRF: James R. Dilorio Water Reclamation Facility; MLD: Million litres per day.

The EMWD plant started participating in DR programs in 2007 by committing to reduce 1.5 MW of power capacity. The facility received USD 100,000 per year by providing grid services to relieve the SCE network. Based on the terms, EMWD could choose to contribute in different levels of responses, depending on its operation and needs, which could be achieved by running its capacity at a lower level or even shutting down completely [218].

Pennsylvania American Water identified that its Shire Oaks facility had the potential to provide grid balance services while fulfilling its technical obligations. The facility started by adding one pump, which was able to respond to the requests without impacting its operating processes. Providing the services of only one pump, the facility was able to offset approximately 2–3% of the total electricity bill, and a second pump was planned to start providing grid services [219].

A DR solution was implemented as a pilot program for two large customers, including the Kind Country South Treatment Plant, located in the USA. The local energy provider, Puget Sound Energy (PSE), and Generac Grid Services conducted a trial to evaluate the project. Generac was responsible for monitoring, controlling, and managing the capacity curtailment in real-time from both customers if any automatic event was needed. In total, the energy provider called four DR events in the winter 2017 peak capacity season, and it was able to curtail an average of 4.09 MW in the season out of the maximum capacity of 6 MW [220].

SA Water has been participating in the electricity spot market in Australia since 2013. Between 2013 and 2017, the company started to be exposed to the spot prices but under hedge contracts, which provided a fixed volume and prices. Since 2017, SA Water has been registered as an AEMO participant. As a market customer, the company began to be completely exposed to spot market prices and it was responsible for managing the risks. Since 2020, SA Water has become a registered self-retailer. The company also participates in the Frequency Control Ancillary Services (FCAS) market [18]. Although water and wastewater utilities can provide grid services and participate in DR programs, not many studies have explored these topics, as shown in Table 22.

Challenges and Opportunities of Using RES and Market Strategies in WWTPs

Most wastewater treatment facilities are not primarily designed to be cost-efficient systems. Almost 90% of the energy consumption in WWTPs is related to three stages: secondary treatment, pumping, and sludge treatment combined with dewatering [2]. The most common alternatives that these facilities adopt to reduce energy costs in WWTPs include (i) optimising energy consumption by improving efficiency, (ii) on-site power generation to reduce operating costs related to energy importation from the main grid, and (iii) energy demand management [3]. Planning and operation studies are essential to understand the potential risks and evaluate the opportunities for WWTPs. They can help to design the best power generation configuration and find the optimal operation strategy for the generation system. Power system planning is a critical techno-economic assessment that is used to investigate and plan future system expansion, feasibility, and generation potential. The main objective of power generation planning is to determine the necessary generating capacity to satisfy the load demand in real time. In the system's planning, it is ideal to have a generation capacity that can supply 100% of the load anytime. Still, it is very challenging to match the generation and demand, mainly if the system is composed of renewable energy sources [221].

Table 21. Renewable energy projects in WWTPs in Australia.

Ref.	Organisation	Technology/System	Details
[222]	Hunter Water	6 MW solar PV	• At Dungog, Tanilba Bay and Karuah facilities, there is a 2.96 MW total operating capacity. A 3.1 MW Balickera Park solar system is the biggest of HW
[223]	Icon Water	720 kW solar PV and 1.23 MW Hydro	• 2.29 MW generation capacity to be installed. At SWTP, the installed capacity of the mini hydro system is 630 kW (able to produce up to 3.4 GWh/y). • Googong Mini Hydro installed capacity of 600 kW with generation potential of 4.2 GWh/y (13% of total electricity demand of Icon Water in 2015–16)
[224]	QST, GoR, and Melb W	Hydrothermal liquefaction	• Technology converts biosolids into biocrude, and the project cost around AUD 11.8 mi. • The plant aims to produce 12–15 megalitres of biofuel per year which can be used as renewable diesel and aviation fuel.
[225]	Loganholme WWTP	Gasification	• Convert 34,000 tonnes of sewage sludge to produce synthetic gas, and the project's investment cost is around AUD 17.3 mi. • Before the project, biosolids were disposed of in landfills, costing around AUD 1.8 mi (30% of the facility's operating costs).
[226]	Melb W	25 MW biogas, 25 MW hydro and 24 MW Solar	• 86.2%, 0.02% and 93.6% of the electricity generated from biogas, hydropower and solar were consumed on-site, respectively. • In ETP, the biogas and new PV systems will provide up to 48% of plant's demand yearly. In WTP, the new PV system will supply up to 12.4 GWh/y. • New mini-hydro projects in three WWTPs (St Albans, Upper Yarra, and O'Shannassy) will generate about 7.1 GWh/year
[227]	SA Water	154 MW PV and 34 MWh battery	• Generate 242 GWh, supplying about 70% of the SA Water's electricity demand yearly, and the system's total investment cost was AUD 300 mi.
[228]	Sydney water	PV, biogas, hydro	• Sydney Water Corporation produces around 20% of its electricity needs through on-site generation based on biogas, hydropower, and PV systems.
[229]	WC	PV, wind, biogas, hydro	• 1.5 GWh of renewable projects. Plan to invest an extra AUD 30 mil in solar generation and participate in pilot programs to provide grid services.

ETP: Eastern Treatment Plant, WTP: Winneke Treatment Plant; SWTP: Mount Stromlo Water Treatment Plant; QST: Queensland sewage treatment; Melb W: Melbourne Water; GoR: Gladstone oil refinery: WC: Water Corporation.

Table 22. Grid services and market participation studies found in the literature.

Ref.	Study Aim	Main Findings
[18]	Investigate the electricity spot price behaviour for SA Water in Australia	• Studied the energy prices in the NEM. SA Water has taken advantage of electricity spot price to manage plant's operation, and could save up to AUD 400,000. • Before 2013, SA Water used energy retail with fixed negotiations; in 2013–2017, operated under spot price with fixed price and fixed volume hedge contracts; from 2017, managed market risks itself and since 2020, became a registered self-retailer.
[194]	Investigated the Laguna WWTP in California, USA, participating in a DR scheme.	• The plant serves around 230,000 people and treats about 66 mL/day of wastewater. • Plant's energy consumption around 3–5 MWh, when not shifting energy loads. • CHP system consists of 4 × 1.1 MW generators and 2 MW Tesla battery • 18 events were requested to evaluate the plant's capability from March to June 2019. • The WWTP could save up to USD 45,500 yearly from DR only and USD 68,340 if combined with other strategies, which represents around 4.8% of plant's energy costs.
[230]	WWTPs, aggregated as VPP, to provide services.	• Integration is needed since one plant has not enough capacity to provide service. • WWTP's potential control reserve in Germany was approximately 300 MW. • Theoretical energy production potential from biogas in WWTPs was 2.1–2.6 TWh/y.
[231]	Control strategy for WWTPs for a short-term demand side	• The proposed control strategy could provide a modest cost savings of 1% if the day-ahead market is considered • If it is applied to the regulating market, the potential savings could be up to 27%.

The planning process can be considered an optimisation problem in which the optimal solution consists of finding the optimal system configuration, including the best technological generation mix, optimal size, capacity, location, and construction time with minimum investment cost [221]. Due to the uncertainty and intermittency, adopting a hybrid configuration system is usually a good alternative for WWTPs. Hybrid systems can maximise the energy generation potential from different resources, and lead to a better cost-effectiveness, energy efficiency, modularity, and flexibility [232].

Although there are several technological solutions and strategies to increase economic benefits for a WWTP, their implementation in a full-scale plant is still very limited. The biggest challenge is commonly related to capital and operating costs. Because of the vast number of available technology resources, determining the optimal planning design and operation strategy of power generation in WWTPs is not an easy task and is no longer a simple technical problem but a complex and difficult challenge that requires an integrated and comprehensive approach to make a cost-effective solution [233].

5. Conclusions

This paper reviewed different renewable energy technologies that can be adopted by WWTPs to improve energy efficiency, reduce operating costs, and move toward sustainability, focusing on providing an overview of the current status of each technology by exploring their energy recovery potential, benefits and drawbacks.

AD is still the most widely used alternative to treat sludge and recover energy in a WWTP due to its maturity technology, sewage sludge treatment efficiency, low operating costs and biogas production as a co-product. In the USA, almost 50% of all the wastewater is treated through AD. Co-digestion and pre-treatment methods are some alternatives to improve biogas production and process efficiency, but the second one is primarily used to enhance sludge biodegradability, sludge management, and reduce environmental impact. Thermochemical processes, including pyrolysis and gasification, can also offer several benefits for treating sewage sludge by converting organic matter into valuable products while addressing the challenges associated with sludge management. Both gasification and pyrolysis are mature technologies that generate high-value co-products, including syngas and bio-oil, and can be used to generate electricity and heating. Additionally, hydropower and wind technologies offer significant benefits as renewable energy sources, but their application in WWTPs is limited due to several practical, technical, and economic challenges. For example, conventional hydropower systems require a significant and consistent flow of water to generate electricity, and, typically, WWTPs do not have the necessary flow rates or water head heights to support hydropower turbines effectively, and wind turbines require substantial space to operate efficiently, and many municipal facilities are located in urban areas or constrained sites where space is limited. On the other hand, other technologies, including Microbial Fuel Cells (MFCs) and Microbial Electrolysis Cells (MECs), hold significant potential for sustainable energy production and municipal wastewater treatment. Despite their promising laboratory-scale performance, large-scale implementation of MECs and MFCs can face some challenges related to scalability, energy efficiency, capital and operational costs, material durability, microbial stability, reactor design, and regulatory approval. Therefore, more academic research and technological development are needed to achieve both technical advancements and system integration. Many of these challenges can be overcome, opening up opportunities for bioelectrochemical technologies to contribute to sustainable energy production, waste treatment, and environmental management on larger-scale facilities. Overall, the successful adoption of renewable energy technologies involves overcoming several challenges that span technical, economic, regulatory, and operational domains. It is important to address these challenges and technology limitations to outline future prospects for achieving a more energy-efficient and sustainable wastewater treatment paradigm.

WWTPs also have a significant potential to contribute to grid services and participate in demand-response programs by leveraging their operational flexibility and energy consumption patterns. By shifting load consumption, optimising processes, integrating renewable energy, and investing in advanced control systems and energy storage, WWTPs can provide valuable services to the grid while benefiting from cost savings and incentives. Additionally, the effective implementation of demand response and the ability to provide grid services for a WWTP requires addressing operational, economic, and regulatory challenges to ensure that energy management strategies align with both treatment efficiency and grid requirements.

The main challenges and limitations of this study included (i) a review and compilation of several types of renewable energy technologies limited only to municipal wastewater and sewage sludge (some technologies can use other types of feedstocks, such as AD, thermochemical processes, MFC, MEC); (ii) some renewable sources are still under experimental stages and early stage development, and thus, their applications in large-scale WWTPs are very limited, making it difficult to quantify their effectiveness, efficiency, or financial viability; (iii) due to the wide range of WWTPs design, treatment processes and capacity, applications of these technologies can have significant differences in performance, including energy production and efficiency; and (iv) many of the studies on renewable energy in WWTPs are based on small-scale pilot projects or case studies and they are not widely implemented in large-scale facilities. Thus, it is hard to measure key parameters, including efficiency, system performance, costs, and operational control.

Therefore, the future research directions regarding the adoption of energy resources in WWTPs can be based on two main topics: (a) further research on emerging renewable energy sources (RES) and (b) optimising traditional RES. For traditional methods, such as AD, the focus should be on enhancing biogas production, improving process efficiency (i.e., co-digestion and pre-treatment), and integrating AD with other energy recovery systems. However, thermochemical processes are also a mature technology, and further research exploring better conversion efficiencies and the production of high-value co-products from sewage sludge while reducing emissions can be developed. In terms of hydropower and solar PV, investigations to overcome site-specific challenges, such as limited space or water flow, with compact systems and more efficient systems can be explored. On the other hand, emerging technologies, particularly MFCs and MECs, improving scalability, energy efficiency, and material durability, alongside overcoming regulatory barriers for large-scale deployment, are the main challenges to be overcome. Further research is needed to integrate these bioelectrochemical systems with other treatment processes to maximise energy recovery and treatment efficiency. Additionally, water electrolysis holds promise for hydrogen production from wastewater, which could contribute to energy storage and fuel cells. The future of WWTPs will also involve incorporating digitalization and smart grids to optimize energy management, enabling WWTPs to provide grid services and become key players in decentralized energy systems.

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