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Review

Towards Energy Neutrality in Full-Scale Wastewater Treatment Plants Under the European Directive 3019/2024: What Are the Technical Possibilities?

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Highlights

What are the main findings?

- Energy audits should be first accomplished to optimize energy consumption.
- Enhanced anaerobic digestion is fundamental for large-scale WWTPs.
- Photovoltaic panels represent a key technology the for medium-scale WWTPs.
- Thermal energy recovery has a minor impact due to the large electricity demand.

What are the implications of the main findings?

- Energy neutrality strategies should be diversified according to WWTP size.
- Hybrid systems are more resilient and allow for 100% renewable generation.
- Hybrid systems can be boosted by the interconnection between industry and research.

Abstract

The European Urban Wastewater Treatment Directive revision introduced the energy neutrality concept, accelerating the transition of wastewater treatment plants (WWTPs) towards a 100% renewable energy share. Energy audits must be initially conducted to assess current energy consumption levels, identifying deviations from benchmarking values, and energy efficiency measures must be implemented. Strategies should be then diversified according to WWTP size: anaerobic digestion (AD) is a core technology for large-scale plants. The refurbishment of conventional digesters into "enhanced" AD, including sludge pretreatment, co-digestion, or two-stage AD, significantly increases energy yields, providing most of the required electricity/heat. Enhanced AD can be complemented by photovoltaic (PV) panels and thermal energy recovery from effluents. For medium-scale plants, instead, PV implementation is a key solution for electricity production, coupled with hydroenergy recovery and, eventually, wind turbines, while heat can be provided by solar thermal panels or thermal energy recovery from effluents. Hybrid systems, which integrate multiple renewable sources, are often the best solution to reach energy neutrality, improving the system's resiliency; however, dedicated mathematical models are needed to size and operate the different components, considering local factors. Future research must connect theoretical and in-field studies to allow a wider implementation of hybrid systems.

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1. Introduction

Wastewater treatment plants (WWTPs) require electricity for all operations, especially biological treatment and advanced pollutant removal; about 60% of the total electricity demand (widely varying between 0.258 and 0.985 kWh/m^3, according to plant size and adopted treatment technologies) [1] is due to aeration, with other major consumers being sludge treatment (15%) and pumping (13%) [2]. WWTP electricity consumption ranges from 0.3 to 0.6 kWh/m^3, reaching about 0.3–3% of national electricity demand in the United States of America (USA) [1]. In sludge lines, the major electricity consumer is mechanical dewatering, which requires 0.018–0.027 kWh/m^3 out of the total 0.074–0.15 kWh/m^3 needed for sludge thickening, digestion, and dewatering [3]. More generally, electricity is required in all WWTP sections, while heat is consumed in relatively small amounts for anaerobic digester heating, sludge drying [4], and office air conditioning.

The ambitious Urban Wastewater Treatment Directive revision (UWWTD, Directive 3019/2024) introduced the mandatory concept of energy neutrality, applicable to medium (10,000–100,000 population equivalent, PE) and large-scale (>100,000 PE) WWTPs, putting the European Union (EU) at the frontline in the sector [5]. An overall neutral net energy balance is required, including both electricity and heat, thus the WWTP must be self-sufficient from an energy perspective. Only under specific conditions, i.e., when the plant cannot achieve energy neutrality by implementing all possible technical measures, a limited percentage of the total energy request (<35%) can be purchased externally, but it must be certified as coming from renewable energy sources (RESs) [5]. By the deadline in 2045, 100% of the required energy must be locally produced in medium and large-scale WWTPs; however, progressive steps are forecast with intermediate deadlines [5], e.g., by the end of 2030, medium and large WWTPs must self-produce at least 20% of the required energy. Despite being EU-centric, the revised UWWTD is expected to influence the wastewater sector globally, accelerating the transition of conventional WWTPs into water resource recovery facilities (WRRFs) [6], i.e., innovative platforms capable of recovering energy, nutrients, and water. However, while industrialized countries can easily achieve energy neutrality by implementing the technologies described in the present review, developing countries rarely implement advanced energy recovery strategies such as sludge pretreatment, co-digestion, and advanced wastewater treatment, so reaching energy neutrality might be more challenging [7].

Besides other important aspects, in the revised UWWTD, an improved effluent quality is sought, requiring, for large and medium WWTPs, advanced "quaternary" treatments for micropollutant removal, further increasing total electricity demand (+1–8 €/PE yr for ozone, +4–14 €/PE yr for granular activated carbon, +8–14 €/PE yr for powdered activated carbon) [8,9]. Another important aspect, specifically mentioned in the revised UWWTD and directly connected to energy neutrality, is energy audits, which become mandatory every four years for all WWTPs, and must be conducted for the first time before the end of 2028 (for large WWTPs) or 2032 (for medium WWTPs) [5]. Energy audits, which thoroughly assess the energy consumption of WWTPs, help identify sustainable strategies for energy efficiency and performance optimization [10] and must also include the upstream sewer networks; in addition, they must be updated every four years. Normally, WWTPs operate at suboptimal energy performance [11]. Standardized methodologies for energy audits focus on the plan–do–check–act methodology and the ISO50001:2018 standard [12]. However, their widespread implementation is hindered by

limited data availability, model complexity, and aging infrastructure [12]; furthermore, specific guidelines for WWTPs are lacking [6]. Technical updates, such as variable frequency drives for pumps and the implementation of high-efficiency blowers, allow for significant energy savings (up to 0.04–0.06 kWh/m^3) [11]. Machine learning and artificial intelligence, in addition, have recently gained momentum thanks to their capability to model, using data-driven approaches, non-linear energy consumption patterns typical of WWTPs, dynamically adjusting operating parameters according to influent variations, with 15–30% energy savings [13]. In all WWTPs, before considering energy neutrality targets, a preliminary measurement campaign must be performed, identifying variations in energy consumption from benchmarking values and implementing technical efficiency measures [14].

Traditionally, energy recovery in WWTPs has been performed by conventional anaerobic digestion (AD) of sewage sludge, converting organic compounds embedded in sludge into biogas, which can be used to produce electricity, heat, and/or biomethane [15]. Due to the absence of stabilization, primary sludge, from the initial sedimentation of raw sewage, has a higher biogas generation potential than secondary sludge, i.e., the excess biomass produced during biological treatment [16]; nonetheless, most of the time, primary and secondary sludge are treated together. Limited sludge biodegradability is observed, especially when exclusively treating excess sludge from biological treatment (secondary sludge), and can also be related to the high concentration of complex refractory substances, which hinder AD process efficiency [15]. Normally, a well-designed and controlled sludge AD system can provide around 40% of total WWTP electricity demand, referring to conventional low-rate sludge AD treating a mixture of primary and secondary sludge [4,17]. On the other hand, heat generation from combined heat and power (CHP) units fed with biogas is typically sufficient to cover thermal energy requirements, mostly connected to digester heating [18]. The limited biogas exploitation in WWTPs has been attributed to its slow generation rate, its low energy content, and biogas upgrade costs; e.g., in 2015, less than 10% of full-scale WWTPs in the USA produced and exploited biogas for energy generation [19].

To overcome these limitations, several modified ("enhanced") AD configurations have been developed, first in the laboratory [15] and then in pilot and full-scale configurations [20,21]. The enhanced AD concept includes sludge pretreatment, anaerobic co-digestion (AcoD) with locally available substrates [22], and two-stage AD. However, even these innovative solutions might not be sufficient to reach energy neutrality, especially if highly biodegradable co-substrates are not locally available. Thus, other technical options might be explored, which must be technologically robust, efficient, and economically sustainable [23]. Keeping in mind that WWTPs require much more electricity than heat, technologies for electricity generation must be prioritized.

The implementation of multiple RESs, such as biogas and photovoltaic (PV), leads to the generation of so-called "hybrid systems" [24]; their design and optimization are complex, given the extreme variability in energy demand on one hand, and energy production on the other hand [25]. Mathematical models can help design and optimize different technologies; often, complete and resilient energy neutrality can be reached only by integrating multiple RESs, after optimizing WWTP energy consumption [26].

Given this complex framework and the extreme relevance of energy considerations in modern WWTPs, this review aims to provide an up-to-date overview of the technological options with a high technology readiness level (TRL), already applicable at an industrial scale, to reach energy neutrality in medium and large-scale WWTPs. After presenting an overview of current state-of-the-art research related to the main technical solutions, a critical comparison is provided. Finally, a conceptual framework to reach energy neutrality is presented, differentiated according to WWTP size (medium versus large-scale

WWTPs). Critical aspects that still need to be addressed are discussed throughout the paper, including future research that is needed. This review aims to boost the transition of conventional WWTPs to 100% renewable WRRFs, allowing for more sustainable wastewater treatment worldwide.

2. Methodology

The literature analysis was done by searching all studies related to the investigated topics in Scopus and Google Scholar, focusing on the last ten years (2015–2026). The general literature background was obtained through the following query of keywords in Scopus: "energy recovery wastewater" OR "energy neutrality wastewater". The specific studies for each technology examined in the following sections were retrieved by using the following keywords: "anaerobic digestion wastewater treatment" (Section 3.1), "hydroenergy recovery wastewater treatment" (Section 3.2), "advanced wastewater treatment" (Section 3.3), "thermal energy recovery wastewater treatment" (Section 3.4), "photovoltaic systems wastewater treatment" (Section 4.1), "solar greenhouses sludge treatment" and "solar thermal wastewater treatment" (Section 4.2), "wind energy wastewater treatment" (Section 4.3), and "hybrid energy systems wastewater treatment" (Section 5). Inclusion criteria included peer-reviewed research or review articles focused on municipal wastewater treatment, written in English, and reporting energy consumption data. Studies exclusively focused on industrial wastewater, theses, editorials, and articles not reporting energy consumption data were excluded from the assessment. The literature analysis was complemented by an analysis of industrial technologies on company websites.

The possible solutions to reach energy neutrality (Figure 1) were split into direct energy recovery from wastewater and sludge (Section 3) and external RES implementation (Section 4). The former forecast conventional AD (Section 3.1), including sludge pretreatment before AD (Section 3.1.1), AcoD (Section 3.1.2), two-stage AD (Section 3.1.3), hydroenergy recovery (Section 3.2), modified wastewater treatment (Section 3.3), and thermal energy recovery (Section 3.4), while the latter include PV module installation (Section 4.1), other solar energy systems (Section 4.2), and wind energy (Section 4.3). Hybrid systems are presented in Section 5 as a combination of different technological solutions. Priority is given to electricity generation, as most of the WWTP's demand is connected to electricity rather than heat. Overall, technologies that can provide both electricity and heat, such as AD, AcoD, or anaerobic wastewater treatment, appear particularly promising in the pursuit of energy neutrality. Energy recovery from sludge through incineration, pyrolysis, or gasification is not discussed in this review, as most thermochemical technologies are installed outside WWTPs and their technological maturity is still limited [27].

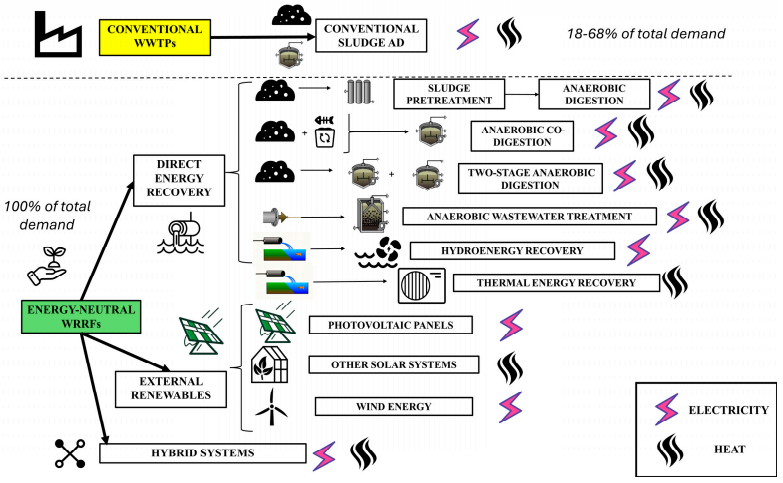

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Figure 1. Overview of the technological solutions to reach energy neutrality in full-scale wastewater treatment plants.

3. Direct Energy Recovery from Wastewater and Sludge

Direct energy recovery from the chemical energy in wastewater and sludge includes sludge AD or AcoD in single or multiple stages, eventually improved by sludge pretreatment, hydroenergy recovery from treated effluents, modified wastewater treatment, and thermal energy recovery from effluents.

3.1. Anaerobic Digestion

AD, where microbial communities degrade organic matter into biogas through four sequential stages (hydrolysis, acidogenesis, acetogenesis, and methanogenesis) under oxygen-free conditions, is a central technology for energy neutrality [28]. While WWTP digesters are designed to optimize methanogenesis rather than methanotrophy (methane oxidation processes observed in microbial methane cycling in soils), understanding methane oxidation pathways (e.g., through quorum-sensing analyses) has received increasing attention as it could help minimize overall biogas losses in digestate storage and handling [29]. In general, AD offers a dual benefit: it stabilizes and reduces sludge volume while producing methane-rich biogas that can be directly converted to heat and electricity or upgraded to biomethane [30]. As WWTPs move towards being resource recovery facilities, AD becomes fundamental for their energy neutrality [31]; therefore, AD process amelioration has been frequently investigated in the literature [32–35].

To meet the European energy neutrality targets, considerable attention must be given to key AD factors, such as substrate composition and process conditions [36]. Numerous strategies have been explored to improve the performance of sewage sludge AD through the so-called "enhanced AD", including the application of different pretreatment methods [37], AcoD with complementary organic substrates [38], two-stage AD systems [39], the addition of conductive materials [40–42], and the optimization of operational parameters [43] (Figure 2). Figure 2 schematically summarizes the main process configurations for enhanced AD, illustrating how pretreatment, co-digestion, and multi-stage digestion can even be combined to intensify biogas production from sewage sludge. Overall, Figure 2 highlights the integrated and complementary nature of these approaches in improving organic matter conversion efficiency and supporting more effective energy recovery in WWTPs.

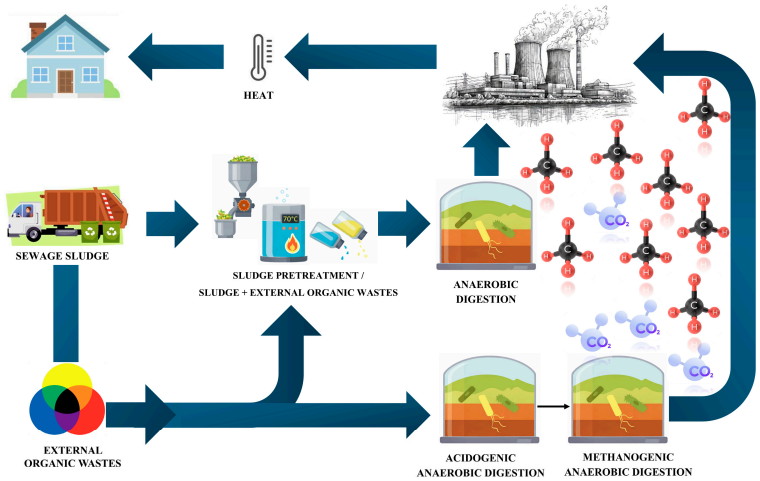

Figure 2. Enhanced anaerobic digestion concept applied to wastewater treatment plants.

3.1.1. Pretreatment Techniques

Sludge pretreatment is one of the most effective strategies for enhancing AD because it increases organic matter solubilization and releases large amounts of biodegradable organic matter into the liquid phase, facilitating microorganisms' activity [44].

Pretreatment techniques are generally classified into three categories (Figure 3): physical, chemical, and biological. Each category can employ specific treatment methods. Physical methods, including ultrasonic waves/microwaves, thermal hydrolysis, high-pressure homogenization, steam explosion and electric decomposition, enhance sludge breakdown and cell lysis through mechanical or thermal effects, accelerating organic matter release [45]. Chemical pretreatments, which may use acid/alkali, Fenton, calcium peroxide, or ozone, employ selected reagents to break down cell walls and promote sludge hydrolysis [46], while biological pretreatments rely on microorganisms (indigenous, external, or added enzyme formulations) to degrade complex organic matter [44]. The choice of the specific sludge pretreatment method to apply depends mainly on downstream processes, sludge's physicochemical characteristics, treatment objectives, available infrastructure, and economic and environmental constraints.

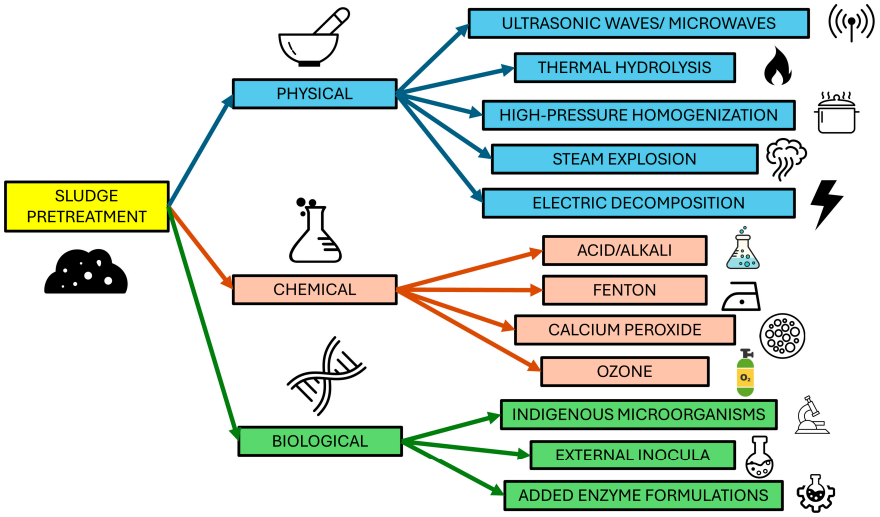

Figure 3. Sludge pretreatment techniques before anaerobic digestion.

All pretreatments aim to increase substrate solubilization, disintegration, and biodegradability before AD [47]. As a result, they improve both biogas quality and quantity, particularly its methane content, reduce the required hydraulic retention time (HRT), and enhance digestate dewaterability, increasing the overall AD efficiency [48]. Nevertheless, different pretreatment methods exert distinct effects on sludge solubilization [44], requiring dedicated studies before moving to industrial applications. In general, physical pretreatments are more efficient in enhancing organic matter dissolution in sludge, followed by chemical and biological ones; the mean dissolution degree of organic matter in sewage sludge after physical, chemical, and biological pretreatments was reported to be around 26.49 ± 14.98%, 14.04 ± 8.91%, and 9.15 ± 8.52%, respectively [44]. Biological pretreatments show the most pronounced effect on biogas yield, surpassing both physical and chemical approaches, but face technological limitations linked to their low TRL [44]. The average increases in biogas yield from AD achieved through physical, chemical, and biological pretreatments were reported as 46.12 ± 41.07%, 40.48 ± 36.84%, and 71.14 ± 78.89%, respectively [44]. However, several sludge pretreatment technologies still suffer from poor energy and economic performance [15], and thus must be optimized through long-term pilot studies before moving to full-scale operations. Bioelectrochemical treatment, electrically

conductive materials bioaugmentation, and microaeration, in particular, stand out as promising research options [49–51], even if their practical implementation is currently challenged by low TRL, safety, operational efficiency, clogging, and scale-up. Ozonation has recently gained popularity for increasing methane content in biogas and improving chemical oxygen demand (COD) and volatile solids (VS) removal, despite most studies being conducted in a laboratory or at a pilot scale [46]; however, optimizing ozone dosage and location is crucial, as it requires huge electricity inputs [52].

A well-established commercial pretreatment method is thermal hydrolysis (THP) [21], where thickened sludge is exposed to high temperature and pressure (typically 160–180 °C, 6 bar) for about 20–30 min, followed by rapid decompression [53]. THP effectively disrupts microbial cells, solubilizes macromolecules, and makes organic compounds more accessible and biodegradable for anaerobic microorganisms [20], showing an interesting capability to remove micropollutants [54]. Full-scale patented systems, such as the Cambi™, BioThelys™, Exelys™, and TurboTec® processes [20,55], enable up to a 50% increase in methane yield and threefold improvement in digester throughput compared to conventional low-rate AD [56]. In addition to improved biogas production and pathogen destruction, THP enhances digestate dewaterability and allows biosolids to meet American Class A standards for agricultural reuse [57]. However, THP is energy-intensive and can lead to the formation of recalcitrant compounds through Maillard reactions, necessitating careful optimization of operating parameters and the implementation of heat recovery systems [58]. Reported THP benefits include increased digestion loading rates, improved sludge biodegradability (particularly in secondary sludge), and enhanced dewaterability [59]. By implementing THP, biogas yield can be enhanced by 59.68 ± 56.60% [44]. THP pretreatment of sewage sludge generally leads to a positive net energy balance and enhanced overall energy recovery when properly integrated with AD and supported by efficient heat recovery systems [56]. In fact, although THP is inherently energy-intensive due to the substantial thermal energy demand for sludge heating, the associated increase in biogas production and improved sludge dewaterability typically compensate for the additional energy demand, especially when efficient heat recovery systems are implemented [56]. Cano et al. [56] reported, for a full-scale treatment plant treating 30,000 t/year of municipal solid waste, that optimized energy integration can achieve economic savings of approximately 5 €/t with net annual benefits around 0.5 M€; THP may increase the revenues of a digestion plant by up to 40%, or even double them when digestate management costs are considered. Despite these advantages, the main limitations of THP remain the high initial capital investment and the excessive energy consumption in systems lacking adequate heat recovery [59]. Nevertheless, THP is widely recognized as a key technology for sludge management improvement in modern WWTPs [59].

Another pretreatment that has been tested at a full-scale level is ultrasonication: by implementing a double-tube ultrasound reactor at 200 kJ/kg total solids (TS) for secondary sludge pretreatment in a German WWTP in Starnberg (100,000 PE), a significant reduction in sludge viscosity was observed [60]; however, an insignificant methane yield increase (+6.2%) was registered, showing a limited economic advantage. More significant increases were observed by implementing the Sonix™ ultrasonic system, with up to a 50% augment in biogas production and 54–70% VS removal [61], even if the specific US energy was not reported, making the comparison among studies challenging. Overall, the differences in the impact of ultrasonication on AD performance (i.e., biogas and methane yields) are mainly attributable to variations in specific ultrasonic energy input, sludge's physicochemical characteristics, process conditions, and ultrasonic reactor configuration. However, a better way to implement sonication might be in the recirculation line of the activated sludge process, with proven reductions in secondary sludge generation [20].

3.1.2. Anaerobic Co-Digestion

The AD of sludge alone is limited by low sludge biodegradability, a suboptimal carbon-to-nitrogen (C/N) ratio, and low methane production [62]. In contrast, AcoD, the simultaneous digestion of sludge with external organic waste, such as food waste, organic fraction of municipal solid waste (OFMSW), organic solid by-products from table olive processing (OSTBOP), agricultural residues, glycerol, or fats, oils, and grease (FOG), has emerged as one of the most effective strategies to enhance the performance of existing digesters from a circular economy perspective by exploiting locally available substrates [63]. AcoD of sewage sludge and food waste has demonstrated environmental and economic benefits, showing remarkable improvements in energy balance (93–196%) and significant reductions in greenhouse gas (GHG) emissions (up to 97%) [64]. By adding 50% OFMSW to sewage sludge on a VS basis, a 20–40% increase in biomethane production was observed [65].

The main AcoD advantage lies in the complementarity between nutrient-rich sludge and carbon-rich co-substrates, which must be properly selected. Sludge, in fact, typically exhibits a low C/N ratio (4–9) and moderate energy content [62,66], whereas much organic waste (animal manure, OFMSW, agricultural straw) is highly biodegradable and shows significant methane potential [67]. By combining these substrates, the overall C/N ratio is optimized, reaching recommended values of 20–30 [62,67], and significantly improving biogas yields (especially in a lab-scale bioreactor, with increases exceeding 100%) compared to sludge mono-digestion [68]. Moreover, process inhibition risks from ammonia or volatile fatty acids (VFAs) are reduced in AcoD operations [67]. Methane yields are strongly influenced by both the type and amount of the selected co-substrate(s); by adding 1% *v*/*v* of crude glycerol as a co-substrate to sludge AD, methane yield can be increased by 176% at a lab-scale level [69].

Various co-substrates have been investigated in the literature (Table 1): AcoD studies in Table 1 are ranked according to the methane yield increase (%) compared to sewage sludge mono-AD, in decreasing order. For each co-substrate, the data in Table 1 are related to bioreactor (lab- or pilot-scale, batch or continuous mode) and feedstock characteristics (TS in %, C/N ratio), and operating conditions (temperature in °C, pH).

Table 1. Performance of AcoD of sewage sludge with co-substrates reported in the literature.

Increase in Methane Yield (%)	Co-Substrates (Content)	Feedstock Characteristics	Operating Conditions	Reference
155	Brewery spent grains (25%)	9.0% TS, C/N = 25	T = 37 °C, pH = 7.7–7.8	[70]
152	Wheat stalk (50%)	4% TS	T = 36 °C, pH = 6.5	[71]
113	Winery wastewater (40%)	34.66 g/L TS	T = 35 °C, pH = 7.1	[72]
108	Food waste (50%)	34.66 g/L TS	T = 37 °C, pH = 5.9–6.0	[73]
91	OFMSW (30%)	7.5% TS, C/N = 27	T = 37 °C, pH = 6.0–8.0	[74]
87	Kitchen waste (50%)	13.0% TS	T = 37 °C, pH = 6.8	[75]
76	Horse waste (50%)	15% TS, C/N = 20	T = 37 °C, pH = 7.5	[76]
68	Municipal solid waste (15%)	23.5 g/L TS, C/N = 24.8	T = 37 °C, pH = 6.5	[77]
66	Banana plant waste (60%)	13.2% TS	T = 37 °C, pH = 7.5	[78]
56	Food waste (60%)	C/N = 8.33	T = 35 °C, pH = 7.2–7.3	[79]
52	Wheat stalk (50%)	C/N = 10.84	T = 36 °C, pH = 6.5	[71]
51	Fish sludge (20%)	8.3% TS	T = 37 °C, pH = 6.8	[80]
50	OSTBOP (60%)	10% TS, C/N = 29.3	T = 35 °C	[66]
43	Food waste (50%)	C/N = 25–30	T = 37 °C, pH = 8.0–8.1	[81]
41	OSTBOP (40%)	10% TS, C/N = 20.8	T = 35 °C	[66]
38	Animal manure (25%)	7.4% TS, C/N = 19	T = 37 °C, pH = 7.7–7.8	[70]
33	Food waste (50%)	C/N = 25–30	T = 55 °C, pH = 7.6–7.7	[81]

28	Food waste (25%)	6.8% TS, C/N = 17	T = 37 °C, pH = 7.7–7.8	[70]
26	Rice straw (40%)	C/N = 25.74	T = 37 °C	[62]
23	Sherry-wine distillery wastewater (50%)	C/N = 16.4	T = 35 °C, pH = 7.5	[82]
14	Orange pulp and brewery spent grain (10%)	C/N = 20.0	T = 37 °C, pH = 7.9	[83]

Table 1 demonstrates that incorporating co-substrates into the AD of sewage sludge can substantially improve methane production, with increases ranging from 14% to 155% compared to sludge mono-AD, depending on the co-substrate type, blending ratio, and operational conditions. The wide observed variability highlights the strong dependence of methane enhancement on substrate/co-substrate characteristics and process conditions. Overall, three main trends can be identified from Table 1: (i) the highest methane yield improvements are associated with lignocellulosic and agro-industrial co-substrates applied in moderate amounts; (ii) optimal performance is generally achieved under mesophilic conditions with C/N ratios in the range of 20–30; and (iii) lower improvements are typically linked to low co-substrate fractions, suboptimal biodegradability, or non-ideal C/N balance. High methane yield improvements (>100%) were achieved with lignocellulosic or agro-industrial residues at moderate-to-high inclusion ratios (25–50%), as they likely improved carbon availability, buffering capacity, and nutrient balance. Brewery spent grain (25%) and wheat stalk (50%) resulted in the highest methane yield enhancements (155% and 152%), suggesting an optimal synergy between structural carbohydrates and readily fermentable organic matter. Conversely, lower yield increases (<30%) were associated with low co-substrate proportions (≤10–25%) or substrates with limited biodegradability, such as mixed fruit residues at a low loading rate.

Methane yield improvement strongly correlates with TS content and C/N ratio. Most high-performing systems operated within an optimum C/N range of 20–30. Substrates outside this ideal range, such as food waste with a low C/N ratio (≈8), still showed improvements but to a lesser extent (≈56%), likely due to ammonia accumulation risks. Additionally, systems with moderate TS content (7–15%) tended to perform better than excessively low or high TS content, reflecting a balance between substrate availability and mass transfer limitations.

Nearly all studies were conducted under mesophilic conditions (35–37 °C) and neutral pH (6.5–7.8), reinforcing the robustness of mesophilic digestion. Only one case investigated thermophilic operations (55 °C), which showed moderate improvements (33%), suggesting that higher temperatures do not inherently guarantee superior methane enhancement, especially when dealing with sewage sludge.

Most studies in Table 1 were conducted at the lab scale and in batch mode, overestimating the methane increase due to controlled conditions and the absence of long-term inhibition; thus, the high energy improvements should be interpreted cautiously. Lower yet more realistic improvements were observed in pilot-scale and semi-continuous systems (76%), as well as in lab-scale semi-continuous systems (51%, 41%, and 26%), emphasizing the importance of HRT, microbial adaptation, and operational stability [62,76]. In fact, care must be exercised in scaling up these optimistic results, as high methane improvements are difficult to reach in full-scale operations, due to operating issues, biological instability, uneven mixing, VFA accumulation, organic load limitations, retention times, and difficulty in guaranteeing continuous feeding: limited improvements in methane yields (9–27%) have been observed in full-scale operations when adding 10–30% grease trap sludge (on VS basis) to sewage sludge [84]. Other important aspects that must be ascertained before moving laboratory results from Table 1 to industrial applications are the effective availability of these organic substrates in the analyzed geographic area,

the costs/logistics connected to substrate transportation and the eventual storage need, as well as the administrative interconnection among different management companies [85].

Overall, AcoD is an effective strategy for improving methane yield, particularly when substrate selection is guided by complementary physicochemical properties, and co-substrate ratios are optimized. However, the predominance of batch, lab-scale studies highlights a critical research gap in long-term, continuous, full-scale validation. Thus, future research should focus on process stability, digestate quality, and the techno-economic sustainability of AcoD to boost industrial implementation.

Despite these limitations, sludge AcoD with other organic wastes can provide significant economic and operational benefits by improving the utilization of existing digester capacity. In this context, retrofitting conventional digesters into AcoD facilities can be a successful strategy for moving WWTPs toward energy neutrality. In fact, existing digesters in WWTPs are typically oversized and operate at low loading rates with limited gas production [51], so they can easily accommodate higher substrate amounts without building new infrastructure. However, a trade-off between increased biogas yield and additional nitrogen loads for the wastewater treatment line, augmented digestate generation, increased solids viscosity (which negatively affects dewaterability), and increased polymer demand for dewatering is observed when switching from sludge AD to AcoD, requiring a tailored selection of co-substrate amounts [86,87], possibly through detailed techno-economic analysis and life cycle assessment (LCA). Although the addition of co-substrates can improve methane yield and energy recovery, in fact, it may also increase ammonium concentrations, particularly when nitrogen-rich substrates are used, potentially inhibiting methanogenic activity [88]. Consequently, careful selection and controlled dosing of co-substrates are essential to maintain stable operations, particularly with respect to overall process balance and the maintenance of an appropriate C/N ratio. In practice, this is typically achieved by co-digesting sewage sludge with carbon-rich substrates to balance the nitrogen-rich nature of sludge and mitigate ammonia-related inhibition [86]. Therefore, despite the improved methane production, AcoD may also increase process complexity and operational costs.

The full-scale Avedøre WWTP in Copenhagen (Denmark) is particularly relevant as it reports the conversion of a conventional WWTP into a bio-refinery capable of recovering energy and resources at an industrial scale, thanks to sludge co-digestion with OFMSW, biological upgrading of biogas to biomethane with hydrogen injection, and the production of microbial proteins by nutrient recovery from WWTP reject water [89]. Its relevance lies in its high efficiency, capability to recover multiple valuable products with economic value, its climate-positive operations and its role as a full-scale testbed for next-generation resource recovery technologies.

3.1.3. Two-Stage Anaerobic Digestion Systems

AD and AcoD in WWTPs are commonly operated as single-stage processes, in which hydrolysis, acidogenesis, acetogenesis, and methanogenesis occur within a single bioreactor. However, these reactions are mediated by diverse microbial consortia with distinct physiological requirements. Thus, conventional single-stage AD frequently shows limited process stability, suboptimal methane yields, and high sensitivity to overloading and inhibition. To overcome these drawbacks, two-stage AD has been proposed as an effective strategy to enhance process controllability, stability, and biogas production [90].

To systematically adjust the environmental conditions to the physiological requirements of different microbial groups, researchers developed approaches based on the spatial or temporal separation of hydrolysis–acidogenesis from acetogenesis–methanogenesis [91]. The first bioreactor is normally operated at a short HRT and low pH (5.5–6.5), favoring the activity of acidogenic microorganisms, while the second bioreactor operates

under neutral pH (6.8–7.5) and longer HRT for methanogenic archaea and VFA conversion into biogas.

Two-stage AD offers several advantages over single-stage AD. By decoupling the biological phases, each stage can be optimized, resulting in higher methane yields and enhanced process stability: methane production can be increased by 15–30% compared to single-stage bioreactors [92], reducing external energy demand [93].

Although two-stage AD requires higher capital investment (additional digesters are needed) and operational complexity (each reactor must be carefully controlled), it is well-suited for large-scale WWTPs seeking enhanced energy recovery, improved biosolid stabilization, and compliance with stringent sludge management regulations. When combined with efficient biogas utilization and AcoD, two-stage AD represents a robust and energy-efficient solution towards energy neutrality [94]. Notably, two-stage AD implementation can often be achieved by retrofitting existing unutilized bioreactors, limiting capital expenditure while improving energy recovery [95].

In addition to increased biogas production, two-stage AD indirectly contributes to energy neutrality by enhancing VS reduction and improving sludge dewaterability [94], reducing energy inputs for digestate management. Improved process stability also enables operations at higher organic loading rates, further increasing the potential for on-site renewable energy generation [96]. However, its techno-economic sustainability must be ascertained case by case, assessing the need for new civil infrastructure, such as additional digesters, as well as for skilled personnel. Other technological options, such as external RES integration (especially PV), might be more favorable to limit plant complexity and reduce capital costs, especially when moving from large-scale to medium-scale WWTPs, where AD is not always used for sludge stabilization.

3.1.4. Process Optimization

To enhance methane production while minimizing overall energy consumption, extensive experimental and numerical optimization studies have been recently conducted [36,96]. Ferrer et al. investigated the effect of operational conditions (temperature, sludge TS, and solids retention time—SRT) on methane production, VFA concentration, digestate hygienization, and dewaterability during long-term AD [96]. Shifting from mesophilic (38 °C) to thermophilic (55 °C) conditions, combined with a short SRT of 10 days, significantly enhanced process performance; methane production was maximized while maintaining acceptable VFA concentrations and achieving complete pathogen removal [96]. These findings indicate that transitioning from mesophilic to thermophilic AD can improve digestate valorization and support the circular economy in WWTPs, despite the higher thermal energy demand needed for digester heating. Despite increasing reaction kinetics and pathogen reduction, however, this transition is characterized by a reduction in process stability, with possible VFA accumulation and reduction in biogas yields [97].

Furthermore, recent investigations explored data-driven and machine learning strategies to determine optimal operating parameter sets for AD and AcoD. Field-scale experimental monitoring coupled with artificial neural networks and deep belief networks revealed that maintaining neutral pH, balanced substrate inputs, and controlled recycling streams can significantly enhance biogas production, identifying the nonlinear relationships between key variables and performance metrics [98]. To reduce time-consuming experimental procedures, mechanistically inspired mathematical models, based on Anaerobic Digestion Model Number 1 and BioModel, as well as simulation tools, are essential for understanding the complex AcoD dynamics, predicting system behavior, and optimizing full-scale operations [36]. When coupling process models with deterministic (gradient-based) and stochastic optimization algorithms (e.g., genetic algorithms, ant colony

optimization, particle swarm optimization), optimal operating conditions can be identified for energy-neutral WWTPs [99].

3.1.5. Full-Scale Applications

Full-scale WWTPs differ substantially from lab-scale investigations, as energy consumption for aeration, pumping, heating, and sludge processing can significantly offset the energy recovered from biogas [100]. Furthermore, full-scale WWTPs must operate continuously while complying with strict effluent and biosolids regulations, leaving little flexibility for experimental modifications [20]. Strategies that perform well in lab-scale systems may therefore be impractical or economically unfeasible at a full-scale level. Pilot-scale validation and long-term operational assessment are essential to bridge the gap between laboratory findings and reliable full-scale implementation.

Achieving energy neutrality in full-scale WWTPs requires integration of AD with pretreatment, AcoD, and process optimization, tailored to site-specific conditions. Table 2 presents a ranking of selected full-scale WWTPs equipped with conventional or enhanced AD based on their net energy performance (energy self-sufficiency ratio), i.e., the percentage of energy produced from biogas to the total plant energy consumption. This ranking highlights the wide variability among existing WWTPs, demonstrating the potential for energy-neutral or even energy-positive WWTPs when AD is integrated with sludge pretreatment, AcoD, or two-stage AD.

Table 2. Energy self-sufficiency ratio of relevant full-scale wastewater treatment plants reported in the literature, incorporating enhanced anaerobic digestion.

Energy Self-Sufficiency Ratio (%)	Wastewater Treatment Plant (WWTP) Location and Potentiality	Treated Substrates	Applied Pretreatment	Biogas/Electricity Production	Reference
150–160	Marselisborg, Aarhus, Denmark; 27,500 m^3 wastewater/day	Sewage sludge + organic waste	Sludge liquor treatment based on Anammox	$5 \cdot 10^6$ m^3/year; 10 GWh/year	[101]
108	Strass, Zillertal, Austria; 42,000 m^3 wastewater/day	Secondary sludge + grease trap + crude glycerol + food waste (two-stage AD)	Pre-denitrification	3 GWh/year	[63,102]
100–105	East Bay Municipal Utility District WWTP, USA; $1.2 \cdot 10^6$ m^3 wastewater/day	Sewage sludge + food waste + high-strength waste + fat, oil, and grease (two-stage AD, 11 bioreactors of 6800 m^3)	None	$8.5 \cdot 10^6$ m^3/year; 52 GWh/year	[63]
100	Braunschweig, Germany; 55,000 m^3 wastewater/day	Mixed sludge + agricultural waste (two-stage AD, 1 bioreactor as 1st stage, 4450 m^3, and 2 bioreactors as 2nd stage, 2100 m^3 + 4450 m^3)	Thermal hydrolysis	$2.2 \cdot 10^6$ m^3/year; 19 GWh/year	[103]
100	Werdhölzli, Zürich, Switzerland; 510,000 m^3 wastewater/day	Sewage sludge + fat, oil, and grease (4 bioreactors of 7250 m^3 and 4 bioreactors of 3500 m^3, mesophilic conditions)	None	41 GWh/year	[63,104]
100	Gloversville–Johnstown Joint, New York (USA); 52,000 m^3 wastewater/day	Mixed sludge + yogurt/cheese whey	None	$33 \cdot 10^6$ m^3/year; 28 GWh/year	[63,105]

		wastewater + settleable solids			
100	La Farfana, Santiago, Chile; 760,000 m^3 wastewater/day	Sewage sludge + food waste	Biological	$31 \cdot 10^6$ m^3/year; 54 GWh/year	[106]
100	Tarnów, Poland; 86,400 m^3 wastewater/day	Mixed sludge	Cambi™ THP	$3 \cdot 10^6$ m^3/year	[107]
98	Iława, Poland; 30,000 m^3 wastewater/day	Sewage sludge + poultry waste + fat waste (mesophilic conditions)	Thermal hydrolysis + biological	$1.2 \cdot 10^6$ m^3/year; 2.54 GWh/year	[108]
85–90	Point Loma, San Diego, California; 900,000 m^3 wastewater/day	Mixed sludge	None	$33 \cdot 10^6$ m^3/year; 193 GWh/year	[63,109]
80–90	Sheboygan, Wisconsin, USA; 70,000 m^3 wastewater/day	Sewage sludge + dairy waste + fat, oil, and grease (3 primary + 1 secondary bioreactor)	None	$5.1 \cdot 10^6$ m^3/year; 32 GWh/year	[63,110]
80	Antonilko, Antonilco de Tula, Hidalgo, Mexico; $4.32 \cdot 10^6$ m^3 wastewater/day	Mixed sludge (30 bioreactors of 13,000 m^3, mesophilic conditions)	Sieving, thinning, biological treatment, and physicochemical treatment	$91 \cdot 10^6$ m^3/year; 197 GWh/year	[111]
56	Seine Aval, Paris, France; $1.5 \cdot 10^6$ m^3 of wastewater/day	Sewage sludge (11 bioreactors of 12,000 m^3)	Screening, grit removal and de-oiling	350 GWh/year	[112]
35	Stickney Water Reclamation Plant, Chicago, USA; $5.3 \cdot 10^6$ m^3 of wastewater/day	Sewage sludge (mesophilic conditions)	None	$35 \cdot 10^6$ m^3/year	[113]

Full-scale WWTPs incorporating advanced AD technologies exhibit a wide range of energy self-sufficiency, from 35% (Chicago, USA) to 150–160% (Aarhus, Denmark). Most facilities reported in Table 2 achieve approximately 100% self-sufficiency, indicating that enhanced AD can fully meet WWTP energy demand, especially in large-scale WWTPs where AcoD is implemented. Denmark's Marselisborg stands out as the best performer: several online sensors in the plant automatically calculate the setpoints of 125 variable speed drives, reducing overall WWTP electricity consumption to around 0.32 kWh/m^3 [101]. Electricity from biogas covers the entire water cycle demand for about 200,000 inhabitants (including freshwater supply), while the excess heat feeds local district heating systems.

Substrate composition strongly impacts the energy self-sufficiency ratio: East Bay Municipal Utility District (USA) achieves 100–105% energy self-sufficiency by processing a combination of sludge, food waste, high-strength industrial waste, and fats and oils. Smaller WWTPs with optimized AcoD, such as Tarnów and Iława (Poland), reach near-complete energy self-sufficiency, demonstrating that substrate quality can outweigh plant potentiality in determining energy performance.

Sludge pretreatment and optimized AD configuration further enhance energy recovery: THP (Braunschweig, Tarnów) and biological pretreatments (La Farfana, Chile) improve sludge biodegradability, while advanced nitrogen removal strategies in the wastewater line, such as the Anammox process implemented at Marselisborg, limit overall electricity demand. Two-stage AD systems, implemented at Strass, East Bay MUD, and Braunschweig (Germany), increase digestion efficiency and biogas yield.

Overall, energy neutrality in WWTPs equipped with AD can be achieved through complementary strategies: (i) reducing overall energy demands through WWTP process modifications (Section 3.3) [114], (ii) maximizing methane production through optimized sludge AD and AcoD implementation [114]; (iii) applying pretreatment methods to enhance substrate bioavailability for AD [115], and (iv) adopting advanced bioreactor configurations, including two-stage AD processes and anaerobic membrane bioreactors (AnMBRs) [116]. Combining these strategies can allow WWTPs to achieve full energy neutrality and even generate 10–30% surplus energy [117]. However, AD alone might be insufficient to reach energy neutrality if performed as a conventional process, or uneconomical, especially for medium-scale WWTPs, where aerobic sludge stabilization is preferred [118]; in these cases, alternative strategies must be sought. The literature studies demonstrated that by reducing WWTP size, the specific costs for co-digestion implementation rise significantly (from 69€ per person at 30,000 PE to 105€ per person at 1000 PE), limiting AcoD applicability [119].

3.2. Hydroenergy Recovery

Another technology commonly implemented in full-scale WWTPs is hydroenergy generation, which is one of the most economical, flexible, and affordable RESs, showing low operational costs and limited technical complexity thanks to the low maintenance required by hydraulic turbines [23]. Hydroenergy production is based on screw Archimedean or Kaplan hydraulic turbines positioned at the plant outlet or in other plant sections, with Kaplan turbines showing better efficiency but also higher installation costs [120]. These turbines are characterized by relatively high discharge flow rates and limited head jumps, and thus are known as low or ultralow head jumps [120]. Hydroenergy systems are categorized into micro (1–100 kW), mini (100 kW-1 MW), small (1–10 MW), and large (>10 MW) systems based on the installed electric power [23]. A worldwide inventory of installed hydroenergy systems is reported in [121], with 49 systems reported in 2021, a prevalence of micro and mini systems, and Switzerland and Korea as the leading countries. However, the total number of installed turbines throughout the world is supposed to be significantly higher, because it is common practice for water utilities to install them when site-specific conditions are favorable. As an example, Jiguanshi WWTP in China (800,000 tons of treated sewage/day) efficiently exploits hydroenergy recovery for electricity generation, showing a practical energy density of 0.035 kWh/m^3 and an excellent recovery efficiency (83.3%), thanks to minimal mechanical and electromagnetic losses [11].

3.3. Modified Wastewater Treatment

Modified wastewater treatment includes all techniques that reduce electricity demand for biological organic matter stabilization, traditionally performed through conventional activated sludge (CAS). In particular, the paradigm shift from CAS or, in more advanced configurations, nitrification–denitrification and biological phosphorus removal to anaerobic treatment is not novel. Anaerobic wastewater treatment technologies include, among others, up-flow anaerobic sludge blanket (UASB) and AnMBR reactors [122]; they are capable of directly generating biogas from organic substances (COD and biochemical oxygen demand—BOD) in wastewater, reducing electricity demand for aeration [11]. AnMBR and UASB show a much higher electricity generation potential from biogas when compared to CAS followed by sludge AD, because in the latter configuration most COD fractions are oxidized in the upstream aerobic process [11]. AnMBR shows superior effluent quality and process stability, while UASB has lower technological complexity and can be easily applied in developing countries [122]. However, the limited COD concentration in municipal sewage hinders direct anaerobic energy recovery due to kinetic limitations [123]; moreover, nutrient removal is substantially absent anaerobically, requiring a

downstream aerobic polishing step. Also, significant amounts of dissolved CH_4 leave the reactor with the effluent, especially at low temperatures, limiting total energy efficiency of the system [123]. Finally, AnMBR suffers from membrane contamination (fouling) and low-temperature process instability [11]. In real municipal wastewater treatment, electricity generation from AnMBR has been shown to decrease from 1.82 to 2.27 kWh/day at 20–25 °C to 0.67 kWh/day at 15 °C [124], while a study on psychrophilic temperature regimes (15, 12, 9, 6, 3 °C) showed that AnMBR can achieve high COD removal (>95%) until 6 °C, but a sudden decrease is observed at 3 °C (86%) [125]. Thus, direct, high-efficiency anaerobic COD conversion to methane is easily achievable only in countries with a warm climate, where reactor heating is not required, and possibly treating highly biodegradable wastewater [122]. In cold climates, instead, longer HRTs are required, or passive solar heating techniques can be implemented to increase reactor efficiency by raising the water temperature by more than 6 °C [126]. Several full-scale UASB reactors are currently operating in tropical areas for municipal wastewater treatment, particularly in Brazil and India [127], with successful case studies also reported in Ghana (Africa), where a 93% COD removal and 98% BOD removal were claimed in a 100,000 PE WWTP (18,000 m^3/d) thanks to a favorable BOD/COD ratio (0.58) and an optimum organic loading rate (1.30 kg COD/m^3 day), with a mean biogas production of 832 m^3/d [128].

Another possibility for direct wastewater COD conversion to methane is so-called decentralized sanitation, where wastewater streams are source-separated into graywater and blackwater, the latter being amenable to direct energy recovery thanks to its higher strength [129]. A successful UASB full-scale application has been recently reported in a new city district (Oceanhamnen) in Helsingborg, Sweden, for decentralized blackwater treatment [129], which is remarkable, considering the unfavorable Scandinavian climate conditions. AnMBR, instead, is mostly reported in large demo plants rather than full-scale facilities; nonetheless, high and stable COD removal was reported in the literature with a good CH_4 production, showing that AnMBR can be competitive with CAS [130–132].

Another promising way to revamp conventional WWTPs towards energy neutrality is chemically enhanced primary treatment (CEPT) followed by partial nitritation (PN)/anammox and sludge AD; CEPT, by dosing alum or iron salts as coagulants and polymers as flocculants, efficiently captures COD, suspended solids and phosphate in raw wastewater, maximizing downstream biogas production from primary sludge while lowering oxygen requirements for secondary biological treatment [133,134]. CEPT is able to capture 43.1–95.6% of COD, 70.0–99.5% of suspended solids, and 40.0–99.3% of phosphate; however, some of the coagulants and flocculants may show inhibitory effects in downstream recovery processes, and high amounts of chemical sludge are produced, with significant economic and environmental impacts [134], requiring detailed life cycle studies [114]. Regarding PN/anammox, current operational challenges include its full-scale applicability due to the necessity to inhibit nitrite-oxidizing bacteria and keep the right balance between oxidizing and reducing conditions in the biological reactors. Despite laboratory-scale studies showing high COD, total nitrogen (TN), and total phosphorus (TP) removal, with the possibility of reaching an energy self-sufficient WWTP [135] when compared to conventional nitrification–denitrification [114], in fact, the full-scale applicability of PN/anammox is still restricted. Concerning these advanced wastewater treatment configurations, few studies are reported in the literature for both CEPT, with some interesting case studies from Hong Kong [134], China [136] and Brazil [137], and Anammox, with most full-scale studies from the Netherlands, including Dokhaven [138] and Olburgen [139] WWTPs.

3.4. Thermal Energy Recovery

Wastewater is characterized by relatively high temperatures, which allow for the recovery of thermal energy through low-temperature water heat pumps [140]. In urban sewage, heat comes from cooking, laundries, and bathing, and is mostly conserved in sewers and WWTPs, with continuously available flow rates [141]. Treated effluent temperatures are well above those of receiving water bodies, with reported values in China of 10–16 °C in winter and 22–25 °C in summer [141]. Thermal energy must preferably be recovered from treated effluents rather than from raw wastewater, due to fouling and corrosion from untreated wastewater, as well as to the decrease in biological activity observed when excessively reducing temperature [141]. The efficiency of water heat pumps is evaluated through the coefficient of performance, which is the ratio between the heating/cooling capacity provided to the downstream user and the consumed electricity. The versatility of the recovered thermal energy allows it to be exploited for several uses, including district heating/cooling, sludge drying, the transition from mesophilic to thermophilic sludge AD, and agricultural greenhouses [141].

An important feature of thermal energy recovery systems is geographical location: northern countries, such as Finland, experience greater temperature variations due to severe and lengthy winter seasons [11]. Similarly, cold climates, such as England's, show restricted applicability of heat recovery systems due to the limitation in effluent temperature for discharge; nonetheless, with proper system management and control, significant operational benefits can be reached [142].

On the other hand, heat is a low-grade energy, in contrast to electricity, while electricity is needed by heat pumps to recover thermal energy from the effluents [11]. Another important aspect is local heat demand due to the short supply distances of recovered heat (<5 km): energy savings are limited if the WWTP is surrounded by few structures and buildings [11]; thus, plant location is crucial.

Remarkable full-scale thermal energy recovery systems reported in the literature include Hammarby Sjöstad (Stockholm, Sweden), where a district heating system is fed by WWTP effluent and heat from Lake Mälaren, producing about 1000 GWh/yr [143], and the Kingston (Hogsmill) project in London, United Kingdom (UK), where a fraction of the treated effluent from a WWTP is diverted to an energy center, and a heat pump extracts thermal energy for a district heating system (about 7 GWh/yr) [144]. Another interesting case study from Poland (Mokrawica WWTP, 10,000 PE) demonstrates the full-scale potential for thermal energy recovery, considering only three operating parameters: the wastewater flow rate, wastewater temperature, and the required temperature for the cooling/heating of the receiving system [145]; the possibility of preheating the wastewater to improve biological treatment in the winter season is also examined. It is also feasible to consider smaller scales for thermal energy recovery systems, such as college campuses: Borders College, Galashiels (Scotland), recovers 1.9 GWh of heat annually, covering about 95% of the college's heat demand, without negative impacts on downstream sewer operations [144]. Finally, the renowned water company Veolia patented the Energido™ technology for heat recovery from sewers and WWTPs, consisting of a flexible, remote heat exchanger (not directly connected to the sewer system) that transports heat from wastewater to a reversible heat pump, which feeds downstream district heating networks [146].

4. Implementation of External Energy Sources

The main possibilities for external RES implementation include PV module installation, other solar energy systems, and wind energy. Despite being mature and convenient technologies, the exclusive implementation of external RESs rarely facilitates energy neutrality due to their variable energy production, limited availability of space for their

installation, and the independence between WWTP energy demand and RES energy production [147]. In a Chinese WWTP treating 50,000 m^3 of wastewater per day, as an example, it has been shown that the implementation of wind power and PV can produce about 40% of the total electricity request, with an additional 2% covered by hydroenergy, while the rest must still be withdrawn from the national electricity grid [148].

4.1. Photovoltaic Installation

Solar energy exploitation has a lower environmental impact than other RESs and can be exploited in multiple ways in WWTPs [23]. Electricity generation from PV panels, in particular, is a mature and flexible technology that allows for direct electricity production from the sun, and can be installed on buildings' rooftops, in closed reactors, and other structures; solar cell efficiency has increased throughout the years thanks to technological advancements [149]. PV modules have been successfully installed in several full-scale WWTPs, providing a significant fraction of the overall electricity demand [150], especially for WWTPs located in warm climates with constant solar energy availability [3]. Besides conventional land-based PV panels, floating PV panels are gaining attention: they are normally installed in dams or natural lakes, but can also be installed in WWTP basins [151]. By implementing floating PV panels in arid zones (such as Southern Australia), energy recovery can be coupled with additional benefits such as reduced water evaporation [151].

Before installing a PV system, the total electricity consumption of the WWTP must be ascertained, including seasonal variations; then, the WWTP layout must be carefully studied to determine the spaces available for PV panel installation [152]. Next, the PV system must be sized, calculating the energy output throughout the year; finally, after choosing a commercial system fitting the model, the ecological benefits and the levelized cost of energy of the upgraded WWTP must be assessed, including the eventual need for storage systems (such as batteries) to optimize system reliability [152]. Table 3 reports meaningful literature studies connected to PV installation in full-scale WWTPs, highlighting its excellent sustainability in warm countries (such as the Mediterranean area), but also in areas such as China and the USA, possibly in combination with other RESs, such as biogas. For small and medium-scale WWTPs, PV can provide the majority of the electricity needed (>50%) [3,153], while for larger WWTPs, a lower share of the overall electricity demand is typically provided by PV due to space limitations for PV panel installation (8–30%), with AD being the major contributor (25–65%) [154]. PV can also be combined with other external RESs, such as wind turbines, in regions where both solar energy and wind availability are consistent [11]. Recently, optimized PV systems have been proposed to match aeration demand for biological wastewater treatment with solar energy production, minimizing the energy withdrawn from the grid, by providing a user-friendly method to calculate PV energy generation from air temperature variations throughout the seasons [155]. The dependence of oxygen request on wastewater load and air temperature has been considered in the model, defining the peak power of the PV system according to the required electricity demand by aerators [155].

Table 3. Remarkable literature results related to photovoltaic energy production in wastewater treatment plants.

Location	Plant Potentiality	Main Results	Reference
Iran	2000–7000 population equivalent (PE)	A 250-kW photovoltaic system with 10 kWh batteries can cover 50% of the total wastewater treatment plant's (WWTP) electricity demand	[153]
Algeria	30,000 PE (4800 m^3 wastewater/day)	A 670-kW_P PV can cover about 53% of the WWTP's electricity request, injecting 510 MWh/yr of electricity into the grid; the overall treatment cost was reduced from 3.4 cent US$/$m^3$ to 2.3 cent US$/$m^3$	[3]

China	Various	The PV potential for urban WWTPs in China has been estimated as 5.6 GW, with 26 out of 31 WWTP-PV projects considered as economically sustainable, with an emissions reduction of 10–40%	[156]
Wuhan, China	372,000 PE	The combination of WWTP process simulation and PV system design/operations maximizes the use of PV modules, reducing operating costs (40–60%) and carbon emissions from electricity (30–50%) by optimizing installed PV power, electricity use/price, and treated water quality	[157]
California, United States of America	Various	41 out of the 105 Californian WWTPs implemented solar PV systems, with a common PV size of 1 MW and a prevalence of rural installation; in smaller WWTPs (<19,000 m^3/d), PV systems were the only on-site RES, providing up to 30–100% of the overall energy demand	[154]
China	Various	By investigating 31 case studies, it was reported that the adoption of PV panels could supply about 20% of the WWTP's yearly electricity demand, with a GHG emissions reduction of around 11% and a payback time of around 7 years	[150]
Crete, Greece	19,400 m^3 wastewater/day	Solar PV (25%) and wind energy (25%) contribute about 50% to the total yearly energy consumption in WWTPs, with a practical energy density of 0.14 kWh/m^3	[11]

Thanks to their simplicity and technological maturity, PV systems are crucial for countries where the number of WWTPs is rapidly growing, such as China, to easily reduce energy withdrawal from the grid [156]. Its economic viability can be directly correlated to local sun availability, which depends on plant latitude [156], also taking into account seasonal variations. The investment payback time for PV panels is typically around 7–10 years, depending on the WWTP's size, electricity prices, self-consumption rates, and local sun irradiation [150,152,158].

4.2. Other Solar Energy Systems

Besides converting solar energy into electricity through PV panels, it is also possible to directly exploit solar radiation or produce thermal energy from the sun. Solar greenhouses, in particular, have gained popularity for drying dewatered sludge, enhancing TS content in dewatered sludge to very high values (>85%) [159]. Solar greenhouses, which are made of a transparent plastic or glass structure, are characterized by a relative simplicity of construction and operations, and need low external energy inputs [159]. The dewatered sludge is distributed in the greenhouse with a pre-defined thickness, and ventilation systems are installed for air circulation, collecting moisture from the sludge [160]. Manual or automatic mixing systems are also present; additional features can be installed to enhance system efficiency, including heating the floor and implementing thermal energy storage [160]. PV panels can be installed on the greenhouse roof, further reducing the greenhouse energy demand and coupling direct solar radiation exploitation with the generation of the electricity needed when the sun is not available (nighttime, winter season) [161]. However, solar greenhouses show limitations in terms of potential odor generation, the need for vast areas, and the necessity to store sludge in the cold months due to a significant reduction in system efficiency [159].

Sludge drying allows for a remarkable reduction in sludge mass and volume, cutting storage, transportation, and disposal costs [160]. The effective techno-economic applicability and the performance of solar greenhouses, however, strongly depend on the specific plant location, with warm climates showing good sustainability in comparison with northern countries [159]. In any case, dried sludge quality must be carefully monitored to avoid (micro)pollutant accumulation in the receiving soils when opting for agricultural

reuse; from an energy recovery perspective, dried sludge is also an excellent fuel for incineration due to its limited moisture content and stable physicochemical characteristics [159]. Innovative sludge drying systems with forced ventilation have been reported in the literature, reducing sludge moisture content from 97% to 5% in about 25 days, limiting energy requirements compared to conventional thermal drying systems, and removing, in addition, volatile components [161]. Despite not directly contributing to energy neutrality, solar greenhouses can significantly reduce digestate transportation and management costs, cutting overall WWTP carbon emissions.

Among the available commercial solar drying systems, the Italian company SERECO patented SOILAR T™, a modular solar greenhouse with manual or automatic loading, a sludge distribution system, and an internal air ventilation flux; the air extraction system self-regulates according to the local input and output conditions [162]. Similarly, HUBER developed a solar drying technology called SOLSTICE™, provided with sludge movement and turning devices, ventilation, and control, which has been installed, among others, in the Peruvian WWTP of Pachacútec and the German WWTP of Bayreuth [163].

Other possibilities for solar energy integration in WWTPs include the installation of solar thermal panels (flat plate or evacuated tube collectors), which can be easily implemented at the industrial scale and allow the recovery of thermal energy for anaerobic digesters and building heating [164]. However, similarly to heat recovery from treated effluents (Section 3.4), they can only provide heat, which is a minor portion of the overall energy request. Their applicability is particularly interesting when transitioning from mesophilic to thermophilic AD, due to the significant increase in heat demand for influent sludge heating, which might not be compensated for by the additional biogas yield.

Finally, concentrated solar power systems allow for the generation of high-temperature heat (150–300 °C), which can be used to pretreat sludge through THP (Section 3.1), for sludge drying and AOP implementation [165,166]. However, similarly to solar greenhouses, they require vast areas and are not adapted to cold countries.

4.3. Wind Energy

Wind energy has reached a good technological maturity thanks to continuous technological advancements; wind turbines can be efficiently implemented in areas with significant and constant wind availability. To assess the techno-economic sustainability of wind energy installation in WWTPs, however, preliminary long-term data collection is required, including a comparison with historical data provided by anemometric stations; after analyzing wind availability and velocity in the selected site, the best position for wind turbine installation must be chosen by simulating local wind conditions for a large area around the WWTP [167].

Despite the literature data regarding wind energy installation in WWTPs being less frequent than other RESs (such as PV), some remarkable case studies are reported and are worth mentioning: Dradenau WWTP in the port of Hamburg (Germany) has recently installed its fourth 180 m high wind turbine, with 3.6 MW of power and the capacity to produce up to 9000 MWh/yr of energy [168]. The other three wind turbines are already in operation at the same plant, with a total installed capacity of 8.6 MW and a maximum potential production of 23,000 MWh/yr of electricity. Severn Trent in the UK broadly evaluated hundreds of possible sites for wind energy production and installed six wind turbines in selected WWTPs (including Derby, Wanlip, and Newthorpe), with a total electricity production of 2.5 GWh/yr [169]. Amsterdam-West WWTP in the Netherlands recently became an energy-positive WWTP, thanks to the installation of four wind turbines, which together generate 21,000 MWh/yr of green energy, equivalent to the energy consumption of 10,000 households [170]. Amsterdam's site is particularly relevant as a mix of different RESs is installed, including PV panels, wind turbines and biogas; thus, it can be

classified as a hybrid system (Section 5). Besides these important examples of large-scale wind turbine use, compact wind turbines have been installed in small WWTPs in the USA: as an example, the village of Cascade in Wisconsin installed two wind turbines of 100 kW each, producing 100% of the energy required by the local WWTP [171].

5. Hybrid Systems and Economic Aspects

The combination of different RESs appears unavoidable, in most cases, to reach complete energy neutrality in WWTPs. Hybrid systems are characterized by a more stable, resilient and sustainable generated voltage, improved overall efficiency, and allow for energy savings when compared to standalone generation systems, even if their capital (CAPEX) and operational (OPEX) costs can be high [24]. Besides energy generation, energy storage is fundamental, as the variable energy request from the WWTP does not match the variable energy production from RESs; hybrid systems including AD can better support a reliable energy supply, as biogas can be easily stored in gasometers, while PV or wind energy systems require more complex storage media, such as batteries or hydrogen [172]. To obtain a reasonable compromise between CAPEX/OPEX and system reliability, it is fundamental to properly design each component's size: a smart management approach allows for the optimal sizing and power management of hybrid systems, such as PV–wind turbines with hydrogen and battery storage [25]. Given the complexity of hybrid systems, a multi-objective optimization approach is often needed, with careful consideration of relevant economic and environmental factors to fully satisfy the dynamic WWTP energy demand [25].

Furthermore, the environmental sustainability of the upgraded WWTPs must be assessed: LCA can be employed to compare the environmental impacts of the baseline scenario (i.e., original plant configuration) and those of the upgraded WWTP, giving useful indications to decision-makers [173]. In addition, system-level trade-offs (e.g., between energy generation and infrastructure integrity) must be carefully balanced [174].

Table 4 summarizes the most relevant literature studies related to hybrid WWTPs: nearly all studies involve medium or large WWTPs, and most of them include AD as the leading technology, consistent with the targets of the EU Directive 3019/2024. In most studies, a combination of AD and PV is considered, which appears to be the leading solution to reach energy neutrality for large-scale WWTPs; some studies also forecast wind turbine installation, thanks to favorable site locations, and storage systems (especially batteries) to improve overall system resiliency. Hydrogen storage appears feasible only if specific economic incentives are available. Furthermore, the possibility of using the excess electricity produced by external RESs to cover the requirements of quaternary wastewater treatment (e.g., reverse osmosis units) is suggested [2], which is particularly remarkable considering the recent revision of the UWWTD.

Table 4. Literature studies related to hybrid energy systems in wastewater treatment plants.

Location	Plant Potentiality	Applied Technologies	Aim of the Work	Main Results	Reference
As Samra (Jordan)	1,460,000 (365,000 m^3/d)	Parabolic trough collectors, photovoltaic (PV), anaerobic digestion (AD)	Compare alternative solar energy systems to minimize energy consumption from the grid and reduce dependence on biogas	The authors succeeded in reducing the reliance on biogas production and diminishing the levelized cost of heat and electricity	[175]
Karaj (Iran)	229,000 (57,120 m^3/d)	PV, wind, and AD	Provide a flexible model for hybrid systems in a wastewater treatment plant (WWTP) to meet the energy demand, sell excess energy to the grid,	The potential of multi-task energy vectors was demonstrated, improving national grid and local WWTP sustainability	[176]

			and generate green hydrogen		
Friuli-Venezia Giulia (Italy)	86,400	PV, wind turbines + batteries/hydrogen as storage media	Design renewable WWTPs through mathematical simulations, integrating reverse osmosis treatment	A 70% renewable share corresponded to the lowest net present cost, as a trade-off between the minimum cost and the maximum renewables generation	[2]
Gubin (Poland)	90,000	AD, PV, geothermal	Implement multiple renewable sources to achieve energy neutrality	During the day, the plant uses 100% self-produced electricity (mean demand of 0.679 kWh/m^3), exploiting PV at its full capacity	[177]
Toukh (Egypt)	32,000 (8000 m^3/d)	Microturbines on CHP units, PV, wind turbines	Provide a 100% renewable standalone system	The exhausted heat from CHP units can be used for additional electricity generation through microturbines, covering most of the request; wind and PV are used as adjuncts	[178]
Jeju Island, South Korea	670,000	AD, PV	Design an energy self-sufficient WWTP through mathematical models	Solar-powered scenarios are less economically profitable than biogas designs, but show lower environmental impacts and higher social benefits	[179]
New York City (USA)	8,600,000	AD, PV + batteries	Transform WWTPs into smart microgrids by implementing renewable sources and interacting with local networks	The produced microgrids are central resilience and community development hubs, improving grid operations and providing services under emergency conditions	[180]
Oahu Island, Hawaii, and Hveragerði, Iceland	80,000 population equivalent (PE) (Hawaii); 2300 PE (Iceland)	AD, PV, wind turbines	Implement multiple renewable sources to fully meet WWTP energy demand	The Hawaiian hybrid system is economically profitable (0.29 $/kWh), but not in Iceland (1.14 $/kWh). Renewable energy sources can fully and safely power the facilities; excess power is sold to the grid	[181]

The importance of considering local factors to design hybrid systems appears fundamental, as in each specific site, only certain RESs are applicable (e.g., PV in Mediterranean areas, wind energy in coastal zones). Finally, nearly all studies mentioned in Table 4 present a mathematical modeling approach, given the system complexity and the dynamic interactions between the different components. The increased resilience of hybrid systems is a further merit when compared to WWTPs exclusively focused on AD or AcoD.

However, a lack of studies combining computational efforts and practical applications emerges from the literature analysis. The outputs from optimization mathematical models still require a "hands-on" industrial implementation, including the detection of possible issues that may emerge in full-scale operations. On one hand, successful case studies at an industrial scale, such as those previously discussed in Section 3.1.5, should be made more visible to researchers and academia to show that achieving 100% energy neutrality is feasible in concrete terms in modern WWTPs, even through complex systems such as hybrid RESs. On the other hand, water utilities should pay more attention to the

continuous technological developments provided by researchers, such as optimization and multi-objective modeling tools, giving indications on how to implement these innovations in daily operations. A stronger interconnection between researchers, providing the required technical know-how for component design and optimization, and water utilities, which manage daily the WWTPs, will be required in the future to reach the ambitious EU energy neutrality targets focused on hybrid energy systems, not exclusively at a European level, but worldwide.

The economic feasibility of hybrid systems strongly depends on WWTP size, local electricity costs, eventual subsidies for RES production, co-substrate availability for AcoD, and operational complexity [147]. A strong dependence on local conditions has been demonstrated [181]; thus, it is fundamental to consider site-specific aspects in the techno-economic assessment. AD, in general, is characterized by high investment costs, operational complexity, and limited convenience for small and medium-scale WWTPs; the main CAPEX is connected to the digester, mixing, pumping and heating device installation, as well as to CHP units, biogas handling and purification systems, and dewatering [182]. CAPEX significantly increases when implementing sludge pretreatment and AcoD [182]. The main OPEX of AD units, instead, is linked to CHP maintenance, energy request, polymer consumption, digestate management and the need for skilled personnel [116,147]. Biogas systems are often considered a high-risk investment due to variability in substrate characteristics, operational issues, and uncertain economic balance [182]. Experiences from small and medium-sized WWTPs show that AD is not economically sustainable due to the high costs per unit of treated PE [147].

PV, instead, is a modular technology, easy to install, with low OPEX, and shows a reduction in overall energy cost for WWTPs, even if it requires vast areas and delivers intermittent energy production, which requires dedicated storage systems; its economic sustainability strongly depends on local incentives and electricity price [23,147]. The main CAPEX of PV systems involves panels, inverters, storage systems, and connection to the grid, while OPEX is mostly connected to maintenance and cleaning operations [147]. Finally, wind turbines show high CAPEX, connected to turbine installation, foundations, electric systems, connection to the grid and control systems, while OPEX is mostly connected to mechanical maintenance, the substitution of components and management of intermittencies [1,147]. Overall, reaching energy neutrality in WWTPs through hybrid systems does not necessarily mean an economically sustainable system, due to high CAPEX, long payback times, the necessity for incentives and strong dependence on the WWTP's size and characteristics [147,31].

6. Technology Comparison and Conceptual Framework for Energy Neutrality

The advantages and limitations of the technologies presented in the current review are summarized in Table 5, highlighting their applicability to full-scale WWTPs. The proposed conceptual framework to reach energy neutrality is reported in Figure 4 (for large-scale WWTPs) and Figure 5 (for medium-scale WWTPs), including the most critical aspects to be analyzed for each technology. The first step to move towards energy neutrality, in all cases, is to conduct a detailed energy audit to establish current energy consumption and detect eventual hotspots where it is possible to implement energy efficiency measures [6,12]. After building an energy balance of all treatment sections and identifying deviations in key performance indicators from benchmark values (e.g., kWh consumed per treated m^3 or kWh consumed per unit of removed COD/BOD) [6], significant reductions in total energy demand can be obtained by replacing existing low-efficiency devices (pumps, blowers, turbines) with modern tools in the identified low-performance sections [12]. While large-scale WWTPs normally possess detailed long-term information about

energy consumption in the different treatment sections, medium-scale WWTPs might require an additional measurement campaign, due to the potential lack of data, to build a robust energy audit (Figure 5). Following the results of energy audits, the possible revamping of the wastewater treatment line with less energy-intensive solutions, such as CEPT, UASB/AnMBR or Anammox, must be considered for large-scale WWTPs (Figure 4). After that, an alternative approach must be followed depending on the WWTP's size.

For large-scale WWTPs, proper valorization of the RESs already installed at the plant appears fundamental, starting from conventional biogas production and possibly upgrading it to "enhanced AD", forecasting sludge pretreatment, AcoD and/or two-stage AD; thus, biogas is the central technology on which energy neutrality can be reached. While two-stage AD is economically sustainable only when unused digesters are present, AcoD and sludge pretreatment appear to be the best strategies to increase energy generation from biogas. Finally, the combination of different RESs (especially AD + PV) in large-scale WWTPs, with eventual energy storage through batteries or hydrogen and tailored process control, allows for a 100% renewable and resilient WWTP. However, space availability at the WWTP must be considered to understand how many PV panels can be positioned, limiting overall PV power. Hydroenergy, despite providing small amounts of electricity, is favored for its simplicity and robustness, while wind turbines are applicable only under favorable wind conditions (e.g., coastal areas). The required heat for large-scale WWTPs can be easily provided by thermal energy recovered from biogas combustion or, alternatively, heat recovery from treated effluents (Figure 4). Upgrading conventional AD to enhanced AD may be sufficient to reach energy neutrality if co-substrates such as OFMSW are locally available, and sludge pretreatment is implemented. However, it is not always possible to upgrade AD to AcoD, as different utilities manage wastewater and waste, discouraging interconnections and potentially limiting digestate reuse in agriculture.

For medium-scale WWTPs, instead, PV implementation as the leading RES is the best strategy, eventually complemented by hydroenergy recovery, thanks to its robustness, and/or wind turbines, especially if AD is not present (this is mostly valid for WWTPs<20,000 PE, where sludge is stabilized aerobically) [118]. For thermal energy generation, heat recovery from effluents can be competitive with solar thermal panels. The availability of financial incentives to reach energy neutrality is critical for both medium and large-scale WWTPs, as energy-neutral WWTPs might not be economically sustainable for water utilities; thus, a dialog between political authorities, regulators and WWTP operators is strongly recommended.

Overall, the adopted framework for reaching energy neutrality in full-scale WWTPs must be tailored to local conditions, including specific RES availability and WWTP characteristics (treated flow rate, wastewater/sludge treatment scheme, climate conditions), and forecast dedicated mathematical models to size and operate each component of the hybrid system, especially if opting for the implementation of hybrid systems.

Table 5. Comparison of the investigated technologies for energy-neutral wastewater treatment plants.

Technology	Advantages	Limitations	Full-Scale Applicability
Conventional anaerobic digestion (AD)	Mature and established; flexible application of the generated biogas	Sludge biodegradability limits the obtainable energy yields; not sufficient to reach energy neutrality targets; low process efficiency	High, but impossibility of reaching energy neutrality targets
Sludge pretreatment before AD	Possibility to significantly improve energy yield by using the same substrate (sludge); commercial technologies already available on the market (especially thermal hydrolysis)	Site-specific conditions and sludge characteristics must be studied on a case-by-case basis to assess techno-economic sustainability and the environmental impacts	High

Anaerobic co-digestion (AcoD)	Contemporary treatment of several substrates in the same digester, with synergistic effects; significant increase in energy yields; reduced process inhibition risks	AcoD of different organic waste may generate legal–administrative limitations; poor quality of one substrate may limit digestate agricultural reuse	Medium to high, according to local substrate availability and characteristics
Two-stage AD	Process conditions in each reactor are tailored for the specific biomass species; increase in biogas yield and digestate stabilization	Necessity to build additional digesters, with an increase in capital costs, and proper process control	Medium (high only in case unutilized digesters are already present at the plant)
Hydroenergy recovery	Simple and robust technology	Limited electricity amounts can be obtained	High, but limited impact
Thermal energy recovery	High efficiency; positive impact on the receiving water bodies	Cold climates (e.g., Scandinavia) limit the extractable energy; low impact on the total plant energy request (only heat is produced)	High, but limited impact
Modified wastewater treatment	Efficient organics capture in primary sludge for CEPT; direct organic matter conversion to methane for anaerobic treatment; reduced oxygen demand and secondary sludge generation	Complex operations; uncertain environmental/economic sustainability; limited full-scale applications; anaerobic treatment applicable only to concentrated streams	Limited to favorable conditions; requires dedicated process control
Photovoltaic installation	Simple, flexible, and mature technology; a significant fraction of the total electricity request can be obtained, especially for small and medium WWTPs	Area availability limits the number of panels that can be installed; low sun availability in cold climates	High but dependent on local climate conditions; applicable to all plant scales
Other solar energy systems	Direct energy exploitation from the sun leads to high system efficiency; positive economic balance in warm areas	Seasonal variations; low sun availability in cold climates; only thermal energy production or direct irradiation exploitation	Limited to warm areas
Hybrid systems	Possibility to obtain a 100% renewable plant; contemporary exploitation of several renewable sources; increased system resilience	Complex design and optimization through mathematical models; site-specific conditions must be considered; high capital and operating costs	High, but site-specific conditions must be addressed to find the optimum

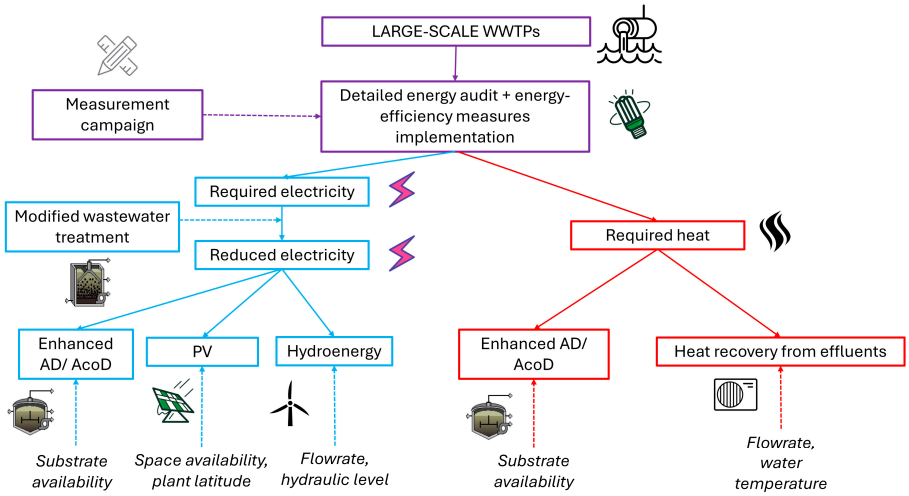

Figure 4. Proposed conceptual framework to reach energy neutrality in large-scale wastewater treatment plants.

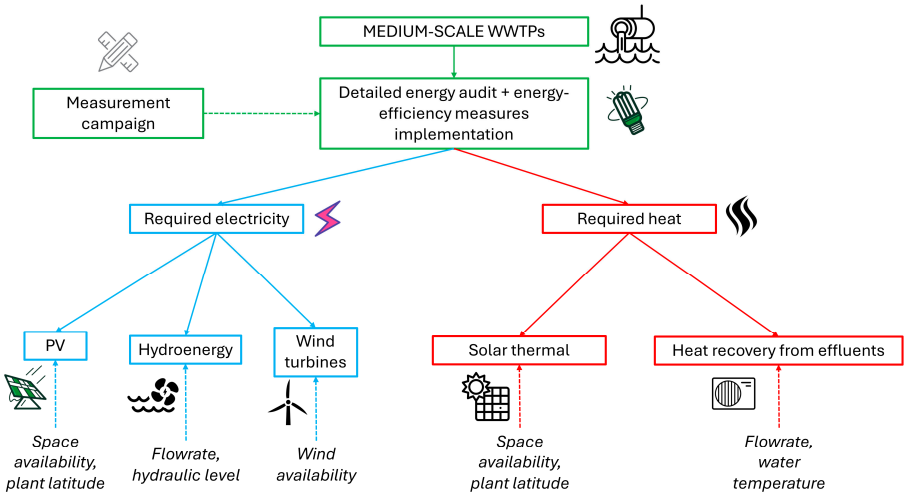

Figure 5. Proposed conceptual framework to reach energy neutrality in medium-scale wastewater treatment plants.

7. Conclusions

In this review, technologies for achieving energy neutrality targets in full-scale WWTPs are critically evaluated, considering their specific applicability at an industrial level. The UWWTD revision is accelerating the transition of all medium (10-100,000 PE) and large WWTPs (>100,000 PE) to 100% renewable WWTPs in the EU, and water utilities must quickly implement sustainable solutions for the energy transition. Energy audits must be applied first to assess current energy consumption and identify critical areas to implement energy efficiency measures, reducing the overall energy demand. Then, alternative strategies must be pursued according to the WWTP's size: while large-scale WWTPs are normally equipped with AD units, upgrading them to "enhanced" AD appears to be the best strategy, especially if organic co-substrates are locally available for AcoD. Sludge pretreatment, and in particular THP, can be a sustainable solution to better exploit its energy content. However, to improve system resiliency and cover eventual additional electricity demands, PV integration is strongly recommended, with additional contributions provided by wind turbines (under favorable site conditions) and hydroenergy recovery. Due to the variable nature of PV/wind systems, however, storage systems such as batteries or hydrogen should be implemented. The required heat can be provided by CHP units fed with biogas or thermal energy recovery from treated effluents. Medium-sized WWTPs, instead, do not always possess AD reactors; thus, the implementation of external RESs, with PV as the leading solution, is probably the best strategy towards energy neutrality. Solar thermal energy or heat recovery from effluents can provide the required heat. Future studies are required to develop flexible design and operational approaches for energy-neutral WRRFs, thoroughly considering climatic conditions, WWTP characteristics, co-substrate(s) presence, and RES availability, exploiting innovative tools such as artificial intelligence and machine learning. The combination of computational studies and in-field long-term pilot trials is fundamental, with fruitful knowledge sharing between researchers and practitioners. Knowledge exchange between water utilities and researchers is mandatory to give visibility to excellent case studies on one hand, and provide innovative solutions to daily practitioners on the other hand. In addition, the availability of dedicated incentive schemes appears to be crucial, as energy-neutral WWTPs are technically achievable, as shown by different virtuous full-scale examples, but might not be economically convenient under current market conditions.

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Abbreviations

The following abbreviations are used in this manuscript:

AcoD	Anaerobic Co-Digestion
AD	Anaerobic Digestion
AnMBR	Anaerobic Membrane Bio-Reactor
AOP	Advanced Oxidation Process
BOD	Biochemical Oxygen Demand
C/N	Carbon to Nitrogen
CAPEX	Capital Costs
CAS	Conventional Activated Sludge
CEPT	Chemically Enhanced Primary Treatment
CHP	Combined Heat and Power
COD	Chemical Oxygen Demand
EU	European Union
FOG	Fats, Oils and Grease
GHG	Greenhouse Gas
HRT	Hydraulic Retention Time
LCA	Life Cycle Assessment
OSTBOP	Organic Solid By-products from Table Olive Processing
OFMSW	Organic Fraction of Municipal Solid Waste
OPEX	Operating Costs
PE	Population Equivalent
PN	Partial Nitritation
PV	Photovoltaic
REC	Renewable Energy Community
RES	Renewable Energy Sources
SRT	Solid Retention Time
THP	Thermal Hydrolysis Process
TN	Total Nitrogen
TP	Total Phosphorus
TRL	Technology Readiness Level
UASB	Up-Flow Anaerobic Sludge Blanket
UK	United Kingdom
USA	United States
UWWTD	Urban Wastewater Treatment Directive
VFA	Volatile Fatty Acid
VS	Volatile Solids
WRRF	Water Resource Recovery Facility
WWTP	Wastewater Treatment Plant

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