



Article

Energy Recovery from Sewage Sludge: The Case Study of Croatia

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Received: 26 April 2019; Accepted: 16 May 2019; Published: 20 May 2019



Abstract: Croatia produced 21,366 tonnes of dry matter (DM) sewage sludge (SS) in 2016, a quantity expected to surpass 100,000 tonnes DM by 2024. Annual production rates for future wastewater treatment plants (WWTP) in Croatia are estimated at 5.8–7.3 Nm³/people equivalent (PE) for biogas and 20–25 kg_{DM}/PE of sewage sludge. Biogas can be converted into 12–16 kWh_{el}/PE of electricity and 19-24 kWh_{th}/PE of heat, which is sufficient for 30-40% of electrical and 80-100% of thermal autonomy. The WWTP autonomy can be increased using energy recovery from sewage sludge incineration by 60% for electricity and 100% of thermal energy (10–13 kWh_{el}/PE and 30–38 kWh_{th}/PE). However, energy for sewage sludge drying exceeds energy recovery, unless solar drying is performed. The annual solar drying potential is estimated between 450–750 kg_{DM}/m² of solar drying surface. The lower heating value of dried sewage sludge is 2-3 kWh/kg_{DM} and this energy can be used for assisting sludge drying or for energy generation and supply to WWTPs. Sewage sludge can be considered a renewable energy source and its incineration generates substantially lower greenhouse gases emissions than energy generation from fossil fuels. For the same amount of energy, sewage sludge emits 58% fewer emissions than natural gas and 80% less than hard coal and fuel oil. Moreover, this paper analysed the feasibility of sludge disposal practices by analysing three scenarios (landfilling, co-incineration, and mono-incineration). The analysis revealed that the most cost-effective sewage sludge disposal method is landfilling for 60% and co-incineration for 40% of the observed WWTPs in Croatia. The lowest CO₂ emissions are obtained with landfilling and mono-incineration in 53% and 38% of the cases, respectively.

Keywords: wastewater treatment; sewage sludge; solar drying; energy recovery; incineration

1. Introduction

Sewage sludge is a by-product of wastewater treatment plants (WWTP), considered valuable for its content of nutrients and energy but also a potential threat to humans and the environment because of the presence of organic pollutants and heavy metals. Sustainable solutions and the best available techniques for the treatment and disposal of sewage sludge, including recovery of energy and nutrients, are currently being discussed in the European Union (EU) [1]. The situation is particularly urgent in large and densely populated cities, which are producing large quantities of sewage sludge and have limited available surface area for its processing and disposal. The amount of sewage sludge produced in the EU per year was 10 million tonnes in 2008, 11.5 million tonnes in 2015 [2] and is expected to approach 13 million tonnes of dry matter (DM) by 2020 [3]. The quantity of sewage sludge generated in WWTPs is increasing with the progressive expansion of wastewater networks, but also due to population growth and industrial development. After adopting the Directive concerning Urban Wastewater Treatment 91/271/EEC, EU member states agreed to implement primary, secondary, and

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tertiary wastewater treatment processes (Figure 1), starting from large agglomerations and subsequently moving onto smaller ones.

Unlike wastewater treatment, at present there is no official regulation framework for the general management and disposal of sewage sludge in the EU. Sewage sludge management solutions need to be assessed taking into account environmental, economic, legislative, technical, and location criteria [4,5]. Different strategies for the treatment and final disposal are possible but the general opinion is that sewage sludge is a valuable source of energy and materials. There are two main pathways of sewage sludge management [6]: (1) organic recycling (use in agriculture, composting and land reclamation), and (2) recovery of energy and nutrients (mono- and co-incineration, pyrolysis, gasification, phosphorus, and nitrogen recovery).

Sewage sludge treatment includes various biological, chemical, and thermal processes, as well as long-term storage, which aim to remove pathogens and reduce sludge volume. Previous research focused on discovering the negative effects of pollutants in wastewater. Yoshida et al. [7] assessed the fate of 32 organic elements and four groups of organic pollutants in a conventional WWTP and concluded that both inorganic and organic elements are accumulated in sewage sludge, which presents a threat to the environment. Hadi et al. [8] investigated the adsorption mechanisms of pollutants in wastewater. Zhang et al. [9] examined the effect of filtration method as an alternative method to treat alfalfa wastewater, which proved to be very effective. Mo et al. [10] studied the adsorption effect of pollutants from agro-industrial waste to wastewater. The negative effects of these harmful elements can be reduced by different methods. The typical sewage sludge treatment process includes dewatering, thickening, stabilization (aerobic or anaerobic digestion), hygienisation, storage, drying, and transport. On the other hand, final disposal of the sewage sludge produced in the EU includes agricultural use (42.4%), incineration (26.9%), landfilling (13.6%) and others (17.1%–composting, long-term storage, and land reclamation) [2].

The average costs of wastewater treatment and recycling of raw sludge in agriculture are estimated at between 100 and $200 \, \text{e}/\text{t}_{DM}$. The costs are between 200 and $400 \, \text{e}/\text{t}_{DM}$ in case of dewatered and dried sewage sludge for landfills, land reclamation and incineration [2,6]. The application of sewage sludge to agricultural lands is regulated by the Sewage Sludge Directive 86/278/EEC. The Directive defines the quantities, properties, composition, sampling, and testing of sewage sludge, as well as the maximum concentrations of pollutants and heavy metals [11,12].

In the past 20 years in the EU, sewage sludge treatment has relied on three main processes: dewatering and drying, stabilisation by anaerobic digestion and thermal treatment [13,14]. Anaerobic digestion (AD) is the preferred stabilisation method as it produces biogas, a valuable energy source [15]. In 2016, the EU produced 16.1 Mtoe (Million of tonnes of oil equivalent) of biogas, with sewage sludge feedstock contributing with 1.4 Mtoe of biogas (8.7%) [16]. Biogas from sewage sludge generated 5400 GWh of electricity and 650 GWh of heat delivered into district heating networks [17]. Beside local use and electricity generation, biogas can be upgraded to biomethane for injection into natural gas networks or as transport fuel [16]. The digested sewage sludge has a recoverable energy potential, although lower than that of raw sewage sludge. Sewage sludge is dried and converted into energy in cogeneration plants, thermal power plants, waste-to-energy plants, cement kilns and mono-incineration plants [4,18–20].

Recently, pyrolysis and gasification have proven to be environmentally safe and economically feasible solutions for sewage sludge treatment. Pyrolysis converts different types of sewage sludge (raw, digested and waste-activated) into usable oil and gas (syngas), forming a stabilized residue (biochar) as a by-product. AD followed by sludge pyrolysis yields higher rates of energy recovery than stand-alone AD or pyrolysis [14,21]. Gasification of sewage sludge, on the other hand, yields syngas that can fuel gas burners, cogeneration (CHP) systems, gas turbines and internal combustion engines. The generated heat and electricity can partially meet the demands of WWTPs. Electricity generation from syngas has shown higher efficiency than electricity generation from biogas [22]. Gasification of

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sewage sludge and waste vegetable oil for generation of syngas, which fuels CHP systems, is also a profitable and clean solution [23].

Nutrient recovery from sludge dewatering streams and incineration sludge ashes are emerging as promising processes with multiple benefits [24]. The recovery of nutrients from dewatering streams reduces the formation of struvite scale in the equipment and the obtained nutrients are recycled as fertilizers into the agricultural sector. Nutrients' recovery specifically focuses on phosphorus, which is a limited resource. The achievable potential for phosphorus recovery from sewage sludge is estimated at 300,000 tonnes per year in the EU. At the moment, about 25% of the phosphorus is recycled through the application of sewage sludge to soil [25]. However, many of the above mentioned technologies are still in the experimental phase or are not yet feasible.

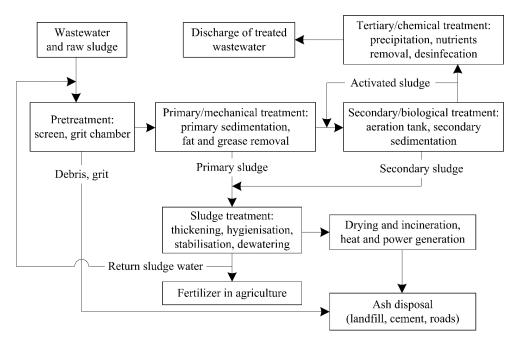


Figure 1. Main processes of wastewater and sewage sludge treatment in the EU.

The impact of the sewage sludge generated in Croatia is minor to the EU. In 2016, the amount of sewage sludge in Croatia was 21,366 tonnes dry matter, which represents less than 0.2% of the total sludge at the EU-28 level (11.5 million tonnes). Following the planned expansion and upgrade of the wastewater treatment system, the amount of sewage sludge could reach 100,000 tonnes by 2024 in Croatia, which would still be less than 1% of the amount generated at EU-28 level. Nevertheless, the EU-28 and Croatia are developing common sewage sludge management and final disposal strategies. In particular, anaerobic digestion for biogas generation, followed by incineration of dried stabilized sludge, and coupled to energy recovery solutions, are gaining much attention, lately.

This paper analyses the sludge management and disposal solutions applicable in Croatia. The biogas generation potential from anaerobic digestion and energy recovery from solar-dried and incinerated sewage sludge are discussed, as well as nutrient recovery and greenhouse gas (GHG) emissions from sludge treatment. The paper is organized as follows: Section 2 gives an overview on the wastewater loads and sewage sludge quantities in Croatia and compares Croatia with the sewage sludge management strategies in the EU while giving particular attention to mono-incineration with energy recovery as the emerging solution for final disposal. Section 3 analyses the energy generation potential of biogas and sewage sludge from the existing WWTP in Zagreb and planned major projects in Croatia. The energy balance between thermal drying and incineration of sewage sludge is studied showing the advantages of solar drying. In the end, disposal of incinerated sewage sludge ash and emissions of GHG are discussed. In Section 4, a discussion on the results was conducted, along with

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the analysis of three potential scenarios in Croatia for sewage sludge management options. Section 5 offers the conclusions of this paper.

2. Sewage Sludge Management in Croatia

2.1. Sewage Sludge Disposal Practices

Sewage sludge is considered a valuable resource because it contains two components that are economically and technically recoverable: energy and nutrients. Old (EU-15) and new EU member states (EU-13) have different strategies regarding sewage sludge management. At present, old member states produce 87.7% of the total quantity of sewage sludge in the EU. Incineration is the second most preferred disposal method in the EU-15 (29.5%), after reuse in agriculture (42.7%) and ahead of landfilling (10.6%), and other methods (17.2%). In the EU-13, incineration is less used (8.3%) with respect to agricultural reuse (41%), landfilling (34.8%), and other methods (15.9%) [2].

Sewage sludge is comparable to wood biomass in terms of energy content [26–28] but with higher inorganic (ash) content. The heating value of sewage sludge dry matter is 17–18 MJ/kg for raw sludge (RS), 14–16 MJ/kg for active sludge (AS) and 8–12 MJ/kg for stabilized sludge (SS) [21,29].

Sewage sludge thermal treatment methods include: mono-incineration and co-incineration, pyrolysis, gasification, wet oxidation, thermal hydrolysis, hydrothermal carbonization (HTC) and biofuel production by microorganisms. The available methods for thermal treatment of sewage sludge are listed in Table 1. Pyrolysis of sewage sludge consist of heating of sewage sludge to elevated temperatures, under anoxic conditions. This process removes the organic substance by thermal cleaning and produces bio-oil and biogas with heating values in the range of 30–37 MJ/kg and 15–20 MJ/m³, respectively [21]. Gasification converts the carbon content of sewage sludge into syngas by partial oxidation at elevated temperatures with a reducing atmosphere. The syngas is composed of H₂, CO, CH₄, CO₂, N₂ and H₂O and achieves heating values in the range of 10–20 MJ/m³, depending on the type of oxidant [22]. Wet oxidation dissolves the organic content of sewage sludge into H₂O and CO₂, in water with oxygen or air as the oxidant, at temperatures between 200 and 300 °C. Wet oxidation is an exothermic process, which can supply process heat. Hydrothermal carbonization is a hydrothermal process that converts the solid fraction of sewage sludge into a char-like product (HTC coal). The reaction is performed at temperatures of around 200 °C and pressures of about 20 bar. After drying, the HTC coal can be used as low-grade solid fuel with heating values of 10–15 MJ/kg [30].

Incineration of sewage sludge is becoming the fastest growing disposal practice in the EU, with an increase from 19% in 2005 to 26.9% in 2010 [2,4] and expected to reach 32% by 2020 [3]. Incineration is the main alternative to agricultural reuse, especially where suitable soils for recycling are not available or public disapproval is present. Incineration reduces the mass and volume of sewage sludge, safely destroys harmful pathogens and can be combined with energy recovery systems. Usually, incineration is performed on stabilized and dewatered sludge. Self-sustained combustion of sewage sludge is achieved with DM contents as low as 30%. However, due to a high water content, dewatered sludge has no practical energy value. In thermal power plants and waste incineration plants, sludge needs drying and grinding before co-incineration with lignite, coal, or municipal waste. Dried sludge (90% DM) achieves heating values between 8 and 12 MJ/kg [31] and is also suitable for mono-incineration and cement production. Generally, mono-incineration plants have higher investment costs (between 200 and $400 \, \text{€/t}_{\text{DM}}$) than co-incineration plants (between 150 and $300 \, \text{€/t}_{\text{DM}}$) [2].

Sewage sludge incineration is a potential source of harmful substances such as dioxins, furans, and heavy metals which are present both in flue gases and in the residual ash. Incinerated sewage sludge ash (ISSA) needs to be disposed of accordingly because of the presence of heavy metals. Sewage sludge ash is disposed in landfills, used as fertilizer in agriculture (depending on heavy metal content), or raw material for concrete and asphalt production. The main drawback of sludge incineration is that it hinders phosphorus recovery.

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Phosphorus recovery from sewage sludge ash is limited only to ashes with high concentrations of phosphorus, like those produced in mono-incineration plants. Phosphorus recovery from diluted ash that is produced in co-incineration plants is not feasible at present. In cement plants, sewage sludge is a source of energy and raw material, but phosphorus remains incorporated in the cement.

Parameter	Anaerobic Digestion	Incineration	Pyrolysis	Gasification	Hydrothermal Carbonization
Temperature	15–60 °C	800–1000 °C	300–900 °C	700–1000 °C	180–250 °C
Main products	stabilized sludge and biogas (CH ₄ , CO_2 , H_2O)	ash and flue gases (CO ₂ , H ₂ O, CO, NO _x , SO _x , PM)	bio-char, bio-oil and biogas (H ₂ , CH ₄ , CO ₂)	bio-char, tar and syngas (H ₂ , CO, CH ₄ , CO ₂)	HTC coal
Harmful substances	pathogens, heavy metals	heavy metals and tra	benzenes, phenols, furans, aldehydes and ketones.		
Heating value	biogas: 15–27 MJ/m ³	SS: 8–12 MJ/kg _{DM} AS: 14–16 MJ/kg _{DM} RS: 17–18 MJ/kg _{DM}	bio-oil: 30–37 MJ/kg biogas: 15–20 MJ/m ³	syngas: 10–20 MJ/m ³	HTC coal: 10–15 MJ/kg

Table 1. Comparison of thermal treatment methods for sewage sludge [18,30,32–34].

2.2. The Public Wastewater System in Croatia

The public water supply system in Croatia has a population coverage rate of 93%, according to the latest published data. Out of 4.285 million inhabitants, the share of population connected to the national water supply system is 84%, while a further 4% have access to local water supply systems. The remaining 12% of the population is using individual solutions for accessing clean drinkable water [35].

On the other hand, the public wastewater system is less developed. Only 55% of the population uses the public wastewater systems. Large differences are encountered between urban and rural areas. The coverage rate for the public wastewater system is an average 75% in cities with more than 150,000 people equivalent (PE) but only 5% in small towns with less than 2000 PE. The total amount of collected wastewater was 378 million m³ in 2017: 47% was generated by households, 33% by the industry, and 20% was from rainfall. Out of the total quantity of treated wastewaters, 32% were treated in wastewater plants with preliminary or primary treatment, 60% in plants with secondary treatment and 8% in plants with tertiary treatment, as shown in Figure 2 [36].

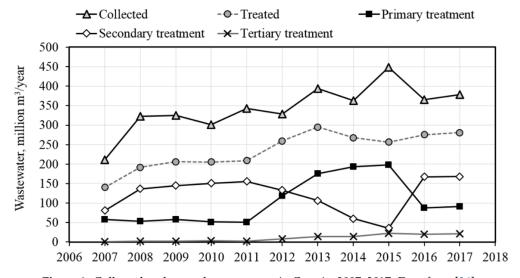


Figure 2. Collected and treated wastewaters in Croatia, 2007–2017. Data from [36].

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At present in Croatia, wastewater and industrial wastewaters are treated in over 200 WWTPs with a total capacity of 4.1 million PE [35]. More than half of the wastewater and sewage sludge is produced in the four major agglomerations (Zagreb, Split, Rijeka, and Osijek), as shown in Figure 3.

The ongoing upgrades of the public wastewater system include all larger cities and industrial areas. In Croatia, 91 agglomerations have wastewater loads larger than 10,000 PE while another 190 agglomerations have wastewater loads in the range between 2000 and 10,000 PE. Following EU directives, secondary wastewater treatment is mandatory to agglomerations larger than 10,000 PE. Furthermore, agglomerations located within ecologically sensitive areas must implement tertiary wastewater treatment, including nitrogen and phosphorus removal. In Croatia, the ecologically sensitive areas are located in the drainage basins of Danube River and Adriatic Sea (Table 2) [37].

Cina of Analamanation	Name Is an a f. A seal and a seal is an	Drainage Basin		
Size of Agglomeration	Number of Agglomerations	Danube River	Adriatic Sea	
ES ≥ 150,000	4	2	2	
$50,000 \le ES < 150,000$	16	9	7	
$15,000 \le ES < 50,000$	43	19	24	
$10,000 \le ES < 15,000$	28	11	17	
$2000 \le ES < 10,000$	190	78	112	
ES < 2000	486	301	185	
Total	767	420	347	

Table 2. Size and number of agglomerations in Croatia. Data from [37].

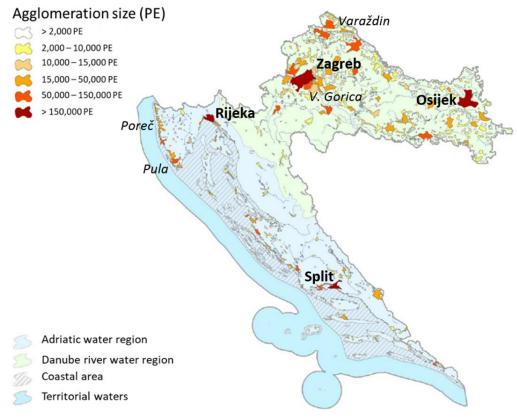


Figure 3. Spatial arrangement of agglomerations in Croatia.

2.3. Sewage Sludge Treatment in Croatia

Over the last decade, Croatia has been producing around 20,000 tonnes of sewage sludge per year (Figure 4). The total quantity of sewage sludge was 21,366 tonnes DM in 2016. The WWTP in Zagreb produces about 70% of the total sludge quantity in Croatia. In the EU, the annual sewage

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sludge production per population equivalent served by wastewater treatment is between 20 and $35 \text{ kg}_{DM}/PE$ [38], while in Croatia it is 20–25 kg_{DM}/PE [35].

The quantity of sewage sludge is expected to increase multifold over the next years, following the planned extensive upgrades in the public wastewater system. According to the estimates of the national water service company [35], sewage sludge production will surpass 100,000 tonnes DM by 2024.

At present, WWTPs in Croatia have individual approaches to sewage sludge management and disposal. The WWTP Zagreb uses long-term storage as an intermediate solution prior to the construction of a mono-incineration plant. As for the long-term solution, mono-incineration is emerging as the preferred solution. The proposal is to build mono-incineration plants in the four major cities of Croatia (Zagreb, Split, Rijeka, and Osijek), which would incinerate the sewage sludge collected from smaller WWTPs in the surrounding regions. Until then, landfilling, recycling in agriculture, and co-incineration in waste incineration plants and cement factories is the short-term solution.

The practice of sludge recycling in agriculture is recently experiencing increasing public disapproval and will most likely be abandoned in the future. In Croatia, the quantity of sewage sludge used in agriculture was 1290 tonnes DM in 2017, representing 6% of the total quantity of produced sludge. More than 70% of that quantity is mixed with biomass waste (leaves, grass, branches, etc.) and stored for composting before application on land. In Croatia, the application of sewage sludge on land must be in line with specific regulations and standards. Following the guidelines of the Sewage Sludge Directive (86/278/EEC), recycling in agriculture is allowed only for treated and stabilized sludge, while respecting the limit values of concentrations for heavy metals and organic pollutants [39].

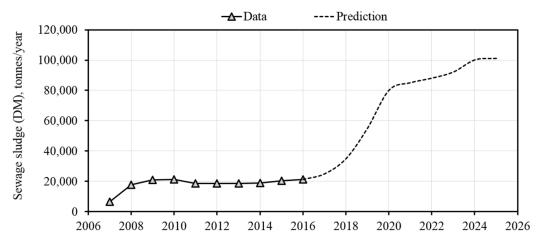


Figure 4. Quantity of sewage sludge produced in Croatia, data for 2007–2016 and predictions to 2025. Data from [35].

3. Analysis and Results

3.1. The Wastewater Treatment Plant Zagreb

The WWTP Zagreb, which is the largest city and capital of Republic of Croatia, has a design capacity of 1.2 million PE and implements secondary wastewater treatment with planned upgrade to tertiary treatment with phosphorus and nitrogen removal. The WWTP Zagreb generates around 15,000 tonnes DM of sewage sludge per year. Sewage sludge is stabilized for a period of 18 days in four AD units with total volume of 35,360 m³, shown in Figure 5. The anaerobic process is enhanced by sludge mixing and heating during mesophilic conditions (37 °C). Sludge stabilization converts around 50% of the organic matter into water, carbon dioxide (CO_2), and biogas with a methane content of 60%. The heating value of raw sludge is 13 MJ/kg_{DM} and that of stabilized sludge 9 MJ/kg_{DM} [40]. The average production of biogas is 7.3 m³/PE per year and its heating value is 20 MJ/m³. Biogas fuels a CHP system with an installed electrical capacity of 2.6 MW, at an electrical efficiency of 38% and a

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thermal efficiency of 50%. The specific electricity consumption is 30 kWh_{el}/PE and the CHP system supplies around 60% of the electricity to the WWTP.

The thermal energy, on the other hand, is used for the heating of AD units. Stabilized sludge is treated with polymers and lime before centrifugal dewatering. The DM content in the dewatered sludge is at least 30%. The largest part of the produced sewage sludge is stored in long-term storages at the plant location while smaller quantities are applied to agricultural surfaces or transported to cement kilns and incineration plants. At present, local authorities are considering the construction of a mono-incineration plant because more than 150,000 tonnes DM of sewage sludge is stored and awaiting final disposal. Data from the WWTP Zagreb shows that the energy potential of biogas is 146 MJ/PE per year and that of sewage sludge DM is 113 MJ/PE per year.



Figure 5. The anaerobic digesters of the WWTP Zagreb.

3.2. Future Wastewater Treatment Projects

Croatia is considering different management strategies for the treatment and disposal of sewage sludge. Croatia counts 281 agglomerations larger than 2000 PE, with a total population of 3.5 million inhabitants and a cumulative wastewater load of 5 million PE. Larger WWTPs (PE > 80,000) will most likely use anaerobic stabilization with subsequent drying and incineration of sewage sludge. Smaller WWTPs, on the other hand, will choose between several variants. In the first variant, when larger WWTPs are close, transport of sewage sludge is seen as an acceptable solution. Further sludge stabilization is performed at the sites of the larger WWTPs. In the second variant, when larger WWTPs are too distant, transport is not justified, and sludge stabilization is performed at the site of the smaller plant. In this case, sludge stabilization includes homogenization and dewatering, or aerobic processes followed by mechanical drying (thickening and dewatering).

Table 3 shows the design hydraulic loads, average physicochemical loads and the expected quantities of the by-products of wastewater treatment in seven selected WWTP projects. These seven WWTPs projects include five major agglomerations with constant wastewater loads and two minor agglomerations with variable wastewater loads due to tourism activity. The specific daily loads are between 90 and 130 L/PE of wastewater, 9 and 11 g/PE of nitrogen, and 1.6 and 2.0 g/PE of phosphorus. The BOD₅-to-COD ratio is between 0.4 and 0.5, which is typical for biologically-degradable domestic wastewaters. In Croatia, the specific annual quantities of sewage sludge and biogas yield are 20–25 kg_{DM}/PE and 5.8–7.3 m³/PE. For comparison, in the EU, the specific quantities are 20–35 kg_{DM}/PE [38] and 6.6–9.5 m³/PE, respectively [41].

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Table 3. Wastewater properties in the planned WWTPs in Croatia (data obtained from environmental studies of specific WWTP).

TA/TA/PD	TATTATED		Diiolea	Osijek	** V 11	Velika	Pula-Nord	
WWTP		Split R	Rijeka	Osijek	Varaždin	Gorica	Low	High
Capacity, PE	Capacity, PE		200,000	170,000	127,000	74,000	13,264	58,000
			Hydraulic	Load				
Domestic wastewater, n	n ³ /d	n/a	18,060	14,700	n/a	6876	1715	7000
Industrial wastewater, r	n ³ /d	n/a	9754	7950	n/a	1749	0	0
Total wastewater, m ³ /	'd	34,650	27,814	22,650	19,849	8625	1715	7000
Infiltration, m ³ /d		14,850	8241	11,350	11,909	3434	744	3000
Total hydraulic load, m	³ /d	49,500	36,055	34,000	31,758	12,059	2459	10,000
		P	hysicochem	ical Load				
Chemical oxygen	mg/L	658	698	633	540	791	647	696
demand (COD)	kg/d	32,571	25,176	21,522	17,147	9538	1592	6960
Biochemical oxygen	mg/L	329	304	300	240	368	324	348
demand (BOD ₅)	kg/d	16,286	10,968	10,200	7616	4438	796	3480
Total suspended	mg/L	384	442	350	293	491	378	406
solids (TSS)	kg/d	19,008	15,946	11,900	9310	5919	928	4060
Total nitrogen (N)	mg/L	60	53	55	39	64	59.3	63.8
iotai introgen (N)	kg/d	2970	1898	1870	1244	777	146	638
Total phosphorous (P)	mg/L	10	9	9	7.8	11	9.7	10.4
iotai phosphorous (i)	kg/d	495	331	306	249	131	23.9	104
			Technolo	gies				
Planned treatment sta	ge	Secondary	Secondary	Tertiary	Tertiary	Tertiary	Seco	ndary
Sludge stabilization	*	AND	AND	AND	AND	AND	A	D
Electricity consumption, k	Wh/PE	37.2	46.6	43.1	40.2	47.6	43	3.5
			By-Prod	ucts				
Sewage sludge, t/y		6500	5120	3450	3285	1661	64	4 5
Debris and grit, t/y		n/a	1400	1200	902	500	10	54
Sand, t/y		n/a	634	540	451	750	10	03
Grease, t/y		n/a	372	310	262	250	4	.0
Biogas, m ³ /y (×1000))	1600,000	1170,000	1022,000	931,000	533,000		-

^{*} AND = Anaerobic Digestion, AD = Aerobic Digestion.

3.3. Energy Recovery from Sewage Sludge

Sewage sludge exhibits variable composition and component concentrations. Sewage sludge contains organic substances, heavy metals, pathogens, and nutrients, such as nitrogen and phosphorous. The heavy metals found in sewage sludge are from anthropogenic sources. Manganese, lead, zinc, and copper are among the most represented heavy metals. Table 4 shows the composition of stabilized sewage sludge from the WWTP in Zagreb [42] and a comparison with the average composition of stabilized sewage sludge in German WWTPs [2]. The heating value of the DM is around 10 MJ/kg, which makes sewage sludge a suitable fuel for energy generation. WWTPs produce sewage sludge with DM contents of around 30% and additional drying is necessary for energy recovery in incineration plants.

In Croatia, large WWTPs will be equipped with anaerobic stabilization of sewage sludge in order to produce valuable biogas. The biogas yield is between 190 and 240 Nm³/t of organic dry matter (ODM), under optimum anaerobic conditions. Between 45 and 55% of the organic matter is converted into biogas, which reduces the amount of sludge DM by 25–33% [41]. The composition of biogas depends on the conditions of the stabilization process and on the sewage sludge properties. Biogas contains mainly methane and carbon dioxide while water vapour, ammonia, and hydrogen sulphide are present in smaller concentrations. Hydrogen sulphide, ammonia, and water vapour, as well as other corrosive trace elements (siloxanes), are removed from biogas before its use in CHP units. The properties of biogas from WWTPs in Croatia are given in Table 5.

Table 4. Composition of sewage sludge in WWTPs in Zagreb and Germany. Data from [2,42].

Parameter	WWTP Zagreb	WWTPs Germany	Unit
Dry matter	29.5–34.8	30.5	%
Volatile matter	n.a.	30	%
Heating value	8.2-9.1	10–12	MJ/kg _{DM}
pH-value	11.6-12.9	7.7	-
Organic matter	n.a.	45-80	% DM
Carbon, C	145-188	330-500	g/kg _{DM}
Oxygen, O	n.a.	100-200	g/kg _{DM}
Hydrogen, H	n.a.	30-40	g/kg _{DM}
Nitrogen, N	26.0-35.1	20–60	$g/kg_{ m DM}$
Phosphorus, P	21.5-30.8	2–55	$g/kg_{ m DM}$
Magnesium, Mg	n.a.	9.17	g/kg _{DM}
Potassium, K	n.a.	2.63	g/kg _{DM}
Calcium, Ca	n.a.	71	$g/kg_{ m DM}$
Cadmium, Cd	<2	1.5-4.5	mg/kg_{DM}
Chromium, Cr	22.5-31.1	50-80	$mg/kg_{ m DM}$
Zinc, Zn	526-711	100-300	$mg/kg_{ m DM}$
Lead, Pb	62.1–74.1	70–100	$mg/kg_{ m DM}$
Copper, Cu	180-496	300-350	$mg/kg_{ m DM}$
Nickel, Ni	26.5–31.1	30–35	mg/kg_{DM}
Cobalt, Co	9.8-11.9	6.53	$mg/kg_{ m DM}$
Mercury, Hg	1.01-1.52	0.3-2.5	mg/kg_{DM}
Arsenic, As	11.95-16.01	4–30	mg/kg_{DM}
Antimony, Sb	n.a.	5–30	$mg/kg_{ m DM}$
Manganese, Mn	n.a.	600-1500	mg/kg_{DM}
Molybdenum, Mo	2.42-3.02	3.9	$mg/kg_{ m DM}$
Tin, Sn	n.a.	30-80	mg/kg_{DM}
Vanadium, V	n.a.	10–100	mg/kg_{DM}

The total wastewater treatment capacity in Croatia is estimated at 4.1 million PE in over 200 WWTPs. The six major WWTPs in Croatia (Zagreb, Split, Rijeka, Osijek, Varaždin, and Velika Gorica) will have an overall capacity of about 2 million PE, after the planned upgrades. The expected annual quantities of sewage sludge and biogas produced in these six WWTPs are 35,000 tonnes DM and 14 million m³, respectively. These quantities of sewage sludge and biogas return specific annual production rates of 17.5 kg/PE of sewage sludge and 7.0 m³/PE of biogas, on average.

Biogas from anaerobic sludge stabilization is subject to variable composition with methane concentrations as low as 40%. Generally, biogas is used to fuel internal combustion engines. Biogas engines are marketed with capacities in the range between 10 kW $_{\rm el}$ and 5 MW $_{\rm el}$. They achieve overall efficiencies of up to 90%, whereas the electrical efficiency is 35%, the thermal efficiency 55%, and the losses 10% [41,43]. Incineration units are not efficient as CHP units. They achieve overall efficiencies of around 80%, where the electrical efficiency is 20% [44] and thermal efficiency 60% [45].

Taking that the average biogas heating value is $21.6~\rm MJ/m^3$ (6.0 kWh/m³), CHP units generate $2.1~\rm kWh_{el}/m^3$ of electricity and $3.3~\rm kWh_{th}/m^3$ of heat per unit of biogas. The generated electricity is used by the WWTP or fed to the grid, possibly under subsidized tariff systems. Estimates for the total energy consumption in the major Croatian WWTPs are in the range between $0.55~\rm and~0.9~\rm kWh/m^3$ of treated wastewater (45–80 kWh/PE). These energy consumptions correspond to WWTPs with secondary wastewater treatment, activated sludge process, and AD of sewage sludge. The electricity consumption is between $0.35~\rm and~0.55~\rm kWh_{el}/m^3$ of treated wastewater (30–50 kWh_{el}/PE). The thermal energy consumption is between $0.15~\rm and~0.35~\rm kWh_{th}/m^3$ of treated wastewater (15–30 kWh_{th}/PE). Generally, the specific energy consumption of the WWTP decreases as its size and capacity increase.

The major electricity consumers in WWTPs are aeration, pumping, sludge thickening, and dewatering [1]. Taking that the biogas yield is in the range between 5.8 and 7.3 m³/PE, the amount of

electricity generated from biogas is 12–16 kWh_{el}/PE. Biogas CHP units will supply about 30% of the electricity demand of WWTPs in Croatia.

Parameter	Input	Unit
Lower heating value	20–25	MJ/m ³
Explosion limit in air	6–12	%
Self-ignition temperature	650-750	°C
Critical pressure	54-59	bar
Critical temperature	224-242	K
Density	1.0-1.2	kg/m ³
Biogas composition		
-methane (CH ₄)	55-70	%
-carbon dioxide (CO ₂)	30-45	%
-hydrogen sulphide (H ₂ S)	0.5 - 1.0	%
-ammonia (NH ₃)	0.05 - 0.10	%
-water vapour (H ₂ O)	1–5	%

Table 5. Properties of biogas produced by anaerobic stabilization of sewage sludge.

The generated heat, on the other hand, is used for heating of digesters, sludge reactors, and office buildings. In the total amount of CHP heat, 50--60% is high-temperature heat (flue gases temperatures of $450\text{--}550\,^\circ\text{C}$) and 40--50% is low-temperature heat (engine cooling fluid temperatures of $80\text{--}90\,^\circ\text{C}$). The amount of available biogas heat is $19.1\text{--}24.1\,\text{kWh}_{\text{th}}/\text{PE}$, which results with 80--100% thermal self-sufficiency. For example, the WWTP in Zagreb uses state-of-the-art wastewater technologies and processes, which ensure average autonomies of 60% for electricity and 100% for heat.

Energy recovery of sewage sludge can be performed in mono-incineration or co-incineration plants. In Croatia, mono-incineration plants are expected to dispose the majority of the produced sludge in the future. Energy recovery systems in incineration plants achieve electrical efficiencies of 20% and thermal efficiency of 60%. Sewage sludge with annual production rates of 20–25 kg_{DM}/PE and heating values of 2.5 kWh/kg_{DM} could be converted into 10–13 kWh_{el}/PE of electricity and 30–38 kWh_{th}/PE of heat. In total, biogas and sewage sludge could supply 20–30 kWh_{el}/PE of electricity and 50–60 kWh_{th}/PE of thermal energy to WWTPs, assuming that incineration plants are built at the same location. The energy autonomy of the WWTP would increase to about 60% for electricity and 100% of thermal energy, with excess heat available. Surely, drying of sewage sludge needs large amounts of energy, but the costs can be significantly reduced using solar energy or waste heat.

3.4. Drying of Sewage Sludge

Drying of dewatered sewage sludge consumes substantial amounts of heat. The amount of water removed during thermal drying, over a range of dry contents from 30–90%, is $2.2~kg_W/kg_{DM}$. Since the latent heat of evaporation of water is $2.5~MJ/kg_W$, drying from 30–90% DM has a minimum energy requirement of $5.5~MJ/kg_{DM}$ or $1.5~kWh_{th}/kg_{DM}$.

However, available drying technologies have higher energy requirements, between 2.9 and $3.6~MJ/kg_W$ per unit of evaporated water. Thus, the thermal energy consumption for drying of sewage sludge to fuel-grade quality is between $1.8~and~2.2~kWh_{th}/kg_{DM}$. In addition to heat, the electricity consumption of the drying equipment is between $0.10~and~0.30~kWh_{el}/kg_{DM}$.

The energy efficiency between waste heat recovery from sewage sludge incineration and thermal drying is questionable. The energy balance of drying and incineration (Q_{EB}) can be calculated as the difference between waste heat recovery (Q_{HR}) and drying energy (Q_{DE}):

$$Q_{\rm EB} = Q_{\rm HR} - Q_{\rm DE} \tag{1}$$

The quantity of recovered waste heat depends on the heat recovery efficiency (η) and the lower heating value of sewage sludge (LHV), which can be predicted from the organic dry matter content (ODM) and the dry matter content (DM₂) as proposed by Komilis et al. [46]:

$$Q_{HR} = \eta \cdot LHV = \eta \cdot [6.0 \cdot ODM - 4.9 \cdot (1 - DM_2)], \text{ kWh/kg}_{DM}$$
 (2)

The drying energy depends on the amount of removed water, which can be determined from the dry matter contents before (DM_1) and after (DM_2) thermal drying. Assuming a specific energy consumption for drying of 3.27 MJ/kg_W or 0.9 kWh_{th}/kg_W, the drying energy is:

$$Q_{\rm DE} = 0.9 \cdot \left(\frac{1}{DM_1} - \frac{1}{DM_2}\right), \, \text{kWh/kg}_{\rm DM}$$
 (3)

Figure 6 depicts the energy balance with respect to the ODM and DM_2 values, assuming an energy recovery efficiency of $\eta = 0.8$ and an initial dry matter content of $DM_1 = 0.3$. It can be seen that the energy balance is negative for sewage sludges with organic matter contents lower than ODM < 0.44, regardless of the dry matter content after thermal drying (DM_2). This is the case for digested sewage sludge with low heating values (LHV < 2.6 kWh/kg_{DM}).

On the other hand, the energy balance is positive over the entire range of DM_2 for sludges with high organic content (ODM > 0.66). This is the case for non-digested sewage sludge with high heating values (LHV > 4.0 kWh/kg_{DM}). In the range of 0.44 < ODM < 0.57, which corresponds to heating values between 2.6 < LHV < 3.4 kWh/kg_{DM}, positive energy balance is obtained with thermal drying. For example, sewage sludge with ODM = 0.5 (LHV = 3 kWh/kg_{DM}), is energy-positive with drying to dry matter contents of DM_2 > 0.9. Positive energy balance, not involving thermal drying (DM_2 = DM_1 = 0.3), can be achieved for ODM > 0.57. In this case, sewage sludge achieves self-sustained combustion (LHV > 3.4 kWh/kg_{DM}) and its water content is evaporated by the produced heat.

The larger WWTPs in Croatia will implement AD technology, thus giving advantage to biogas energy rather than to that of sewage sludge. On the other hand, thermal disposal of digested sewage sludge is encumbered by low heating values (LHV = 2–3 kWh/kg_{DM}) and high-water contents (70–80%). Thermal drying and waste heat recovery from incineration plants will be necessary prior to thermal disposal of sewage sludge. Recently, solar drying has received increasing attention, although its capacity is much lower than that of conventional drying. In Germany, for example, the annual capacity of solar drying is 350 tonnes of DM on average while fluidized beds, belt drying, and drum drying have capacities between 3000 and 5000 tonnes DM [2]. The solar drying capacity can be increased to around 1000 tonnes DM using waste heat from incineration plants or thermal power plants. Solar drying is performed inside heated and well-ventilated greenhouses [47]. Continuous turning and spreading of sewage sludge is needed to achieve dry matter contents of 75–80%.

The evaporation potential in Croatia is estimated using the Penman–Monteith monthly method [48]. The annual evaporation potential is between 900 and 1500 kg $_{\rm W}/{\rm m}^2{\rm year}$. When drying sewage sludge from 0.30–0.75 DM content, the necessary water removal is 2 kg $_{\rm W}/{\rm kg_{DM}}$. Thus, the specific capacity of solar drying in Croatia is between 450 and 750 kg $_{\rm DM}/{\rm m}^2{\rm year}$.

Table 6 shows the surface requirements for solar drying in the four major WWTPs in Croatia. Despite low production capacities and large space requirements, solar drying is considered sustainable and economical, especially in regions with favourable climate. In Croatia, solar drying of sewage sludge is expected to become an integral part of the future wastewater treatment system. Solar dryers will operate as intermediate stations between WWTPs and incineration plants, providing drying and short-term storage. It is estimated that 50 solar dryers would be sufficient in Croatia. The annual production of sewage sludge is expected to reach 100,000 tonnes DM after the planned upgrades and expansions in the wastewater treatment system. If all of the produced sewage sludge is to be dried in 50 solar dryers, then the surface of one solar dryer should be 3300 m² on average.

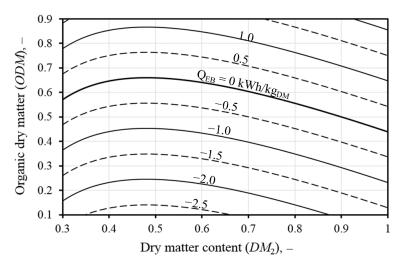


Figure 6. Energy balance between waste heat recovery and thermal drying of sewage sludge.

Table 6. Surface requirements for solar drying of sewage sludge in Croatian WWTPs.

WWTP	Sewage Sludge Quantity [t _{DM} /year]	Evaporation Potential [kg _W /m ² year]	Sludge Solar Drying Capacity [kg _{DM} /m²year]	Solar Drying Surface [m ²]
Zagreb	15,000	1115	558	26,900
Split	6500	1523	762	8500
Rijeka	5120	1297	649	7900
Osijek	3450	919	460	7500

3.5. Disposal of Incinerated Sewage Sludge Ash (ISSA)

Although the volume of sewage sludge is reduced by 90% during incineration, ISSA is produced as by-product. ISSA contains inorganic compounds such as oxides of silicon (SiO_2), calcium (CaO_3), iron (Fe_2O_3), aluminium (Al_2O_3), phosphorus (P_2O_5), sulphur (SO_3), magnesium (SiO_3), and titanium (SiO_3), but also unincinerated organic matter in smaller quantities [49]. ISSA can also contain heavy metals in traces, such as Hg, Cd, As, Sb, and Pb. Therefore, ISSA requires appropriate treatment in order to prevent its harmful impact on the environment and human health. ISSA was recently considered as an additional material in the construction industry for concrete and cement [42], brick and asphalt production, or for the extraction of phosphorus, which is present in mass fraction of up to SiO_3 0.

In recent years, several technologies were developed for phosphorus recycling from ISSA, including pyrolytic processes and various wet processes. Pyrolytic processes partially remove metals from ash, but phosphorus remains in the form of insoluble apatite [50]. Apatite cannot be used by plants and has low value as fertilizer. In wet processes, acids or bases are added to ISSA, in order to dissolve phosphorus. Afterwards, phosphorous can be recovered through the precipitation of ammonium, calcium, sodium, iron, or aluminium phosphate, which are compounds identical to the ones found in mineral phosphate fertilizers.

3.6. Avoided CO₂ Emissions

The avoided CO₂ emissions by using sewage sludge as an energy source is analysed for the case of WWTP Rijeka. The annual quantity of sewage sludge produced in WWTP Rijeka is 5120 tonnes DM, with a heating value of around 10 MJ/kg. The energy potential of this quantity of sewage sludge is 14,200 MWh, which exceeds the WWTP's thermal energy demand. Assuming that the electrical and thermal efficiency of the CHP are 30% and 45% [51], the energy content of sewage sludge could be converted into 4260 MWh of electricity and 6390 MWh of thermal energy.

In addition to its energy generation potential, another advantage of sewage sludge energy recovery is the reduction of GHG emissions, when compared against energy generation from fossil fuels. Sewage sludge is of organic origin and, according to IPCC recommendations [52], can be considered renewable

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energy source, which means that no direct CO_2 emissions originate from energy generation. However, Chen and Kuo [51] calculated GHG emissions for different sewage sludge management scenarios and obtained 223 kg CO_{2eq} /t of indirect GHG emissions for incineration process. Therefore, the incineration of 5120 tonnes DM of sewage sludge would generate 1142 tonnes CO_{2eq} of indirect GHG emissions.

Compared to sewage sludge energy generation, a CHP unit on natural gas would originate around 2700 tonnes of CO₂ emissions for the same amount of electricity and heat (Table 7).

Parameter	Value	Unit
Electricity production	4260	MWh
Heat production	6390	MWh
Total efficiency of CHP plant	80	%
Total rated thermal input of natural gas	48,000	GJ
CO ₂ emissions factor for natural gas	56.1	kg/GJ
CO ₂ emissions from CHP plant	2693	t

Table 7. CO₂ emissions from natural gas CHP.

Electricity generation from hard coal in thermal power plants and thermal energy from extra light fuel oil in district heating plants would originate over 5900 tonnes CO_2 of emissions (Table 8). Taking into account both direct and indirect GHG emissions, energy generation from sewage sludge avoids around 1500 t_{CO2} if compared to natural gas CHP and 4800 t_{CO2} if compared to hard coal and fuel oil. Therefore, the reduction of GHG emissions obtained by energy generation from sewage sludge is 58% compared to natural gas and 80% compared to hard coal and fuel oil. Likewise biomass and biogas, sewage sludge is a renewable energy source, which contributes the reduction of GHG emissions and to the fulfilment of international agreements on climate change mitigation.

Parameter	Value	Unit
Electricity generation from hard coal	4260	MWh
Efficiency of thermal power plant	36	%
Total rated thermal input from hard coal	42,667	GJ
CO ₂ emissions factor for hard coal	94.6	kg/GJ
CO ₂ emissions from thermal power plant	4036	t
Thermal energy generation from extra light fuel oil	6390	MWh
Efficiency of district heating	90	%
Total rated thermal input of extra light fuel oil	25,600	GJ
CO ₂ emissions factor for extra light fuel oil	74.1	kg/GJ
CO ₂ emissions from district heating	1897	t
Total CO ₂ emissions	5933	t

Table 8. CO₂ emissions from hard coal and extra light fuel oil.

4. Discussion

In Croatia, three scenarios for the management and treatment of sewage sludge can be considered: treatment in mono-incineration plants (TMP), treatment in cement plants (TCP), and the business-as-usual (BAU) scenario. In the BAU scenario, sewage sludge is treated by landfilling. Sludge is landfilled at current landfills and it is assumed that, in the future, it will be landfilled at regional waste management centres. According to [53], 10 waste management centres are predicted in Croatia, operational by 2023. The TCP scenario considers incineration of sewage sludge in cement plants. At present, cement plants in Croatia treat the refuse-derived fuel (RDF) from waste management centres and could also use the sewage sludge from WWTPs as a fuel and filler in cement production. Only three cement plants meet the necessary requirements for utilization of sewage sludge. The TMP scenario considers four mono-incineration plants in Zagreb, Split, Rijeka, and Osijek. These plants would accept the sewage sludge and utilize it for energy recovery.

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The three scenarios consider a total of 281 WWTPs larger than 2000 PE and take into account the costs and emissions from transport, but also the gate-fees for the three scenarios. The gate-fee for mono-incineration is assumed $100~\mathbb{e}/\mathbb{t}_{DM}$ [54] and those for co-incineration and landfilling 30 and $62~\mathbb{e}/\mathbb{t}_{DM}$ [55], respectively. The cost of transport is related to the size of the truck (up to 25 t of capacity) and distance between destinations (up to 600 km). Road transport with trucks is considered, whereas the emission levels are estimated from the Bilan Carbone model [56]. Table 9 presents the methodology for the three sludge treatment scenarios.

The three scenarios generate different amounts of CO_2 emissions during sewage sludge treatment and disposal. It was estimated that sewage sludge incineration in cement plants and in mono-incineration plants generates 488.7 kg $_{CO2eq}/t_{DM}$ while landfilling generates 10.8 kg $_{CO2eq}/t_{DM}$ [2].

Table 10 presents the costs and emissions for the three possible scenarios applied to the 281 WWTPs larger than 2000 PE in Croatia. The analysis shows that landfilling (BAU scenario) is the most cost-effective option for sewage sludge management. This is due to lower transport costs, mainly because 10 waste management centres are planned across Croatia, compared against three cement plants (TCP scenario) and four mono-incineration plants (TMP scenario). Moreover, it can also be noticed that the BAU scenario has the lowest emission, especially for smaller WWTPs (<10,000 PE).

However, in the case of larger WWTPs (>150,000 PE), the TCP scenario has the lowest costs while the TMP scenario has the lowest emissions. The lowest costs in the TCP scenario are explained by the low gate-fee for incineration in cement plants while the lowest emissions are explained by the fact that mono-incineration plants are planned near the four largest cities in Croatia, thus reducing sewage sludge emissions from transport. For one part of medium sized WWTPs (15,000–150,000 PE) the BAU scenario is still the one with the lowest costs and emissions. Landfilling of sewage sludge will be banned in all EU countries by 2025. Therefore, thermal treatment methods such as incineration in cement plants or in mono-incineration are emerging as alternative options for sewage sludge disposal, especially for cities generating large amounts of sewage sludge.

Scenario Factor	_ Mono-Incineration	Treatment in Cement Plants	Landfilling at Waste Management Centres	Unit
Sewage sludge treatment facilities	Zagreb, Split, Rijeka, Osijek	Koromačno, Kaštel Sućurac, Našice	Kaštijun, Marišćina, Babina Gora, Piškornica, Orlovnjak, Šagulje, Biljane Donje, Bikarac, Lučino, Zagreb	/
Transport costs	trip o	mber of trips per year	€/year	
Gate-fee	100	30 62		€/t _{DM}
Emissions	kilomet	n factor for specific truck	t _{CO2} /year	
Truck size (Bilan Carbone model)	Different truck capaciti	/		
Number of trips/year	The ar	/		

Table 9. Parameters of the sewage sludge treatment scenarios.

Table 10. Results of three scenarios (treatment in mono-incineration plants—TMP; treatment in cement plants—TCP; treatment in waste management centres—BAU).

WWTP Size (PE)		2000-10,000	10,000–15,000	15,000–150,000	>150,000	Total
WWTP number		190	28	59	4	281
Lowest costs	TMP	0	0	0	0	0
	CMP	67	10	32	4	113
	BAU	123	18	27	0	168
I	TMP	71	11	22	4	108
Lowest CO ₂ emissions	CMP	16	3	5	0	24
	BAU	103	14	32	0	149

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5. Conclusions

The optimal solution for sewage sludge management depends on the expected quantities and sludge properties, the capital investment, the operational challenges and costs, the ecological and technological constraints, the legal and location restrictions, as well as on the chosen type of application or disposal of by-products. The fastest growing methods for sewage sludge treatment and disposal are anaerobic digestion and incineration. Incineration of sewage sludge has become more interesting lately because it significantly reduces the sludge volume and mass, destroys the harmful substances, and can be coupled to energy recovery systems. Nutrient recovery from wastewater and sewage sludge is also becoming increasingly important. Nutrient recovery from sewage sludge ash is more difficult and feasible only for ash with high concentrations of nutrients.

In Croatia, plans indicate that WWTPS larger than 100,000 PE will use sludge stabilization by anaerobic digestion with biogas production, followed by thickening and dewatering. It was estimated that biogas will supply 30–40% of the electricity needs and 80–100% of thermal energy needs to WWTPs in Croatia. On the other side, final disposal of sewage sludge is yet to be resolved. At the moment, mono-incineration is seen as the most promising technology. Mono-incineration plants are planned in the four major cities of Croatia. Energy recovery from sewage sludge incineration can be feasible if solar drying is used instead of conventional drying techniques. The capacity of solar dryers is estimated between 450 and 750 kg $_{\rm DM}/{\rm m}^2{\rm year}$ in Croatia, while a final dry matter content of 75–80% can be achieved. In that case, biogas generation and energy recovery from sewage sludge could supply 60% of the electricity and 100% of the thermal energy necessary for the operation of WWTPs.

Sewage sludge is of organic origin and is considered emission-neutral, according to IPCC guidelines. Compared to conventional energy generation from fossil fuels, sewage sludge emits 58% less GHG emissions than CHP units on natural gas and 80% less emissions than hard coal power plants and fuel oil district heating systems. This is a significant contribution to climate change mitigation policy and testifies that sewage sludge is a valuable source of renewable energy. Moreover, an analysis of three scenarios (landfilling, incineration in cement plants, and incineration in mono-incineration plants) was performed and showed that business-as-usual (landfilling) is still the cheapest solution, especially for small WWTPs. It should be taken into account that landfilling of biodegradable waste will be prohibited in the EU. Co-incineration and mono-incineration become increasingly interesting for larger WWTPs.

Regarding nutrients' recovery (phosphorus, nitrogen and potassium), effective and feasible techniques are necessary, especially if mono-incineration is to become the principal method for the final disposal of wastewater sludge.

Author Contributions: D.Đ. conceived the research and wrote the paper; P.B. analysed the data and wrote the paper; and \check{Z} .J. validated the analysis, supervised the project and reviewed the paper.

Funding: This research received no external funding.

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

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