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Analysis of Sewage Sludge Disposal Routes – Varazdin and Medimurje County

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Abstract: The aim of this paper is to analyse sewage sludge production at the level of Medimurje and Varazdin counties with economic analysis of acceptable technical/technological solutions for sludge management routes. The topic is very broad, so the focus was placed on four variants of sludge disposal, which were determined by preliminary analysis to be the most applicable for the area in question. These are: 1) disposal of sewage sludge in agriculture, 2) incineration of sludge in a central mono-incinerator, 3) composting for the area of Varazdin County and at the same time use of sludge reed beds for the area of Medimurje County, and 4) export of sludge outside the state borders. Based on the analysis carried out for the described four variants, sludge incineration in a regional mono-incinerator turned out as the economically most advantageous solution, while the variant that includes disposal of sludge in agriculture has showed as the most expensive one. The last one also showed the largest range of costs uncertainties, but the mentioned facts are greatly influenced by unfavourable legislation, the changes of which in a more rational direction would greatly contribute to the greater competitiveness of this variant. Overall, taking into account the lowest cost and uncertainties in the predicted unit costs, the sludge composting in the Varazdin County and the construction of a reed beds for the Medimurje County, turned out to be the optimal variant. This solution is also the one that was ultimately adopted in practice.

Keywords: composting; incineration; reed beds; sewage sludge treatment and disposal; use in agriculture

1 INTRODUCTION

The wastewater collected by the public drainage system is taken to the wastewater treatment plant (WWTP) and after reaching the required level of treatment, it is discharged into the recipient. The by-product of every technological process of municipal WWT is sewage sludge, which requires further processing and disposal in the most economical way, while considering its technical and ecological suitability. On average globally, generated unit quantities of daily sludge production amount to 35 - 85 g DM/PE (dry matter / population equivalent) [1]. The available data for Croatia, based on operational WWTP, show, this value amounts to 50 - 55 g DM/PE daily [2].

The aim of this paper is to analyze the sludge production for Medimurje and Varazdin counties and give analysis of economically acceptable technical and technological solutions for sludge treatment and disposal routes.

All conventional sludge treatment methods ultimately generate stabilized and dehydrated sludge that also requires further disposal. Also, additional sludge processing procedures result in either a new form of sludge or a new by-product of its processing: dried sludge, sewage sludge ash, compost (or sludge like compost within reed beds) etc. So, all these processes generate sludge, ash or compost that ultimately needs to be disposed of somewhere or used in some other applications [4].

According to EUROSTAT data, even at the EU level there are no unified strategies or guidelines for sludge disposal. Use in agriculture is dominant method in Ireland, Portugal, UK, Denmark, Spain and Luxembourg, while in the Baltic countries, as well as Finland, Slovakia, Hungary and Czech Republic, the use of sludge on non-agricultural lands prevails. On the other hand, in some of the most developed countries such as the Netherlands, Switzerland, Germany, Belgium and Austria, thermal treatment of sludge, primarily incineration, is the predominant method of its disposal. Although limited and for the most part even prohibited by EU regulations, disposal of sludge in landfills is still the predominant method of disposal of sludge in Italy, Greece, Romania, but unfortunately also in Croatia [5].

According to Tarpani et al. [6] over 70% of generated sludge in Europe is treated thermally (incineration) or used as a fertilizer in agriculture. The best solution is to include the waste produced from wastewater treatment into the cycle of matter and energy, preferably as it happens in nature, but also in any other sustainable way. This is also the basis of Council Directive 91/271/EEC [7] which states: "Sludge from wastewater treatment will be reused whenever possible."

Since there are many acceptable methods of sludge treatment (thickening, stabilization, dehydration, thermal hydrolysis, drying, solidification, mono-incineration, pyrolysis, gasification, composting, grounding, etc.), combined with many acceptable methods of its final disposal and/or use (landfilling treated sludge, use of sludge in agriculture or on non-agricultural land, disposal of ash in specially arranged landfills for non-hazardous waste, use of sludge (ash) in construction, different types of co-incineration of sludge (e.g. with municipal solid waste or in cement kilns), export of dehydrated or dried sludge or sewage sludge ash outside the country in which it originated), the resulting number of different solutions for complete sludge management is even higher, which further complicates the process of finding the optimal solution. To select the optimal solution (or combination of solutions), it is usually necessary to apply a multi-criteria decision methodology, which involves defining the criterion structure and evaluating the variants according to the adopted criteria [8]. In the continuation of this paper, a technical-economic analysis of the selection of the optimal variant of sludge disposal for area of northern Croatia will be presented. Nevertheless, it is noted that within the framework of conducting a comprehensive analysis, as part of future steps, it is necessary to conduct an analysis of environmental and sociological impacts, which would complete the whole in terms of the basic requirements of sustainable development.

The relevant input data for determining sewage sludge production was the projected capacity of the agglomerations (WWTPs) in the Medimurje and Varazdin counties defined as part of the Water Area Management Plan 2016-2021 [3] and corrected according to data obtained from the responsible utility companies Medimurske vode d.o.o. and Varkom d.o.o.

The analysis covers 7 agglomerations of more than 2,000 population equivalent (PE) in Medimurje County and 11 agglomerations in Varazdin County, as shown in Fig. 1.

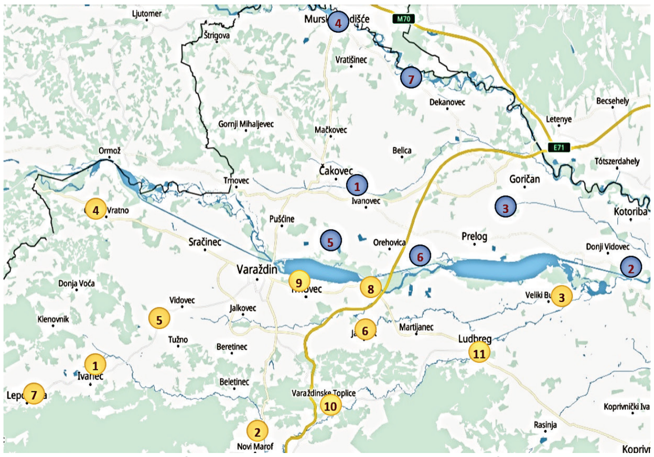

Figure 1 Considered agglomerations in Varazdin County (yellow marks: 1 - Ivanec, 2 - Novi Marof, 3 - Veliki Bukovec, 4 - Cestica, 5 - Greda, 6 - Jalzabet, 7 - Lepoglava, 8 - Semovec, 9 - Varazdin, 10 - Varazdinske Toplice, 11 - Ludbreg) and Medimurje County (blue marks: 1 - Cakovec, 2 - Donja Dubrava, 3 - Donji Kraljevec, 4 - Mursko Sredisce, 5 - Novo Selo na Dravi, 6 - Podbrest, 7 - Podturen) [3]

2 COST ANALYSIS

For the considered WWTPs, the amounts of generated sewage sludge were calculated, as well as the production of dehydrated sludge with 23 and 33% DM and the amount of generated dry sludge in the case of solar drying up to 75% DM (Tab. 1). Ash production (t/year) was also calculated in the case that the entire sludge is incinerated in a central mono-incinerator presumably located next to WWTP Varazdin, as by far the largest one within analyzed area. The starting point for determining sludge production was the predicted capacity of built and planned WWTPs. The capacities of the WWTPs considered were taken over as the planned capacities of the planned agglomerations from the Water Area Management Plan 2016-2021 year, corrected according to data obtained from the responsible utility companies Medimurske vode d.o.o. and Varkom d.o.o. Data on the unit costs of solar drying, transportation of dehydrated and dried sludge, sampling and analysis of sludge, transaction costs and premiums to farmers for disposal in agriculture, data on the costs of composting and reed beds, unit costs of sludge incineration in mono-incinerators and ash disposal, as well as the costs of sewage sludge export outside the country, were taken from the Action Plan for Sewage Sludge Disposal [9] and Vouk et. al. (2017) [10] and corrected to a certain extent considering the current situation and price movements on the market.

In the particular case, already by carrying out preliminary analyses, the most cost-effective solution was to build plants for sewage sludge solar drying in two locations, the largest WWTPs for each county. The location of WWTP Cakovec was chosen as the location of the central plant for solar drying of sludge in Medimurje County, and the location of WWTP Varazdin as the location of the central plant for solar drying of sludge in Varazdin County, considering that such an approach results in a lower unit price of total sludge treatment (solar drying including transportation costs). The calculated costs of sludge solar drying include the cost of building, operation, maintenance and depreciation of solar sludge drying plants and the cost of road transport of dehydrated sludge from individual WWTPs to the regional center in Cakovec or Varazdin, as shown in Tab. 2.

Table 1 Calculation of the generated quantities of dehydrated and solar-dried sludge and the amount of ash in the case of sludge incineration

WWTP	PE	Sludge production	Quantities of dried (dewatered) sludge			Ash production
			75 % DM	33 % DM	22% DM	
		t DM/year	t/year			t/year
Cakovec	84,123	1,647	2,196	4,990	7,485	815
Donja Dubrava	13,000	254	339	771	1,157	126
Donji Kraljevec	9,000	176	235	534	801	87
Mursko Sredisce	12,000	235	131	712	1,068	116
Novo Selo na Dravi	5,000	98	130	297	445	48
Podbrest	10,000	196	261	593	890	97
Podturen	17,600	345	459	1,044	1,566	170
Ivanec	11,806	231	308	700	1,050	114
Novi Marof	7,464	146	195	443	664	72
Veliki Bukovec	2,588	51	68	154	230	25
Cestica	4,111	80	107	244	366	40
Greda	5,162	101	135	306	459	50
Jalzabet	3,138	61	82	186	279	30
Lepoglava	6,894	135	180	409	613	67
Semovec	2,254	44	59	134	201	22
Varazdin	129,933	2,543	3,391	7,707	11,561	1,258
Varazdinske Toplice	5,423	106	142	322	483	53
Ludbreg	8,260	162	216	490	735	80
TOTAL:	337,756	6,611	8,815	20,034	30,052	3,271

Table 2 The cost of construction and maintenance of a plant for solar drying of sewage sludge with included road transportation costs

WWTP	Cost of construction, operation and maintenance for solar drying		Regional center (RC)	Distance from the RC	The cost of road transport of dried sludge to the RC		Total cost
	€/tDM	€/year		km	€/t·km	€/year	€/year
Cakovec	50	82,333	Cakovec	0.2	0.65	973	83,306
Donja Dubrava	50	12,723		33	0.52	19,848	32,572
Donji Kraljevec	50	8,808		19	0.62	9,395	18,204
Mursko Sredisce	50	11,745		20	0.62	13,186	24,931
Novo Selo na Dravi	50	4,894		11	0.65	3,181	8,074
Podbrest	50	9,787		11	0.65	6,362	16,149
Podturen	50	17,225		18	0.62	17,406	34,631
Ivanec	45	10,399	Varazdin	30	0.55	17,411	27,810
Novi Marof	45	6,575		22	0.59	8,547	15,122
Veliki Bukovec	45	2,280		30	0.55	3,817	6,096
Cestica	45	3,621		25	0.59	5,349	8,971
Greda	45	4,547		20	0.62	5,672	10,219
Jalzabet	45	2,764		12	0.65	2,178	4,942
Lepoglava	45	6,073		40	0.49	11,961	18,034
Semovec	45	1,985		8	0.65	1,043	3,028
Varaždin	45	114,451		0.2	0.65	1,503	115,954
Varazdinske Toplice	45	4,777		16	0.62	4,767	9,544
Ludbreg	45	7,276		22	0.59	9,459	16,734
TOTAL:		312,263				142,057	454,321

The variant that includes composting of sludge in the Varazdin County and reed beds in the Medimurje County involves the construction of a composting plant in Varazdin and the transportation of sewage sludge from smaller WWTPs in the Varazdin County to the central composting plant and the construction of reed beds in Cakovec and the transportation of sludge from smaller WWTPs in the Medimurje County on the reed beds located by the Cakovec WWTP. The total cost includes the construction, operation, maintenance and depreciation of the composting plant in Varazdin and the cost of road transportation of dried sludge from smaller WWTPs to the composting plant, as well as the cost of reed beds construction, emptying and sludge removal, sampling and the cost of road transportation of sludge from smaller WWTPs to the reed beds (Tab. 3).

In practice, the solution with the construction of reed beds in Cakovec and a composting plant in Varazdin was adopted. This includes collecting of sludge from smaller WWTPs in the area of Medimurje and Varazdin County, on two biggest central WWTPs, but it does not exclude the possibility that some of the smaller WWTPs will adopt a separate solution for sludge disposal. Sludge that is brought from smaller WWTPs to the reed beds in Cakovec is previously thickened and stabilized and contains around 3% DM in order to ensure a good distribution of liquid (non-dehydrated) sludge over the entire surface of the reed beds.

Table 3 Total cost of sewage sludge composting in the area of Varazdin County and reed beds in the area of Medimurje County

WWTP	Distance from the composting plant (CP)	The cost of road transport of dried sludge to the CP		Cost of composting*		Total cost
	km	€/t·km	€/year	€/tDM	€/year	€/year
Ivanec	30	0.55	17,411	115	26,576	43,987
Novi Marof	22	0.59	8,547	115	16,802	25,349
Veliki Bukovec	30	0.55	3,817	115	5,826	9,642
Cestica	25	0.59	5,349	115	9,254	14,604
Greda	20	0.62	5,672	115	11,620	17,292
Jalzabet	12	0.65	2,178	115	7,064	9,242
Lepoglava	40	0.49	11,961	115	15,519	27,480
Semovec	8	0.65	1,043	115	5,074	6,117
Varazdin	0	0.65	1,503	115	292,486	293,989
Varazdinske Toplice	16	0.62	4,767	115	12,207	16,975
Ludbreg	22	0.59	9,459	115	18,594	28,052
		TOTAL 1:	71,707		421,022	492,728
WWTP	Distance from the reed beds (RB)	The cost of road transport of fresh sludge to the RB		Cost of reed beds**		Total cost
	km	€/t·km	€/year	€/tDM	€/year	€/year
Cakovec	0,2	0,65	7,136	90	148,199	155,335
Donja Dubrava	33	0,52	145,555	90	22,902	168,457
Donji Kraljevec	19	0,62	68,897	90	15,855	84,752
Mursko Sredisce	20	0,62	96,698	90	21,140	117,838
Novo Selo na Dravi	11	0,65	23,326	90	8,808	32,135
Podbrest	11	0,65	46,652	90	17,617	64,269
Podturen	18	0,62	127,641	90	31,006	158,647
		TOTAL 2:	515,905		265,528	781,433
					TOTAL (1+2):	1,274,161

*Including construction, operation, maintenance and depreciation

**Including reed beds construction, emptying, sludge removal, sampling costs

Table 4 Total cost of sludge disposal in agriculture

WWTP	Cost of transportation of dried sludge		Cost of sampling and analysis		Transaction costs	Premium for farmers	Total cost
	€/t	€/year	€/tDM	€/year	€/t	€/t	€/year
Cakovec	13	97,302	90	148,199	5	10	357,774
Donja Dubrava	13	15,037	90	22,902	5	10	55,289
Donji Kraljevec	13	10,410	90	15,855	5	10	38,277
Mursko Sredisce	13	13,880	90	21,140	5	10	51,036
Novo Selo na Dravi	13	5,783	90	8,808	5	10	21,265
Podbrest	13	11,567	90	17,617	5	10	42,530
Podturen	13	20,357	90	31,006	5	10	74,853
Ivanec	13	13,656	90	20,799	5	10	50,211
Novi Marof	13	8,633	90	13,149	5	10	31,744
Veliki Bukovec	13	2,993	90	4,559	5	10	11,007
Cestica	13	4,755	90	7,242	5	10	17,484
Greda	13	5,971	90	9,094	5	10	21,954
Jalzabet	13	3,630	90	5,528	5	10	13,346
Lepoglava	13	7,974	90	12,145	5	10	29,320
Semovec	13	2,607	90	3,971	5	10	9,586
Varazdin	13	150,290	90	228,902	5	10	552,603
Varazdinske Toplice	13	6,273	90	9,554	5	10	23,064
Ludbreg	13	9,554	90	14,552	5	10	35,130
TOTAL:		390,672		595,023			1,436,471

The variant with disposal of sludge in agriculture includes the cost of transporting dried sludge to agricultural areas without any restrictions, located within a radius of up to 50 km from any of the considered WWTP assumed following unit costs: the cost of 13 €/t for transportation within a radius of 10-50 km, the cost of sampling and analysis (for this analysis was assumed to be 90 €/t of dried sludge), transaction costs (5 €/t of dried sludge) and premium for farmers which take over sludge (10 €/t of dried sludge), This is shown in detail in Tab. 4.

The variant with sludge incineration in a mono-incinerator includes the construction of a mono-incinerator within the WWTP Varazdin perimeter and the collection of dried sewage sludge from two central plants for sludge solar drying: in Cakovec and Varazdin. The central plant for solar drying in Cakovec is 21 km distant from the location of the mono-incineration plant, while the plant for solar drying in Varazdin is within the WWTP perimeter and in the immediate vicinity of the incinerator. The cost of incineration in a mono-incinerator includes the cost of solar drying, the cost of transporting sludge from central plants for sludge solar drying to the mono-incinerator, the cost of construction, operation, maintenance and depreciation of the mono-incinerator (with assumed incineration unit price at €65/t DM) and the cost of ash disposal (Tab. 5). It was assumed that the ash will be disposed of at an organized non-hazardous waste disposal site, close to the incinerator.

Table 5 Total cost of sludge incineration and ash disposal

WWTP	The cost of solar drying	The cost of sludge transportation to the incinerator	Mass of sludge incinerated	Cost of incineration*	Ash production	Cost of ash disposal**	Total cost
	€/year	€/year	tDM/year	€/year	t/year	€/year	€/year
Cakovec Donja Dubrava Donji Kraljevec Mursko Sredisce Novo Selo na Dravi Podbrest Podturen	217,866	164,748	2,950	191,770	1,460	58,381	632,765
Ivanec Novi Marof Veliki Bukovec Cestica Greda Jalzabet Lepoglava Semovec Varazdin Varazdinske Toplice Ludbreg	236,454	2,163	3,661	237,969	1,811	72,445	549,032
TOTAL:	454,321	166,911	6,611	429,739	3,271	130,826	1,181,797

*Cost of incineration (including construction, operation, maintenance and depreciation) = 65 €/tDM

**Cost of ash disposal = 40 €/t

Table 6 The total cost of export and disposal of sludge outside the state

WWTP	The cost of solar drying	Payment to a legal entity*	Total cost of export of dried sludge with 75% DM	Total cost of export of dewatered sludge with 33% DM	Total cost of export of dewatered sludge with 22% DM
	€/year	€/t	€/year	€/year	€/year
Cakovec	83,306	105	313,838	523,936	785,905
Donja Dubrava	32,572	105	68,197	80,967	121,450
Donji Kraljevec	18,204	105	42,867	56,054	84,081
Mursko Sredisce	24,931	105	57,816	74,739	112,108
Novo Selo na Dravi	8,074	105	21,777	31,141	46,712
Podbrest	16,149	105	43,553	62,282	93,423
Podturen	34,631	105	82,862	109,617	164,425
Ivanec	27,810	105	60,164	73,530	110,296
Novi Marof	15,122	105	35,576	46,487	69,731
Veliki Bukovec	6,096	105	13,188	16,119	24,178
Cestica	8,971	105	20,236	25,604	38,406
Greda	10,219	105	24,365	32,150	48,225
Jalzabet	4,942	105	13,541	19,544	29,316
Lepoglava	18,034	105	36,926	42,937	64,406
Semovec	3,028	105	9,205	14,038	21,058
Varazdin	115,954	105	472,025	809,251	1,213,877
Varazdinske Toplice	9,544	105	24,405	33,776	50,663
Ludbreg	16,734	105	39,370	51,445	77,168
TOTAL:	312,263		1,379,913	2,103,618	3,155,427

* that transports and disposes of sludge outside the state

The solution that envisaged sewage sludge export outside the state assumes that a certain legal entity (company) will take over dried sludge (with around 75% DM) from the planned two locations of the sludge solar sludge plants and transport it over the border to Hungary where it will be disposed. In this variant, the cost of sludge solar drying and the cost of payment to a legal entity, which includes the cost of transportation and disposal of sludge outside the state, are included in total costs (Tab. 6). Given that the transportation represents the most significant component of the final price, solutions with the export of dehydrated sludge that excludes sludge solar drying (sludge with 22% and 33% DM) are not economically acceptable, since significantly larger total quantities of sludge would require transportation over significant distances. This would not only inevitably result in unreasonably high costs but would also have a negative impact on the environment (increased emissions from transport, etc.), ultimately resulting in the reduced overall sustainability of such a solution. It is noted here that the final method of disposal in the country to which the sludge is exported (in this case Hungary) is left to the choice of the legal entity (company) that took over the sludge and charged an adequate fee included in the presented analysis (assumed with the amount of 105 €/t as shown in Tab. 6). However, given that in this particular case receiving country is Hungary and taking into account the currently prevailing method of sludge disposal, it is to be expected that this sludge, in a certain way, would ultimately be disposed of in agriculture.

Based on the analyzes carried out for the described four variants (Fig. 2) in the area of Medimurje and Varazdin County, it is evident that sludge incineration in a regional mono-incinerator represents economically the most advantageous solution with the total cost estimated of €1.18 million/year. In the second place, slightly more expensive, is the variant with reed beds in the area of Medimurje County and composting of sludge in the area of Varazdin County, 7.81% more expensive than the variant with sludge incineration. Although the variant with disposal of sludge in agriculture turns out to be economically the most unfavorable (47.97% more expensive than the variant with incineration), with the adoption of more rational legislation, i.e. by reducing the costs of sampling and analysis of sludge and soil, its better economic profitability could be expected. Export of sludge outside Croatia, although a more cost-effective variant than the use of processed sludge on the agricultural land (16.76% more expensive than the variant with sludge incineration), does not represent an acceptable solution. It is justified to use it only as a temporary solution until the establishment of an appropriate sludge management system in the region in question. Considering that all the presented results and rankings of individual variants are based on the assumed unit prices of individual processes, a kind of sensitivity analysis was carried out bellow.

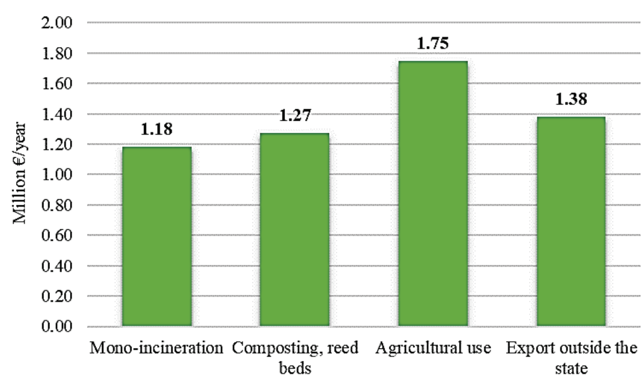

Figure 2 Total costs of sludge disposal according to the variants considered in Medimurje and Varazdin counties

3 RISK ANALYSIS

Given that costs in sludge disposal analysis are variable, and of stochastic character, it is necessary to carry out additional risk analysis that determines dependence of the final results on changes in assumed unit prices. Hereby, the ranges of possible total costs for each of analysed variants of sludge disposal were defined (Tab. 7).

Below are the results of the economic risk analysis, giving an indication of the possible ranges of total costs of the considered scenarios relation to the assumed fixed and variable inputs (unit costs). In the concrete example, the unit costs of the following parameters were varied: sludge solar drying total cost, the cost of sampling and analysis of sludge and soil (when it is used in agriculture), premium for farmers cost, total incineration costs, ash disposal costs, total cost of sludge export outside the country, total costs of reed beds and total composting costs were selected as stochastic parameters.

Table 7 Ranges of unit prices of assumed variable input parameters

Parameter	Minimum value	The most probable (expected) value	Maximum value
The cost of solar drying	40/45 €/t DS*	45/50 €/t DS*	50/55 €/t DS*
Sampling and analysis of sludge and soil when sludge is used in agriculture cost	50 €/t DS	90 €/t DS	110 €/t DS
Premium for farmers	0 €/t	10 €/t	15 €/t
Transportation of dried sludge costs (when used in agriculture)	10 €/t	13 €/t	20 €/t
Incineration cost	60 €/t DS	65 €/t DS	130 €/t DS
Ash disposal cost	30 €/t	40 €/t	50 €/t
Sludge export and disposal outside the country – total cost	85 €/t	105 €/t	125 €/t
Reed beds cost	85 €/t DS	90 €/t DS	105 €/t DS
Composting cost	100 €/t DS	115 €/t DS	125 €/t DS

* The cost of construction, operation and maintenance of a plant for solar drying of sludge - estimated regarding the capacity of the plant next to WWTP Varazdin (lower unit value) and WWTP Cakovec (higher unit value)

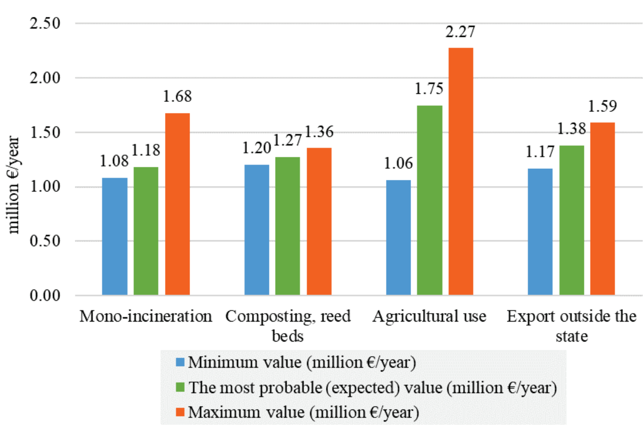

Figure 3 Total costs of sludge disposal according to the variants considered in Medimurje and Varazdin counties

Tab. 7 shows the analyzed ranges of variable parameters considered through risk analysis. In the same way, it is possible to include other and additional parameters through risk analysis, e.g. the composition of the sludge generated, the capacities of selected WWTP, etc. The following values are defined for all the selected stochastic inputs: minimum, maximum and most likely value. Specific values were determined on the basis of collected literature data and actual data characteristic of the analyzed geographical area. Fig. 3 shows the expected (possible) ranges of total costs for each of the four analyzed variants of sludge disposal.

Figure 4 Constructed reed beds within WWTP Cakovec

Figure 5 Constructed composting plant within WWTP Varazdin

Regarding the presented results of the performed risk analysis, the alternative where sludge is being composted in Varazdin County and sludge reed beds are used in Cakovec County proved to be the most acceptable. This solution is also the one that was ultimately adopted in practice (Fig. 4 and Fig. 5). At the same time solution with agricultural use of sludge shows the largest range of possible expected costs, and thus risks. However, with the reduction of specific sampling and analysis costs when sludge is used in agriculture, a significant improvement in the profitability of this solution is to be expected. Incineration of sludge in central mono-incinerator located by the WWTP Varazdin, although the most favourable if only the most probable (expected) value is observed, shows somewhat larger deviations in the positive direction (possible increase of the total cost), which is why this variant is ultimately ranked behind the selected solution with composting and sludge reed beds.

However, it is necessary to emphasize that all analyses and evaluation of individual options refer exclusively to economic criteria. In reality, it is necessary to include other criteria, primarily environmental impacts, which in such cases are most often quantified using life cycle analysis (LCA) and models based on them [10]. With the eventual inclusion of additional criteria, such as sociological ones, the analysis can be extended by carrying out a multi-criteria analysis. Also, the sensitivity analysis can be expanded to additional parameters by varying the expected amount of sludge generated at each WWTP or its basic characteristics (such as moisture content) etc.

4 CONCLUSION

Different sewage sludge disposal routes in the area of northern Croatia (Varazdin and Medimurje County) were analysed regarding technical and financial considerations. Four variants (solutions of sludge disposal) were considered: sludge incineration in central mono-incinerator, use of sewage sludge in agriculture, combination of reed beds and composting in two regional centres and export of the sludge outside the state.

The total capacity of all WWTPs (agglomerations) considered is 337.756 PE, i.e. 150.723 PE in the area of Medimurje County and 187.033 PE in the area of Varazdin County. Results show that the economically most favourable is to build 2 plants for sludge solar drying: by the WWTP Cakovec - central plant for Medimurje County, and by the WWTP Varazdin - central plant Varazdin County. Based on the analysis carried out, it is evident that sludge incineration in a regional mono-incinerator represents the economically most advantageous solution, at the total cost of €1.18 million/year. In second place is the variant with reed beds in the area of Medimurje County and composting of sludge in the area of Varazdin County, 7.81% more expensive than the variant with sludge incineration.

Even though the variant with sludge disposal in agriculture turned out to be the most economically unfavourable (as much as 47.97% more expensive than the variant with incineration), with the adoption of more rational legislation, i.e. by lowering the costs of sampling and analysis of sludge and soil, better economic profitability can be expected. Export of sludge outside of Croatia, does not represent an acceptable solution, and could be justified only as a temporary solution until the establishment of an appropriate sewage sludge management system in the region. Based on the results of the economic risk analysis, a solution with combination of reed beds in Medimurje County and composting in Varazdin County turned out to be the most favourable regarding reliability of the analysis made and the obtained estimates of the total costs. Also, this is the solution that for the most part corresponds to the solution adopted in practice.

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5 REFERENCES

[1] Jamshidi, A., Mehrdadi, N., & Jamshidi, M. (2011). Application of sewage dry sludge as fine aggregate in concrete. *J. Environ. Stud., 37*(59).
[2] Vouk, D., Serdar, M., Nakic, D., & Anic-Vucinic, A. (2016). Use of sludge generated at WWTP in the production of cement mortar and concrete. *Civil Engineer., 68*(3), 199-210.
[3] Hrvatske vode, Plan upravljanja vodnim područjima 2016.-2021. NN 66/16. (in Croatian)
[4] Fytili, D. & Zabaniotou, A. (2008) Utilization of sewage sludge in EU application of old and new methods – A review. *Renew. Sust. Energ. Rev., 12*(1), 116-140. https://doi.org/10.1016/j.rser.2006.05.014
[5] Eurostat. (2022) Sewage sludge production and disposal. https://ec.europa.eu/eurostat/databrowser/view/ENV_WW_SPD__custom_863447/bookmark/table?lang=en&bookmarkId=5758a478-af17-400c-9e31-2c73b4cc6903 (Accessed 17 January 2023). (in Croatian)
[6] Tarpani R.R.Z., Alfonsin C., Hospido A., Azapagic A, (2020), Life cycle environmental impacts of sewage sludge treatment methods for resource recovery considering ecotoxicity of heavy metals and pharmaceutical and personal care products. *Journal of Environmental Management*, 260, 109643, https://doi.org/10.1016/j.jenvman.2019.109643
[7] EC Directive, (1991), Council Directive 91/271/EEC of 21 May 1991 concerning urban waste-water treatment, NoL135/40, *Official Journal of the European Communities*, 30.5.91. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A31991L0271. (Accessed 17 January 2023).
[8] Vouk, D., Nakic, D., Bubalo, A., & Bolanca, T. (2022) Environmental aspects in selecting optimum variant of sewage sludge management. *Environm. Eng. and Manag. J., 21*(3), 443-456. https://doi.org/10.30638/eemj.2022.042
[9] Akcijski plan za korištenje mulja iz uređaja za pročišćavanje otpadnih voda na pogodnim površinama, HIDROPROJEKT-ING Zagreb, Hidroing Osijek, Građevinski fakultet Sveučilišta u Zagrebu, Institut IGH, 2020. (in Croatian)
[10] Vouk, D., Nakic, D., & Anic-Vucinic, A. (2017) Possibilities of sewage sludge disposal - Split-Dalmatia County. *Hrvatska vodoprivreda, 219*(2), 12-15.

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