water

Article

Supplementary materials for "Integrating life-cycle perspectives and spatial dimensions of sewage sludge mono-incineration"

David Wagner [1], Georg Neugebauer [1,*], Florian Kretschmer [2] and Gernot Stoeglehner [1]

[1] Institute of Spatial Planning, Environmental Planning and Land Rearrangement, University of Natural Resources and Life Sciences, Peter Jordan-Strasse 82, 1190 Vienna, Austria
[2] Institute of Sanitary Engineering and Water Pollution Control, University of Natural Resources and Life Sciences, Muthgasse 18, 1190 Vienna, Austria
* Correspondence: georg.neugebauer@boku.ac.at

Received: date; Accepted: date; Published: date

Abstract: Here, all supplementary materials concerning the article "Integrating life-cycle perspectives and spatial dimensions of sewage sludge mono-incineration" are listed. Information are given with regard to (1) the detailed description of indicators and applied value scores of the MCA, (2) additional results of the MCA and (3) and overview on invested WWTPs.

Keywords: Integrated spatial and energy planning; sludge to energy; Phosphorous recovery; energy recovery; waste water treatment; circular economy; secondary resources recovery

---

1. Detailed descriptions of indicators and applied value scores - MCA

1.1. Category - Energy (En1, En2)

En1 Reduced consumption of nonrenewable energy sources

This indicator shows whether the produced thermal energy by mono-incineration can be used or not. Even a positive energy balance, so a thermal energy production, is worthless if there are no thermal energy consumers in the direct surrounding of the mono-incinerator. The indicator En1 contributes to the amount of thermal energy produced that can be consumed within the direct surrounding of the mono-incinerator. The availability of energy consumers defines the rating. If there is a heat demand by 100 % of the produced thermal energy, the indicator is accounted in a positive rating, y = 1. A thermal energy production without energy consumers relates to a negative rating y = 0. The Austrian Federal Ministry for Science and Economics provides data about the Austrian heat demand. Raster data and CSV-data are provided by the project "Austrian heat map" [1]. The GIS-raster data used for calculation (En1) is the dataset "Energy density 2025 / Wärmebedarfsdichte 2025 (BAU-Scenario)". It is a business as usual (BAU) Scenario that assumes that the energy policy framework and the plan of measures implemented in 2014, remain the same, without strengthening or weakening of measures [2, p. 11]. Moreover, the CSV-dataset "Fernwärmenetze (17.01.2018)" ("district heating systems") are used to distinguish the distance between mono-incineration facilities and existing district heat systems. Therefore XY-coordinates from the 41 WWTPs are compared with the information about existing district heat systems [3]. The software ArcMap was used to analyze available data about the Austrian heat demand. Tools used to calculate the heat consumption potential was the "Buffer" function to create an individual radius around each location of WWTP. The tool "Zonal statistics as table" was used to calculate the content of the intersection of raster cells (heat demand) within the individual radius (buffer). Finally, the tools "Distance to nearest hub" was used to define the distance between each WWTP and the closest surrounding district heating system.

The operational hours are assumed at the highest possible level of 8760 h per year. Scenarios that comprise a 100 % potential that the produced thermal energy can be consumed by thermal energy consumers, are rated with y=1. Scenarios with no potential to supply the demand of surrounding thermal energy consumers receive a low score, y=0. The rating scheme for the value score is shown in Table S1.

Table S1. Value scores for the energy utilization potential (En1).

Indicator	low score (y=0)	average score (y=0,5)	high score (y=1)
Energy utilization potential	0 % potential consumption of produced thermal energy	50 % potential consumption of produced thermal energy	100 % potential consumption of produced thermal energy

En2 Increase in consumption of nonrenewable energy resources

This indicator accounts whether there is an additional external heat demand to dry the sludge. There can only be an additional external heat demand to dry sludge in case that the sludge is dried at another location than the sludge is mono-incinerated. If mono-incinerator and drying device is situated at the same location there is no additional heat demand because the incineration heat can be utilized to dry the sludge. This interplay is to use the heat from the mono-incineration to dry the sludge, and forms a great advantage to reduce additional energy demand. Therefore, the scenario with the biggest additional heat demand is accounted with a low score, y=0. In case of no additional heat demand a high score, y=1 is accounted. The rating scheme results from the highest value that occurred and the lowest possible value.

Table S2. Value scores for the additional thermal energy demand for sludge drying (En2).

Indicator	Low score (y=0)	Average score (y=0,5)	High score (y=1)
Additional thermal energy demand for sludge drying	>278 GWh/a	139 GWh/a	0 GWh/a

1.2. Category - Ecology (Eco1, Eco2)

Eco1 Distance

This indicator accounts the amount of CO_2 emissions [t CO_2 e] caused by the transportation of sewage sludge with a lorry. In principle a higher negative environmental impact is caused by growing transport distance [km/a]. The ecological impact is accounted in t CO_2 equivalents per year. A scenario without emissions receives a high score, y = 1. The scenario with the highest amount of CO_2 emissions receives a low score, y=0.

Table S3. Value scores for the CO2 emissions (Eco1).

Indicator	Low score (y=0)	Average score (y=0,5)	High score (y=1)
Transport emissions	> 2.000 t CO_2e/a	1000 t CO_2e/a	0 t CO_2e/a

Eco2 Incineration

This indicator accounts the CO_2-emissions that are saved because sewage sludge (renewable resource) is utilized for energy production instead of fossil fuels. The amount of heat produced by mono-incineration that can be consumed, substitutes CO_2 emissions from fossil fuels. In principle a higher positive environmental impact is caused by growing substitution of fossil fuels for energy production [t CO_2e/a]. The ecological impact is accounted in saved t CO_2 equivalents per year. A scenario with a high level thermal energy consumption receives a high score, y = 1. The scenario without thermal energy consumption receives a low score, y=0.

Table S4. Value scores for the substituted CO_2 emissions from fossil fuels (Eco2).

Indicator	Low score (y=0)	Average score (y=0,5)	High score (y=1)
Substituted CO_2 emissions from fossil fuels	0 t CO_2e/a	58.000 t CO_2e/a	>116.000 t CO_2e/a

Eco3 Incineration

This indicator was planned to be used but is finally not part of the MCA. The reasons for that decision are explained as follows. Not only the sludge transport but also the process of mono-incineration itself produces CO_2 emissions. Nowadays, most of produced toxic gases are filtered by flue gas purification. Nevertheless, there is emissions that could be accounted. However, those emissions accounted from the incineration process itself do not serve to evaluate different spatial scenarios. It makes no difference if the yearly sludge amount is incinerated at several decentral or only few central mono-incinerators. The emissions are the same in any case, they are only produced at varying locations in Austria. Meaning that the sludge amount is constant and there is no difference in produced emissions from the mono-incineration process in regard to different spatial scenarios. In case that the incineration emissions would be included into the MCA, each spatial scenario would receive the same score. This results in lower weighting power of the remaining evaluation criteria without including relevant new information. Consequently, it is not feasible to include the emissions by the mono-incineration process into the MCA. Only the transport emissions that show crucial differences in regard to each spatial scenario are accounted.

1.3. Category - Cost (Co1, Co2, Co3)

Co1 Economic risk

This indicator accounts the range of investment costs. In principle, investment costs constitute an economic risk and it is assumed that decision makers try to prevent risks as far as possible. The investments for mono-incinerators change according to the size of the incinerator. The size is aligned to the yearly sludge load that is planned to be mono-incinerated. An overview to the assumptions for investment cost in accordance to the capacity of the incineration facility are shown in Table S5.

Table S5. Overview to the investment cost of a mono incineration infrastructure in relation to size classes.

Capacity [1000 * t DS/a]	Investment Cost [million €]	Category [number]	Reference	Characteristics of incineration technology
0-2	0,6-1,1	1	[4]	No complete mono-incineration (Carbonization)
2-5	7	2	[5]	Complete mono-incineration (fluidized bed)
5-8	12	3		
8-11	15	4		
11-14	18	5		
14-17	22	6		
17-20	24	7		
20-23	26	8		
23-26	28	9		
26-29	31	10		
29-32	34	11		
32-35	35	12		
35-38	37	13		
>38	40	14		

Values for investment cost concerning the standard mono-incineration technology (fluidized bed), category 2-14, change between 7-40 Mill €. Investment cost for smaller yearly sludge loads, category 1, range between 0,6-1,1 Mill € (Gittler, 2019). Stakeholders (e.g. municipalities, waste water associations, plant operators) try to minimize risks. Therefore, the scenarios with the highest overall investment cost is accounted as y = 0 and no overall investment is accounted as y = 1. The rating scheme for the value score is shown in Table S6. The rating scheme results from the highest value that occurred and the lowest possible value.

Table S6. Value scores for the investment cost (Co1).

Indicator	Low score (y=0)	Average score (y=0,5)	High score (y=1)
Investment cost	410 Mill €	205 Mill €	0 €

Co2 Economic risk

This indicator accounts the range of specific costs for sludge disposal via mono-incinerator. In principle, specific costs constitute an economic risk. If specific costs are too high, the sludge disposal is more and more difficult. Hence, it is assumed that decision makers try to prevent risks as far as possible. The specific costs for mono-incinerators change according to the size of the mono-incineration facility. The size is aligned to the yearly sludge load that is planned to be mono-incinerated. Values for specific costs concerning the standard mono-incineration technology (fluidized bed) range from 160 €/t for big size incinerators (35.000 t DS/a) to 510 €/t for small size incinerators (2.000 t DS/a) according to [6]. Stakeholders (e. g. municipalities, waste water associations, plant operators) try to minimize risks. Therefore, the scenarios with the highest specific costs is accounted as y = 0 and the lowest specific costs is accounted as y = 1. The rating scheme for the value score is shown in Table S7.

Table S7. Value scores for the specific costs (Co2).

Indicator	Low score (y=0)	Average score (y=0,5)	High score (y=1)
Specific cost	510 €/t DS	334 €/t DS	160 €/t DS

Co3 Economic risk

This indicator measures the transport cost for varying spatial solutions and accounts the range of sludge transport costs from the supplier WWTPs to the mono-incinerators. In principle, transport costs constitute an economic risk. With rising transport costs it is more and more difficult to build up an economically efficient process chain. Hence, it is assumed that decision makers try to prevent this risk as far as possible. Each scenario shows varying transport cost. Therefore, the transport effort can be compared for each scenario. Stakeholders (e.g. municipalities, waste water associations, plant operators) try to minimize risks. Therefore, the scenarios with the highest overall transport cost is accounted as y = 0 and no transport costs is accounted as y = 1. The rating scheme for the value score is shown in Table S8. The rating scheme results from the highest value that occurred and the lowest possible value.

Table S8. Value scores for transport costs (Co3).

Indicator	Low score (y=0)	Average score (y=0,5)	High score (y=1)
Transport cost	>8.2 Mill €/a	4.1 Mill €/a	0 €/a

2. Additional results – MCA

2.1. Overall results – absolute numbers

Table S9. Overall results of the MCA in total numbers.

	Unit	**D1**	**D2**	**D3**	**D4**	**D5**	**D6**	**D7**	**D8**
En1	[GWh/a]	164	228	241	291	174	238	215	218
En2	[GWh/a]	0	0	99	139	0	0	0	0
Env1	[t CO2 e./a]	364	283	182	142	364	283	283	283
Env2	[t CO2 e./a]	52,508	72,928	76,405	93,182	55,509	75,846	67,750	69,179
Co1	[Mill €]	201	201	201	201	201	201	201	201
Co2	[€/t DS]	469	469	469	469	469	469	469	469
Co3	[Mill €/a]	2.84	2.21	1.42	1.1	2.84	2.21	2.21	2.21
		C1	C2	C3	C4	C5	C6	C7	C8
En1	[GWh/a]	239	311	340	373	239	311	270	276
En2	[GWh/a]	0	0	199	278	0	0	0	0
Env1	[t CO2 e./a]	2060	1602	1030	801	2060	1602	1602	1602
Env2	[t CO2 e./a]	75,012	97,238	106,267	116,686	75,012	97,238	84,687	86,474
Co1	[Mill €]	137	137	137	137	137	137	137	137
Co2	[€/t DS]	231	231	231	231	231	231	231	231
Co3	[Mill €/a]	8.3	6.46	4.15	3.27	8.3	6.46	6.46	6.46

2.2. Overall results – Alternative A

Table S10. Overall results of the MCA for alternative A.

		D1	**D2**	**D3**	**D4**	**D5**	**D6**	**D7**	**D8**
Energy utilisation potential	(En1)	0.09	0.09	0.09	0.10	0.09	0.10	0.10	0.10
External energy demand	(En2)	0.13	0.13	0.08	0.06	0.13	0.13	0.13	0.13
Emissions	(Eco1)	0.10	0.11	0.11	0.12	0.10	0.11	0.11	0.11
Emissions	(Eco2)	0.06	0.08	0.08	0.10	0.06	0.08	0.07	0.07
Investment costs	(Co1)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Specific costs	(Co2)	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Transport cost	(Co3)	0.11	0.12	0.14	0.14	0.11	0.12	0.12	0.12
Total score		0.50	0.55	0.52	0.54	0.51	0.55	0.55	0.55
		C1	C2	C3	C4	C5	C6	C7	C8
Energy utilisation potential	(En1)	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
External energy demand	(En2)	0.13	0.13	0.04	0.00	0.13	0.13	0.13	0.13
Emissions	(Eco1)	0.00	0.03	0.06	0.08	0.00	0.03	0.03	0.03
Emissions	(Eco2)	0.08	0.10	0.11	0.13	0.08	0.10	0.09	0.09
Investment costs	(Co1)	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Specific costs	(Co2)	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
Transport cost	(Co3)	0.00	0.04	0.08	0.10	0.00	0.04	0.04	0.04
Total score		0.52	0.60	0.60	0.61	0.52	0.60	0.59	0.59

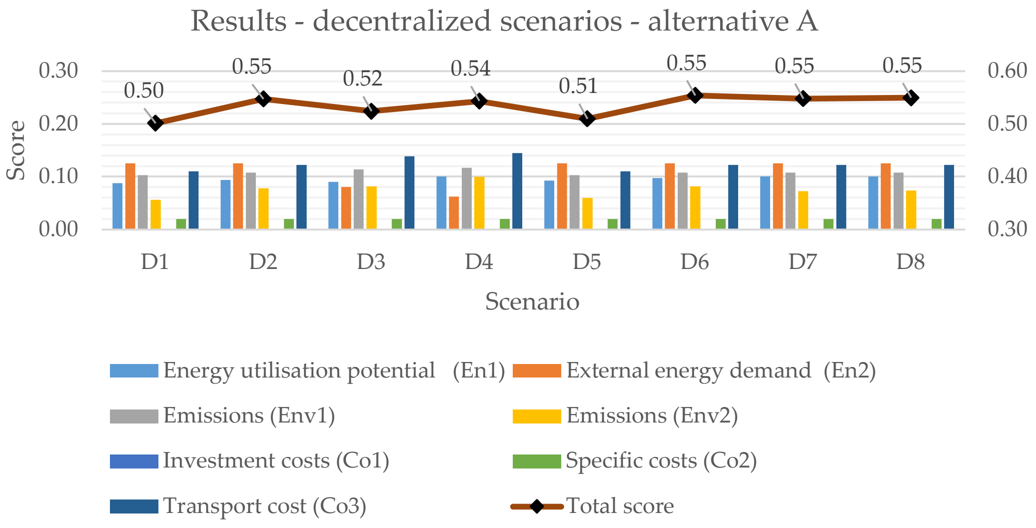

Figure S1. Overall results for alternative A concerning decentralized scenarios (1a, 1b). The score (left y-axis) of each evaluation criteria (En1, En2, Env1, Env2, Co1, Co2, Co3) is shown for all scenarios (D1-D8). The total score (right y-axis) for each scenario is shown by line above the evaluation bars.

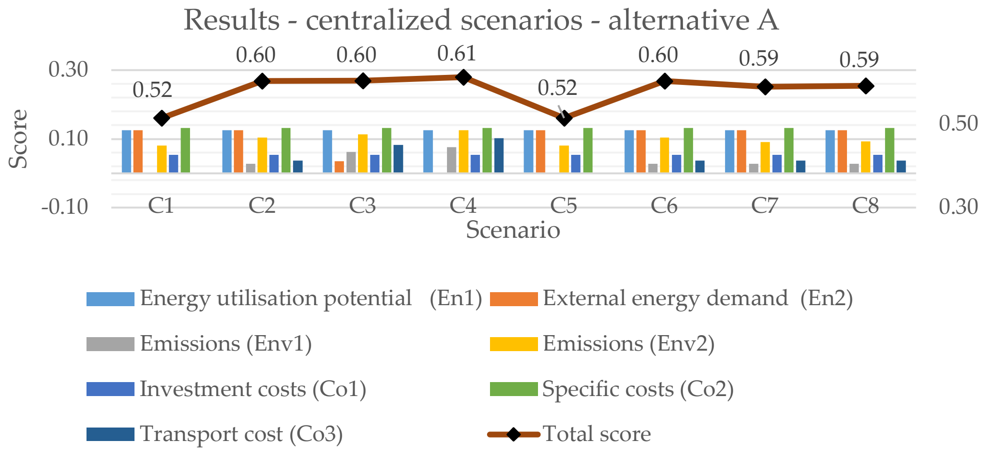

Figure S2. Overall results for alternative A concerning decentralized scenarios (2a, 2b). The score (left y-axis) of each evaluation criteria (En1, En2, Env1, Env2, Co1, Co2, Co3) is shown for all scenarios (C1–C8). The total score (right y-axis) for each scenario is shown by line above the evaluation bars.

2.3. Overall results – Alternative B

Table S11. Overall results of the MCA for alternative B.

		D1	D2	D3	D4	D5	D6	D7	D8
Energy utilization potential	(En1)	0.10	0.11	0.10	0.11	0.11	0.11	0.11	0.11
External energy demand	(En2)	0.14	0.14	0.09	0.07	0.14	0.14	0.14	0.14
Emissions	(Eco1)	0.12	0.12	0.13	0.13	0.12	0.12	0.12	0.12
Emissions	(Eco2)	0.06	0.09	0.09	0.11	0.07	0.09	0.08	0.08
Investment costs	(Co1)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Specific costs	(Co2)	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Transport cost	(Co3)	0.09	0.10	0.12	0.12	0.09	0.10	0.10	0.10
Total score		0.54	0.58	0.55	0.57	0.55	0.59	0.59	0.59

		C1	C2	C3	C4	C5	C6	C7	C8
Energy utilization potential	(En1)	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14
External energy demand	(En2)	0.14	0.14	0.04	0.00	0.14	0.14	0.14	0.14
Emissions	(Eco1)	0.00	0.03	0.07	0.09	0.00	0.03	0.03	0.03
Emissions	(Eco2)	0.09	0.12	0.13	0.14	0.09	0.12	0.10	0.11
Investment costs	(Co1)	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Specific costs	(Co2)	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11
Transport cost	(Co3)	0.00	0.03	0.07	0.09	0.00	0.03	0.03	0.03
Total score		0.54	0.63	0.61	0.62	0.54	0.63	0.61	0.61

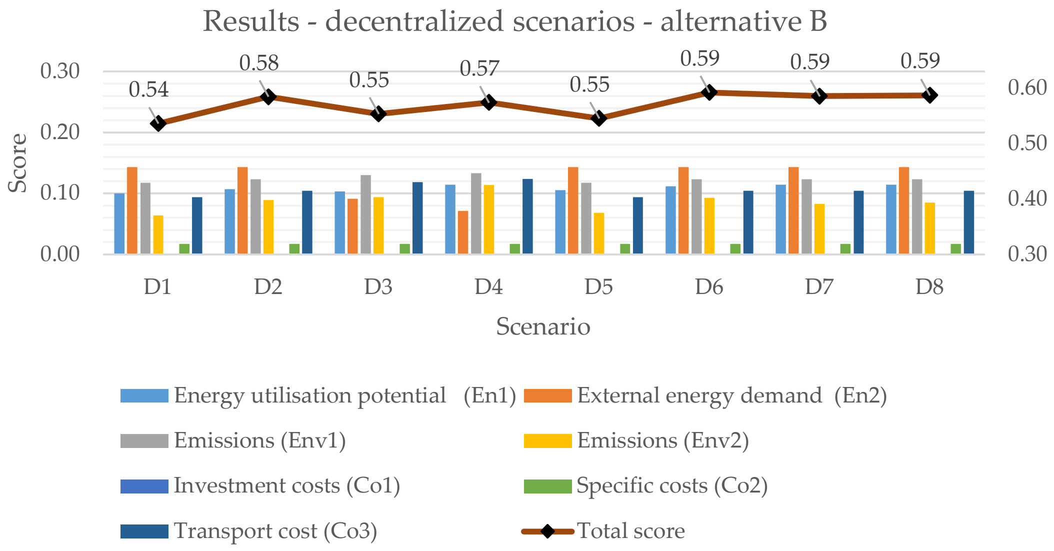

Figure S3. Overall results for alternative B concerning decentralized scenarios (1a, 1b). The score (left y-axis) of each evaluation criteria (En1, En2, Env1, Env2, Co1, Co2, Co3) is shown for all scenarios (D1–D8). The total score (right y-axis) for each scenario is shown by line above the evaluation bars.

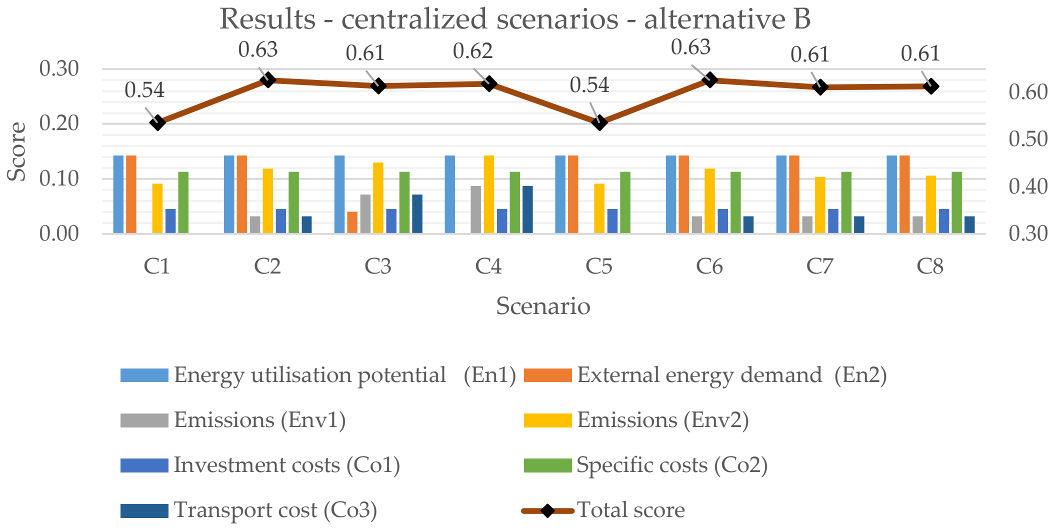

Figure S4. Overall results for alternative B concerning decentralized scenarios (2a, 2b). The score (left y-axis) of each evaluation criteria (En1, En2, Env1, Env2, Co1, Co2, Co3) is shown for all scenarios (C1–C8). The total score (right y-axis) for each scenario is shown by line above the evaluation bars.

3. Overview on investigated WWTPs

Table S12. Overview to the 41 WWTPs with PE > 50,000. The location and the produced yearly sludge amount (rounded to hundreds) is given for each WWTP (BMNT, 2018; EEA, 2016).

Overview to basic data of WWTPs					
OBJECT-ID	**Name**	**Entering load**	**DS_{100}**	**Latitude**	**Longitude**
		[PE]	**[t/a]**		
1	Wulkaprodersdorf (Wulkatal)	59,744	1000	47,8006	16,5173
2	ARA GAV Amstetten	134,757	2300	48,1086	14,8963
3	ARA AV An der Traisen	171,371	2900	48,3632	15,7644
4	ARA AV Wr. Neustadt-Süd	106,504	1800	47,8335	16,2756
5	ARA GAV Raum Krems	106,817	1800	48,4007	15,6629
6	ARA AV Raum Korneuburg	54,053	900	48,3324	16,332
7	ARA Groß-Enzersdorf	72,055	1200	48,1788	16,5466
8	ARA AV Schwechat	163,084	2700	48,1346	16,5412
9	ARA GV Abwasserbeseitigung Raum Bad Vöslau	77,646	1300	47,969	16,2424
10	ARA Mödling	56,716	1000	48,0962	16,3302
11	ARA AV Großraum Bruck/Leitha - Neusiedl/See	68,478	1100	48,0308	16,8261
12	Hauptkläranlage Wien	2,551,005	42,700	48,1723	16,4653
13	Wasserverband Wörthersee Ost	243,694	4100	46,6061	14,3337
14	Stadtgemeinde Villach	140,149	2300	46,612	13,8771
15	WV Millstätter See	101,651	1700	46,7796	13,519
16	Reinhalteverband "Mittleres Lavanttal"	108,361	1800	46,7368	14,846
17	Graz-Gössendorf	515,612	8600	46,9964	15,472
18	Gratkorn	341,120	5700	47,1341	15,3341
19	Hartberg	81,329	1400	47,271	15,9797
20	Wildon	91,011	1500	46,879	15,5305
21	Pöls-VKA	127,147	2100	47,2178	14,5966
22	Knittelfeld	88,367	1500	47,2211	14,8436
23	AGRANA	131,584	2200	48,3624	14,015
24	Asten - Regionalkläranlage	851,592	14300	48,2366	14,4122
25	Welser Heide	132,709	2200	48,1822	14,1375
26	Steyr und Umgebung	101,035	1700	48,0639	14,4328
27	Traunsee-Nord	93,169	1600	47,9421	13,8032
28	Ager-West	52,349	900	48,0154	13,7466
29	ARA Salzach-Pongau	77,513	1300	47,4386	13,2109
30	ARA Saalachtal-Saalfelden	78,582	1300	47,4632	12,8266
31	ARA Siggerwiesen	476,240	8000	47,8597	13,0025
32	Vils	70,440	1200	47,554	10,6583
33	Innsbruck	251,289	4200	47,2637	11,4466
34	Fritzens	74,882	1300	47,3051	11,6085
35	Kirchbichl	73,376	1200	47,5349	12,1086
36	Strass	138,366	2300	47,4026	11,8354
37	Ludesch	57,886	1000	47,1746	9,77011
38	Dornbirn	63,315	1100	47,4317	9,72592
39	Hofsteig	132,743	2200	47,4859	9,67653
40	Hohenems	121,343	2000	47,3656	9,66306
41	Meiningen	226,850	3800	47,3085	9,58972
Sum		8,665,934	145,200		

Table S13. Top 10 hotspots of sludge production in Austria, WWTPS PE>50,000 (EEA, 2016).

Top 10 hotspots – sludge production					
Ranking	**Object-ID**	**Name**	**Latitude**	**Longi-tude**	**Entering load [PE]**
1	12	Hauptkläranlage Wien	48,1723	16,4653	2,551,005
2	24	Asten - Regionalkläranlage	48,2366	14,4122	851,592
3	17	Graz-Gössendorf	46,9964	15,472	515,612
4	31	ARA Siggerwiesen	47,8597	13,0025	476,240
5	18	Gratkorn	47,1341	15,3341	341,120
6	33	Innsbruck	47,2637	11,4466	251,289
7	13	Wasserverband Wörthersee	46,6061	14,3337	243,694
8	41	Meiningen	47,3085	9,58972	226,850
9	3	ARA AV An der Traisen	48,3632	15,7644	171,371
10	8	ARA AV Schwechat	48,1346	16,5412	163,084

Author Contributions: Conceptualization, structure and methodology, D.W., G.N., F.K., G.S.; data curation, case study analysis, D.W.; writing—original draft preparation, D.W., G.N.; writing—review and editing, D.W., G.N., F.K., G.S.; visualization, D.W.; supervision, G.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funing. This article is based on the Master thesis of the first author titled “Spatial perspectives of sewage sludge mono-incineration” elaborated at the University of Natural Resources and Life Sciences, Vienna (BOKU) and the Czech University of Life Sciences Prague.

Acknowledgments: The open access publishing was supported by BOKU Vienna Open Access Publishing Fund. Thank you!

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

References

[1] e-think, ‘Ergebnisse — Austrian Heat Map’, *Fernwärme und Kraft-Wärme-Kopplung in Österreich*, 2019. http://www.austrian-heatmap.gv.at/ergebnisse/ (accessed Mar. 10, 2019).

[2] L. Kranzl, ‘Bewertung des Potenzials für den Einsatz der hocheffizienten KWK und effizienter Fernwärme- und Fernkälteversorgung’, p. 147, 2015.

[3] EEA, ‘Waterbase - UWWTD. Urban Waste Water Treatment Directive – reported data — European Environment Agency (EEA)’, *Waterbase - UWWTD: Urban Waste Water Treatment Directive – reported data*, 2019. https://www.eea.europa.eu/data-and-maps/data/waterbase-uwwtd-urban-waste-water-treatment-directive-5 (accessed Jul. 22, 2019).

[4] S. Gittler, ‘PYREG- Investitionskosten das System P 500 Klärschlamm (mit Abgasreinigung)’. PYREG Carbon Technology Solutions, 2019.

[5] J. Franck, ‘Ressource Klärschlamm: Ansätze für eine zukunftsfähige Nutzungsstrategie’. Dr. Born – Dr. Ermel GmbH, 2017, Accessed: Aug. 20, 2019. [Online]. Available: https://born-ermel.eu/vortraege/vortraege-detailansicht/monoklaerschlammververbrennung-verwertung-oder-doch-nur-entsorgung.html.

[6] J. Franck, ‘Monoverbrennung von Klärschlamm Ab welcher Größe ist das realistisch’. Dr. Born – Dr. Ermel GmbH, 2015, Accessed: Oct. 21, 2019. [Online]. Available: https://docplayer.org/26547701-Monoverbrennung-von-klaerschlamm-ab-welcher-groesse-ist-das-realistisch-dr-born-dr-ermel-gmbh-ingenieure-joern-franck-19.html.