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Supplementary material

Environmental-economic analysis of integrated organic waste and wastewater management systems: a case study from Aarhus City (Denmark)

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Table S1 shows the inventory for the Waste-to-Energy (WtE) plant and the two waste water treatment plants (WWTP) considered in the study. The WtE material and energy consumption are based on Vestforbrænding WtE plant in Copenhagen Municipality (Vestforbrænding green accounts, 2011). The emission resulting from the combustion process is based on average Danish domestic waste composition. The procedure for the distribution of the emissions among the different waste fractions is described in detail in [11].

Table S1. System level Life Cycle Inventory. The values reported refer to all the waste (commercial and domestic) combusted in the WtE and all the wastewater treated in the two WWTPs according to the scenarios.

Item	REF	AS1	AS2a	AS2b	U.M.
Incineration process					
D-OF combusted	28,527	24,052	24,052	0	ton DW
D-IF combusted	27,408	27,408	27,408	27,408	ton DW
C-OF combusted	41,855	41,855	41,855	41,855	ton DW
C-IF combusted	40,214	40,214	40,214	40,214	ton DW
Total waste combusted	138,004	133,529	133,529	109,477	ton DW
Material and energy consumption					
Biofuel	154	149	149	122	ton
Emergency diesel	1,927	1,865	1,865	1,529	L
Electricity consumption	19,910	19,460	19,460	17,041	MWh
Heat consumption	1,725	1,686	1,686	1,476	MWh
Tap water	44,966	43,508	43,508	35,671	m^3
Calcium carbonate ($CaCO_3$)	2,070	2,003	2,003	1,642	ton
Sodium hydroxide (NaOH)	166	161	161	132	ton
Ferric chloride	7	7	7	6	ton
Trimercaptotriazin	6	5	5	4	ton
NH_3 (24%) for NO_x abatement	485	470	470	385	ton
Air emissions					
CO_2 fossil share	92,153	92,020	92,020	91,308	ton
CO_2 biogenic share	187,046	178,537	178,537	132,801	ton
TOC	0.35	0.34	0.34	0.28	ton
TSP	0.58	0.56	0.56	0.46	ton
HCl	6.8	6.6	6.6	5.4	ton
HF	136	132	132	108	kg
SO_2	11	11	11	9	ton

NO_X	209	202	202	166	ton
Hg	1.35	1.35	1.35	1.34	kg
Cu	0.94	0.94	0.94	0.92	kg
Pb	3.99	3.99	3.99	3.98	kg
As	0.43	0.43	0.43	0.42	kg
Cd	0.32	0.32	0.32	0.32	kg
Cr	1.13	1.12	1.12	1.10	kg
Ni	1.49	1.49	1.49	1.47	kg
Dioxin/Furans	35	34	34	28	mg
PM_{10}	463	449	449	367	kg
$PM_{2,5}$	391	379	379	310	kg
Se	0.80	0.80	0.80	0.80	kg
Zn	1.68	1.68	1.68	1.68	kg
Benzo(a)-pyrene	579	561	561	459	g
Benzo(b)-flouranthene	1,229	1,193	1,193	975	g
Benzo(k)-flouranthene	651	632	632	516	g
Indeno-(1,2,3-c,d)-pyrene	795	772	772	631	g
HCB	3.11	3.02	3.02	2.47	g
PCB	0.08	0.08	0.08	0.06	g
Production					
Electricity	91,562	89,492	89,492	78,367	MWh
Heat	605,424	591,738	591,738	518,176	MWh
WWTP Marselisborg					
External carbon (D-OF treated)	0	3,356	3,356	21,395	ton DW
COD inflow - sewage	19,561	19,561	19,561	19,561	ton COD
Material and energy consumption					
Water for biopulp production	0	0	4,195	26,744	m^3
Water for FWD	0	229,317	0	0	m^3
Electricity (consumption)	8,000,000	9,784,359	8,356,872	10,275,057	kWh
Electricity (consumption) for biopulp production	0	0	251,709	1,604,647	kWh
Electricity consumption for FWDs	0	36,917	0	0	kWh
Fe	170,000	170,000	170,000	170,000	kg
Emissions to surface water from wastewater					
Suspended solids	509,600	572,395	572,395	909,919	kg
NVOC	824,000	925,537	925,537	1,471,297	kg
BOD	201,600	226,442	226,442	359,968	kg
COD	2,432,000	2,731,681	2,731,681	4,342,469	kg
Total-N	223,808	223,987	224,163	226,074	kg
Total-P	30,000	33,741	32,180	33,318	kg
Lead	79	88	88	140	kg
Cadmium	4.3	4.8	4.8	7.7	kg
Copper	352	395	395	629	kg
Chrome	78	88	88	139	kg
Mercury	5.7	6.4	6.4	10.1	kg
Nickel	246	277	277	440	kg
Zinc	3,760	4,223	4,223	6,714	kg
Emissions to soil from sludge application					
Lead	261,998	471,719	510,677	1,847,326	g
Cadmium	5,326	6,844	7,636	20,051	g
Copper	1,314,285	1,678,337	1,873,767	4,880,984	g
Mercury	7,710	9,431	10,578	25,994	g
Nickel	123,268	162,376	180,706	489,434	g
Zinc	5,390,286	6,595,845	7,397,362	18,185,398	g
Total N	288,225	303,832	400,091	832,059	kg
Total P	450,000	506,108	507,668	828,217	kg
NPE-NP1EO+NP2EO+NP	13,035	15,943	17,881	43,928	g

Emissions to air					
CH_4	24.4	29.8	33.5	82.2	ton
N_2O, indirect	1.8	1.8	1.8	1.8	ton
N_2O, direct	10.6	11.2	10.7	10.7	ton
C soil stock after 100 years	776	949	1,064	2,614	ton CO_2
Production					
Electricity	9,898	12,106	13,577	33,355	MWh
Heat	10,690	13,075	14,664	36,025	MWh
Avoided fertilizer P	427,500	480,803	482,285	786,806	kg
Avoided fertilizer N	181,582	191,414	252,057	524,197	kg
WWTP Egaa					
External carbon (D-OF treated)	0	1,119	1,119	7,132	ton DW
COD inflow - sewage	5,950	5,950	5,950	5,950	ton COD
Material and energy consumption					
Water for biopulp production	0	0	1,398	8,915	m^3
Water for FWD	0	76,439	0	0	m^3
Electricity (consumption)	2,300,000	2,862,184	2,412,437	3,016,785	kWh
Electricity (consumption) for biopulp production	0	0	83,903	534,882	kWh
Electricity consumption for FWDs	0	12,306	0	0	kWh
Fe	150,000	150,000	150,000	150,000	kg
Emissions to surface water from wastewater					
Suspended solids	63,987	79,627	79,627	163,694	kg
NVOC	103,464	128,754	128,754	264,686	kg
BOD	25,314	31,501	31,501	64,758	kg
COD	305,371	380,012	380,012	781,208	kg
Total-N	58,376	58,436	58,495	59,131	kg
Total-P	4,824	7,318	6,655	7,034	kg
Lead	10	12	12	25	kg
Cadmium	0.5	0.7	0.7	1.4	kg
Copper	44	55	55	113	kg
Chrome	10	12	12	25	kg
Mercury	0.7	0.9	0.9	1.8	kg
Nickel	31	39	39	79	kg
Zinc	472	588	588	1,208	kg
Emissions to soil from sludge application					
Lead	28,500	85,894	88,880	413,420	g
Cadmium	1,090	1,466	1,581	4,218	g
Copper	425,000	552,518	597,039	1,521,747	g
Mercury	940	1,170	1,269	3,037	g
Nickel	27,800	38,466	41,379	114,364	g
Zinc	938,000	1,168,368	1,266,628	3,033,004	g
Total N	75,178	80,381	110,183	254,172	kg
Total P	72,360	109,766	110,429	217,278	kg
NPE-NP1EO+NP2EO+NP	690	859	931	2,226	g
Emissions to air					
CH_4	10.7	13.3	14.4	34.4	ton
N_2O, indirect	0.5	0.5	0.5	0.5	ton
N_2O, direct	2.8	3.0	2.8	2.8	ton
C soil stock after 100 years	162	202	219	523	ton CO_2
Production					
Electricity	6,000	7,467	8,095	19,356	MWh
Heat	3,000	3,733	4,048	9,678	MWh
Avoided fertilizer P	68,742	104,278	104,907	206,414	kg
Avoided fertilizer N	47,362	50,640	69,415	160,129	kg
Transport					

Aarhus-Incinerator	532,923	449,327	449,327	0	tkm
Aarhus-Marselisborg	0	59,009	59,009	376,181	tkm
Aarhus-Egaa	0	8,605	8,605	54,860	tkm
Spreading of sludge					
Spreading by vacuum tanker Marselisborg	17,629	21,561	24,182	59,407	m^3
Spreading by vacuum tanker Egaa	3,683	4,583	4,969	11,881	m^3

Table S2. Input-output inventory for the two wastewater treatment plants included in the waste and wastewater management systems.

Input-Output parameters	UM	Marselisborg - RS	Egaa - RS	Marselisborg 2026 - AS1	Egaa – AS1	Marselisborg 2026 –AS2	Egaa – AS2
Influent wastewater load[1]	PE	400,000	120,000	400,000	120,000	400,000	120,000
Influent wastewater capacity[1]	PE	480,000	120,000	480,000	120,000	480,000	120,000
Input (/year)							
Wastewater input[1]	m^3	20,000,000	8,370,910	20,000,000	8,370,910	20,000,000	8,370,910
Water for biopulp production[2]	m^3	-	-	-	-	4,195	1,398
Water for FWD[3]	m^3	-	-	229,317	76,439	-	-
Electricity (consumption)[4]	kWh	8,000,000	2,300,000	9,784,359	2,862,184	8,356,872	2,412,437
Electricity (consumption) for biopulp production[2]	kWh	-	-	-	-	251,709	83,903
Electricity consumption for FWDs[3]	kWh	-	-	36917,4	12305,8	-	-
Fe[1]	kg	170,000	150,000	170,000	150,000	170,000	150,000
COD influent wastewater[1]	ton	19,561	5,950	19,561	5,950	19,561	5,950
N influent wastewater[1]	ton	2,100	548	2,100	548	2,100	548
P influent wastewater[1]	ton	480	77	480	97	480	97
COD influent wastewater - FWD[2]	ton	-	-	4,363	1,454	-	-
Nitrogen – FWD[5]	ton	-	-	113.7	37.9	-	-
Phosphorous – FWD[5]	ton	-	-	59.8	19.9	-	-
External carbon[5]	ton COD	-	-	-	-	4363	1454
N - external carbon[5]	ton N	-	-	-	-	114	38
P - external carbon[5]	ton P	-	-	-	-	60	20
COD in the ingestate[6]	ton COD	11,737	4,165	14,354	5,183	16,100	5,619
Output							
Electricity[7]	MWh	9,898	6,000	12,106	7,467	13,577	8,095
Heat[7]	MWh	10,690	3,000	13,075	3,733	14,664	4,048
Final digestate							
Digestate production[8]	ton COD	4,231	884	5,175	1,100	5,804	1,193
Avoided fertilizer P[9]	ton	428	69	481	104	482	105
Avoided fertilizer N[9]	ton	182	47	191	51	252	69
Rejectwater[10]	ton COD	168	60	206	74	231	81
Rejectwater[10]	ton N	32	8	33	9	35	9
Rejectwater[10]	ton P	39	6	44	10	43	9
Emission into surface water from wastewater[11]							
Suspended solids	kg	5.10E+05	6.40E+04	5.72E+05	7.96E+04	5.72E+05	7.96E+04
NVOC	kg	8.24E+05	1.03E+05	9.26E+05	1.29E+05	9.26E+05	1.29E+05
BOD	kg	2.02E+05	2.53E+04	2.26E+05	3.15E+04	2.26E+05	3.15E+04
COD	kg	2.43E+06	3.05E+05	2.73E+06	3.80E+05	2.73E+06	3.80E+05
NH_x-N	kg	4.35E+04	5.46E+03	4.89E+04	6.80E+03	4.89E+04	6.80E+03
Nitrites +nitrates-N	kg	1.62E+05	2.03E+04	1.82E+05	2.53E+04	1.82E+05	2.53E+04
Total-N	kg	2.24E+05	5.84E+04	2.24E+05	5.84E+04	2.24E+05	5.85E+04
Total-P	kg	30,000	4,824	33,741	7,318	32,180	6,655
Lead	kg	7.86E+01	9.86E+00	8.82E+01	1.23E+01	8.82E+01	1.23E+01

Cadmium	kg	4.29E+00	5.38E-01	4.82E+00	6.70E-01	4.82E+00	6.70E-01
Copper	kg	3.52E+02	4.42E+01	3.95E+02	5.50E+01	3.95E+02	5.50E+01
Chrome	kg	7.81E+01	9.80E+00	8.77E+01	1.22E+01	8.77E+01	1.22E+01
Mercury	kg	5.66E+00	7.10E-01	6.35E+00	8.84E-01	6.35E+00	8.84E-01
Nickel	kg	2.46E+02	3.09E+01	2.77E+02	3.85E+01	2.77E+02	3.85E+01
Zinc	kg	3.76E+03	4.72E+02	4.22E+03	5.88E+02	4.22E+03	5.88E+02
Emission into soil from digestate[11]							
Lead	g	2.62E+05	2.85E+04	4.72E+05	8.59E+04	5.11E+05	8.89E+04
Cadmium	g	5.33E+03	1.09E+03	6.84E+03	1.47E+03	7.64E+03	1.58E+03
Copper	g	1.31E+06	4.25E+05	1.68E+06	5.53E+05	1.87E+06	5.97E+05
Mercury	g	7.71E+03	9.40E+02	9.43E+03	1.17E+03	1.06E+04	1.27E+03
Nickel	g	1.23E+05	2.78E+04	1.62E+05	3.85E+04	1.81E+05	4.14E+04
Zinc	g	5.39E+06	9.38E+05	6.60E+06	1.17E+06	7.40E+06	1.27E+06
Total N	kg	2.88E+05	7.52E+04	3.04E+05	8.04E+04	4.00E+05	1.10E+05
Total P	kg	4.50E+05	7.24E+04	5.06E+05	1.10E+05	5.08E+05	1.10E+05
NPE-NP_1EO+NP_2EO+NP [12]	g	1.30E+04	6.90E+02	1.59E+04	8.59E+02	1.79E+04	9.31E+02
Sludge treatment							
C soil stock increase[13]	ton C	212	44	259	55	290	60
Emission into air[14]							
CH_4	ton	24.4	10.7	29.8	13.3	33.5	14.4
$N_2O_{, indirect}$	ton	1.76	0.46	1.76	0.46	1.76	0.46
$N_2O_{, direct}$	ton	10.63	2.77	11.21	2.97	10.65	2.78

[1] Data on wastewater loads and WWTP treatment capacity received from Aarhus Vand and in agreement with the reported COD data for 2013 adjusted for the actual PE load in the reference scenario 2026 (Nature Agency, 2015).

[2] Data for AS2 on biopulp production was adopted for preprocessing of the organic fraction of domestic waste collected by truck. The water and energy consumption for the production of the biopulp ingestate was taken from ECOGI technology (KomTek Miljø af 2012 A/S).

[3]The extra water consumption associated to the FWDs is set equal to 3.6 L/person/day (New York City DEP, 1999). One person produces 25 kg FWD COD/year (Nordic Council of Ministers, 2007).The FWD water use equals the total amount of COD received via the FWDs divided by the 25 kg COD/person/year multiplied by 0.0036 m3/person/day*365 days/year.

[4]Electricity consumption for the reference scenarios was received from Aarhus Vand. For the AS1, the electricity consumption at plant level was increased proportional to the amount of COD in the influent wastewater delivered by the FWDs. For the AS2´s, the extra electricity consumption per ton COD in the biopulped D-OF is increased proportional to 20% of the electricity consumption per ton COD treated at the WWTP reference scenario (Pedersen, 2013).

[5]The N and P content in organic household waste was obtained from Thomsen et al. (2015)

[6]National average assumed for centralised WWTPS with anaerobic sludge digestion equal to 60% of the influent COD (Thomsen et al., 2015; Nielsen et al., 2015). For Egaa this fraction is set equal to 70% due to the plant design including the Anammox technology prior to the aerobic biotank *(personal communication Peter Balslev, Aarhus Vand; Thomsen et al., 2015)

[7]Electricity and heat production for the reference scenario was received from Aarhus Vand and upscaled according to the COD content in the ingestate in the two alternative scenarios.

[8]Data on the final sludge production is provided by Aarhus Vand for the reference scenario upscaled according to the extra amount of COD in the inlet wastewater and COD in organic household waste pretreated according to the ECOGI technology.

[9]The avoided import of mineral N and P fertilizer was set equal to the bioavailable fraction of N and P in the final sludge (Jensen et al., 2015; Seghetta et al., 2016).

[10]Reported by Aarhus Vand for the reference scenario and upscaled according to the content of N and P in the added organic household waste.

[11,12]Calculated based on heavy metal content in the ingestate and the monitored distribution between sludge and effluent wastewater.

[13]10% of the added carbon estimated undecomposed after 100 years (Mogensen et al., 2014; Petersen et al., 2013)

[14]Calculated according the Danish emission model (Thomsen et al., 2015; Nielsen et al, 2016; Thomsen 2016)

Table S3. Distribution of the waste categories in organic and fossil fractions[1].

Organic fraction (D-OF)	**Fossil fraction (D-IF)**
Vegetal waste	Carton with plastic
Animal waste	Carton with Al foil
Newsprints	Soft plastic
Magazines	Plastic bottles
Advertisements	Other hard plastic
Books and phonebooks	Non-recyclable plastic
Office paper	Diapers
Clean paper	Cotton sticks
Paper and carton containers	Other cotton etc.
Cardboard	Wood
Dirty paper	Textiles
Dirty cardboard	Shoes, leather
Kitchen tissues	Rubber
Yard waste	Office articles
Animal etc	Cigarette butts
	Other combustibles
	Vacuum cleaner bags
	Clear glass
	Green glass
	Brown glass
	Other glass
	Aluminium containers
	Aluminium foil
	Metal like foil
	Metal containers
	Other of metal
	Soil
	Rocks, stones and gravel
	Ash
	Ceramics
	Cat litter
	Other non-combustibles
	Batteries

[1] Data for reference system are obtained from the Green Account (AffaldVarme Aarhus, 2014). Starting from data for reference system, data for AS1, AS2a and AS2b are allocated on the basis of total dry weight showed in Table S1.

Table S4. FWD installation percent based on an increase in COD in the influent of 25%.

% FDW installation	63
Total number of FWDs[1]	176,260
Total FWD organic matter COD [ton][2]	9,271
Total organic matter COD [ton][3]	37,085
Number of persons/household[4]	2.1
Number of FWDs, Egå[5]	27,649
Number of FWDs, Marselisborg[5]	82,946
FWD [kg COD/person/year][4]	25

[1] Number of FWDs upon 100% installation'

[2] The amount of COD delivered to the sewer system upon 100% installation

[3] The organic fraction of organic household waste, D-OF, in units of COD; using a conversion factor of 1.3 ton COD/ton Dry weight organic household waste

[4] DANVA, 2011.

[5] Calculated from the COD amounts allocated divided by 1.2 person/household*0.025 ton COD /person)

Table S5 Detailed result from the LCIA of the three scenarios for the impact categories climate change (CC) in units of [kg CO2 eq.], Fossil depletion (FD) in units of [kg oil eq.], human toxicity (HT) in units of [kg 1,4-DB eq.] , Terrestrial Ecotoxicity (TE) in units of [kg 1,4-DB eq.], Freshwater Eutrophication (FE) in units of [kg P eq.], Marine Eutrophication (ME) in units of [kg N eq.].

		Transport	WtE-Direct emissions	WtE-Material and energy consumption	WtE-Avoided heat	WtE-Avoided electricity	WWTP Egaa-Direct emissions	WWTP Egaa-Material and energy consumption	WWTP Egaa-Avoided heat	WWTP Egaa-Avoided electricity	WWTP Egaa-Avoided mineral fertilizers	WWTP Marselisborg-Direct emissions	WWTP Marselisborg-Material and energy consumption	WWTP Marselisborg-Avoided heat	WWTP Marselisborg-Avoided electricity	WWTP Marselisborg-Avoided mineral fertilizers	Total
CC	**REF**	6,63E+05	9,22E+07	8,67E+06	-1,52E+08	-3,16E+07	1,07E+06	9,24E+05	-7,55E+05	-2,07E+06	-8,10E+05	3,53E+06	2,92E+06	-2,69E+06	-3,42E+06	-3,71E+06	-8,74E+07
	AS1	5,59E+05	9,20E+07	8,46E+06	-1,49E+08	-3,09E+07	1,15E+06	1,14E+06	-9,39E+05	-2,58E+06	-9,75E+05	3,66E+06	3,61E+06	-3,29E+06	-4,18E+06	-4,04E+06	-8,51E+07
	AS2a	6,43E+05	9,20E+07	8,46E+06	-1,49E+08	-3,09E+07	1,11E+06	9,93E+05	-1,02E+06	-2,79E+06	-1,18E+06	3,47E+06	3,13E+06	-3,69E+06	-4,68E+06	-4,71E+06	-8,80E+07
	AS2b	5,36E+05	9,13E+07	7,34E+06	-1,30E+08	-2,70E+07	1,31E+06	1,37E+06	-2,43E+06	-6,68E+06	-2,59E+06	3,17E+06	4,29E+06	-9,06E+06	-1,15E+07	-8,93E+06	-8,92E+07
FD	**REF**	2,29E+05	0,00E+00	2,44E+06	-5,25E+07	-8,04E+06	0,00E+00	2,36E+05	-2,60E+05	-5,27E+05	-1,63E+05	0,00E+00	7,44E+05	-9,26E+05	-8,69E+05	-8,33E+05	-6,04E+07
	AS1	1,93E+05	0,00E+00	2,38E+06	-5,13E+07	-7,86E+06	0,00E+00	2,92E+05	-3,24E+05	-6,56E+05	-2,12E+05	0,00E+00	9,22E+05	-1,13E+06	-1,06E+06	-9,19E+05	-5,97E+07
	AS2a	2,22E+05	0,00E+00	2,38E+06	-5,13E+07	-7,86E+06	0,00E+00	2,53E+05	-3,51E+05	-7,11E+05	-2,38E+05	0,00E+00	8,00E+05	-1,27E+06	-1,19E+06	-1,00E+06	-6,02E+07
	AS2b	1,85E+05	0,00E+00	2,06E+06	-4,49E+07	-6,88E+06	0,00E+00	3,49E+05	-8,39E+05	-1,70E+06	-5,00E+05	0,00E+00	1,10E+06	-3,12E+06	-2,93E+06	-1,79E+06	-5,90E+07
HT	**REF**	1,14E+04	8,40E+05	2,02E+06	-9,19E+06	-7,85E+06	5,88E+05	2,45E+05	-4,56E+04	-5,14E+05	-1,27E+06	3,45E+06	7,40E+05	-1,62E+05	-8,48E+05	-7,80E+06	-1,98E+07
	AS1	9,60E+03	8,39E+05	1,97E+06	-8,99E+06	-7,67E+06	7,74E+05	3,04E+05	-5,67E+04	-6,40E+05	-1,91E+06	4,31E+06	9,28E+05	-1,99E+05	-1,04E+06	-8,76E+06	-2,01E+07
	AS2a	1,10E+04	8,39E+05	1,97E+06	-8,99E+06	-7,67E+06	8,31E+05	2,62E+05	-6,15E+04	-6,94E+05	-1,93E+06	4,78E+06	7,93E+05	-2,23E+05	-1,16E+06	-8,83E+06	-2,01E+07
	AS2b	9,21E+03	8,29E+05	1,71E+06	-7,87E+06	-6,72E+06	2,14E+06	3,54E+05	-1,47E+05	-1,66E+06	-3,82E+06	1,19E+07	1,08E+06	-5,47E+05	-2,86E+06	-1,45E+07	-2,01E+07
TE	**REF**	2,48E+01	2,07E+02	1,17E+03	-6,20E+03	-3,87E+03	3,94E+03	1,11E+02	-3,07E+01	-2,54E+02	-4,99E+03	1,64E+04	3,55E+02	-1,09E+02	-4,18E+02	-2,78E+04	-2,14E+04
	AS1	2,09E+01	2,07E+02	1,14E+03	-6,06E+03	-3,78E+03	5,06E+03	1,37E+02	-3,82E+01	-3,16E+02	-6,95E+03	2,06E+04	4,35E+02	-1,34E+02	-5,12E+02	-3,09E+04	-2,11E+04
	AS2a	2,41E+01	2,07E+02	1,14E+03	-6,06E+03	-3,78E+03	5,47E+03	1,20E+02	-4,15E+01	-3,42E+02	-7,52E+03	2,30E+04	3,81E+02	-1,50E+02	-5,74E+02	-3,27E+04	-2,08E+04
	AS2b	2,01E+01	2,05E+02	9,88E+02	-5,31E+03	-3,31E+03	1,37E+04	1,65E+02	-9,91E+01	-8,18E+02	-1,55E+04	5,83E+04	5,22E+02	-3,69E+02	-1,41E+03	-5,65E+04	-9,48E+03
FE	**REF**	6,11E+00	0,00E+00	2,65E+03	-5,53E+03	-1,13E+04	6,71E+03	3,42E+02	-2,74E+01	-7,39E+02	-2,10E+03	4,17E+04	1,05E+03	-9,77E+01	-1,22E+03	-1,30E+04	1,85E+04
	AS1	5,15E+00	0,00E+00	2,58E+03	-5,41E+03	-1,10E+04	1,02E+04	4,29E+02	-3,41E+01	-9,20E+02	-3,17E+03	4,69E+04	1,33E+03	-1,19E+02	-1,49E+03	-1,46E+04	2,47E+04
	AS2a	5,93E+00	0,00E+00	2,58E+03	-5,41E+03	-1,10E+04	9,53E+03	3,66E+02	-3,70E+01	-9,97E+02	-3,20E+03	4,54E+04	1,13E+03	-1,34E+02	-1,67E+03	-1,47E+04	2,18E+04
	AS2b	4,94E+00	0,00E+00	2,25E+03	-4,73E+03	-9,65E+03	1,27E+04	4,98E+02	-8,84E+01	-2,38E+03	-6,32E+03	5,49E+04	1,54E+03	-3,29E+02	-4,11E+03	-2,40E+04	2,02E+04
ME	**REF**	1,75E+02	8,14E+03	1,37E+03	-4,35E+03	-5,18E+03	6,53E+04	1,65E+02	-2,15E+01	-3,39E+02	-7,17E+02	2,50E+05	4,97E+02	-7,68E+01	-5,60E+02	-3,40E+03	3,11E+05
	AS1	1,47E+02	7,88E+03	1,34E+03	-4,25E+03	-5,06E+03	6,58E+04	2,04E+02	-2,68E+01	-4,22E+02	-8,87E+02	2,52E+05	6,19E+02	-9,39E+01	-6,85E+02	-3,71E+03	3,13E+05
	AS2a	1,70E+02	7,88E+03	1,34E+03	-4,25E+03	-5,06E+03	6,86E+04	1,77E+02	-2,91E+01	-4,58E+02	-1,06E+03	2,61E+05	5,34E+02	-1,05E+02	-7,68E+02	-4,26E+03	3,24E+05
	AS2b	1,41E+02	6,46E+03	1,16E+03	-3,72E+03	-4,43E+03	8,25E+04	2,41E+02	-6,95E+01	-1,09E+03	-2,29E+03	3,03E+05	7,33E+02	-2,59E+02	-1,89E+03	-7,97E+03	3,72E+05

Table S6 Detailed result from the LCIA of the four scenarios for the Stepwise impact categories Global Warming (GW), Human Toxicity carcinogens (HTc), Human Toxicity non-carcinogens (HTnc) and Eutrophication Aquatic (EA) in Euro2003.

		Transport	WtE-Direct emissions	WtE-Material and energy consumption	WtE-Avoided heat	WtE-Avoided electricity	WWTP Egaa-Direct emissions	WWTP Egaa-Material and energy consumption	WWTP Egaa-Avoided heat	WWTP Egaa-Avoided electricity	WWTP Egaa-Avoided mineral fertilizers	WWTP Marselisborg-Direct emissions	WWTP Marselisborg-Material and energy consumption	WWTP Marselisborg-Avoided heat	WWTP Marselisborg-Avoided electricity	WWTP Marselisborg-Avoided mineral fertilizers	Total
GW	**REF**	5,50E+04	7,65E+06	7,20E+05	-1,26E+07	-2,62E+06	8,86E+04	7,67E+04	-6,26E+04	-1,72E+05	-6,73E+04	2,93E+05	2,42E+05	-2,23E+05	-2,83E+05	-3,08E+05	-7,25E+06
	AS1	4,64E+04	7,64E+06	7,02E+05	-1,24E+07	-2,56E+06	9,55E+04	9,49E+04	-7,79E+04	-2,14E+05	-8,10E+04	3,04E+05	3,00E+05	-2,73E+05	-3,47E+05	-3,35E+05	-7,06E+06
	AS2a	5,33E+04	7,64E+06	7,02E+05	-1,24E+07	-2,56E+06	9,18E+04	8,24E+04	-8,45E+04	-2,32E+05	-9,83E+04	2,88E+05	2,60E+05	-3,06E+05	-3,89E+05	-3,91E+05	-7,30E+06
	AS2b	4,45E+04	7,58E+06	6,09E+05	-1,08E+07	-2,24E+06	1,09E+05	1,13E+05	-2,02E+05	-5,54E+05	-2,15E+05	2,63E+05	3,56E+05	-7,52E+05	-9,55E+05	-7,41E+05	-7,41E+06
HTc	**REF**	2,97E+02	5,66E+03	1,21E+04	-3,55E+06	-2,62E+04	9,89E-15	1,28E+03	-1,76E+04	-1,71E+03	-6,37E+04	7,88E-14	3,01E+03	-6,27E+04	-2,83E+03	-3,92E+05	-4,09E+06
	AS1	2,51E+02	5,50E+03	1,18E+04	-3,47E+06	-2,56E+04	1,23E-14	1,49E+03	-2,19E+04	-2,13E+03	-9,59E+04	8,85E-14	3,66E+03	-7,66E+04	-3,46E+03	-4,41E+05	-4,11E+06
	AS2a	2,88E+02	5,50E+03	1,18E+04	-3,47E+06	-2,56E+04	1,23E-14	1,34E+03	-2,37E+04	-2,31E+03	-9,70E+04	8,85E-14	3,19E+03	-8,59E+04	-3,88E+03	-4,44E+05	-4,13E+06
	AS2b	2,41E+02	4,53E+03	1,00E+04	-3,04E+06	-2,24E+04	2,53E-14	1,66E+03	-5,67E+04	-5,53E+03	-1,92E+05	1,41E-13	4,17E+03	-2,11E+05	-9,53E+03	-7,28E+05	-4,24E+06
HTnc	**REF**	3,42E+02	1,91E+03	2,61E+04	-4,62E+05	-1,11E+05	8,12E+05	3,29E+03	-2,29E+03	-7,25E+03	-8,81E+05	4,68E+06	1,09E+04	-8,15E+03	-1,20E+04	-5,47E+06	-1,42E+06
	AS1	2,88E+02	1,90E+03	2,55E+04	-4,51E+05	-1,08E+05	1,01E+06	4,12E+03	-2,85E+03	-9,02E+03	-1,33E+06	5,72E+06	1,35E+04	-9,97E+03	-1,46E+04	-6,15E+06	-1,31E+06
	AS2a	3,32E+02	1,90E+03	2,55E+04	-4,51E+05	-1,08E+05	1,10E+06	3,63E+03	-3,09E+03	-9,78E+03	-1,34E+06	6,39E+06	1,19E+04	-1,12E+04	-1,64E+04	-6,17E+06	-5,82E+05
	AS2b	2,77E+02	1,86E+03	2,22E+04	-3,95E+05	-9,47E+04	2,62E+06	5,37E+03	-7,38E+03	-2,34E+04	-2,64E+06	1,56E+07	1,74E+04	-2,75E+04	-4,03E+04	-1,01E+07	4,97E+06
EA	**REF**	3,20E+01	1,48E+03	1,59E+02	-6,17E+02	-5,03E+02	4,23E+04	1,76E+01	-3,06E+00	-3,30E+01	-7,29E+03	2,22E+05	5,07E+01	-1,09E+01	-5,44E+01	-4,51E+04	2,12E+05
	AS1	2,70E+01	1,43E+03	1,55E+02	-6,03E+02	-4,92E+02	5,54E+04	2,14E+01	-3,80E+00	-4,10E+01	-1,10E+04	2,42E+05	6,23E+01	-1,33E+01	-6,65E+01	-5,07E+04	2,36E+05
	AS2a	3,11E+01	1,43E+03	1,55E+02	-6,03E+02	-4,92E+02	5,37E+04	1,89E+01	-4,12E+00	-4,45E+01	-1,11E+04	2,39E+05	5,44E+01	-1,49E+01	-7,46E+01	-5,10E+04	2,31E+05
	AS2b	2,59E+01	1,18E+03	1,33E+02	-5,28E+02	-4,31E+02	6,92E+04	2,54E+01	-9,86E+00	-1,06E+02	-2,19E+04	2,85E+05	7,48E+01	-3,67E+01	-1,83E+02	-8,34E+04	2,49E+05

Table S7. Unit prices of market and non-market goods in the economic analysis

Market goods	**Price**	**Unit**
Electricity[1]	0.38	DKK/kWh
Water[2]	25	DKK/m^3
Heat[2]	44.6	DKK/GJ[
Labour[2]	374,400	DKK/person/year
Transportation[2]	15.22	DKK/km
Wastewater[3]	30	DKK/m^3 (paid by households).
Transportation cost[4]	15.22	DKK/km
Biogas	1.8	DKK/Nm^3
Sludge	244	DKK/ton
Fertilizer N[8]	8,775	DKK/ton N
Fertilizer P[8]	12,000	DKK/ ton P
Grinder installation cost	11,74	DKK/item
Non-market goods (shadow prices)		
CO_2 [4]	115.83	DKK/ton
N_2O[5]	34,517.34	DKK/ton
CH_4[5]	2,895.75	DKK/ton
NO_x[6]	55	DKK/ton
N-leaching[7]	40,000	DKK/ton
Cadmium[10]	2,455	DKK/ton
Tax and subsidy		
Subsidy for the electricity for sale[2]	0.414	DKK/kWh
Subsidy for the heat for sale[2]	8.86	DKK/GJ
Investment and Maintenance		
Incineration		
Investment cost	900,000,000	DKK
Lifespan	30	Years
Maintenance cost	30,000,000	DKK/year
Egaa WWTP (old)		
Investment cost	185,000,000	DKK
Lifespan	30	Years
Maintenance cost	2,200,000	DKK/year
Marselisborg WWTP (old)		
Investment cost	380,000,000	DKK
Lifespan	30	Years
Maintenance cost	3,800,000	DKK/year
Egaa WWTP (new)		
Investment cost	80,000,000	DKK
Lifespan	30	Years
Maintenance cost	619,000	DKK/year
Marselisborg WWTP (new)		
Investment cost	1,600,000,000	DKK
Lifespan	30	Years
Maintenance cost	16,000,000	DKK/year

[1]Eurostat[2] AarhusVand, 2015; [3]Pizzol et al., 2013;[4]Energinet, 2013;[5]EPA, Emission Factors for Greenhouse Gas Inventories, 2014;[6]Energistyrelsen, 2010; [7]Jacobsen et al., 2009; [8]Jensen et al., 2015; [9]NATIONS, F.A.A.O.O.T.U., 2015; [10] Pizzol et al., 2014

A noteworthy factor is the maintenance and discounted investment costs of new Egaa plant are less than the old one

Table S8: The fixed cost of eight plants [mill DKK].

	REF-Marseliborg	REF-Egaa	AS1-Marseliborg	AS1-Egaa	AS2-Marseliborg	AS2-Egaa	AS2b-Marseliborg	AS2b-Egaa
Investment cost (DKK)	1600	185	1600	80	1600	80	1600	80
Lifetime (year)	30	30	30	30	30	30	30	30
Interest costs (DKK)	80	9.25	80	4	80	4	80	4
Depreciation cost (DKK)	53.3	6.2	53.3	2.7	53.3	2.7	53.3	2.7
Operation and maintenance cost (DKK)	9	2	9237	6	9142	0.6	9145	0.6

Table S9: Shadow prices of environmental outputs, [DKK/ton].

Emission to air	
CH_4	2,896
N_2O, indirect	34,517
N_2O, direct	34,517
Emission to surface water from wastewater	
Nitrite+nitrate-N	40,000
Emission to soil	
Cadmium	2,455,000

Figure S1. Structure of costs for WWTPs in different scenarios

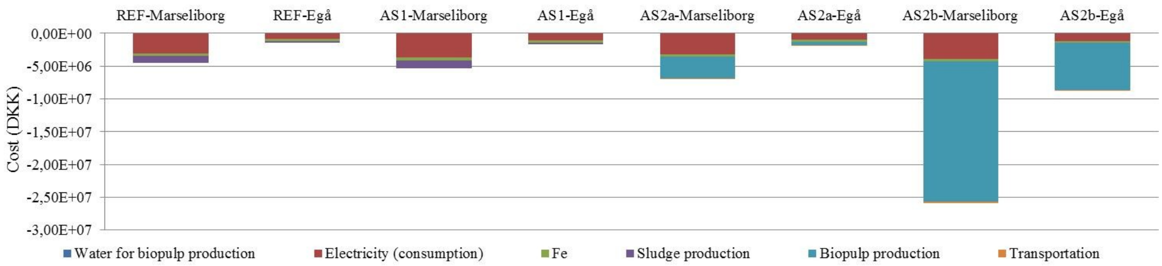


Figure S2. Structure of revenues for WWTPs in different scenarios.

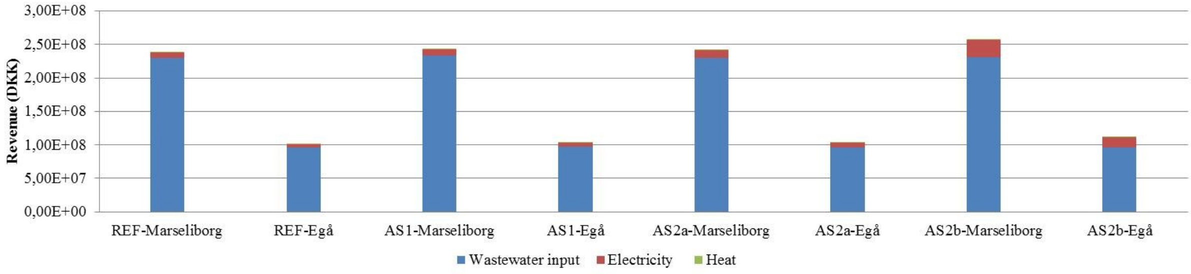


Figure S3. Return on Investment as function of the amount of external carbon in the ingestate at Marselisborg WWTP.

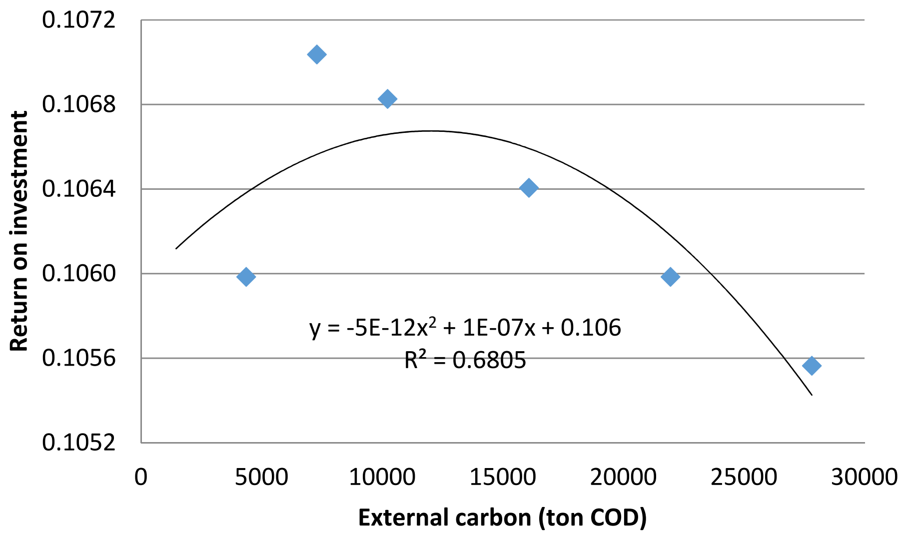


Figure S4. Return on Investment as function of the amount of external carbon in the ingestate at Egaa WWTP.

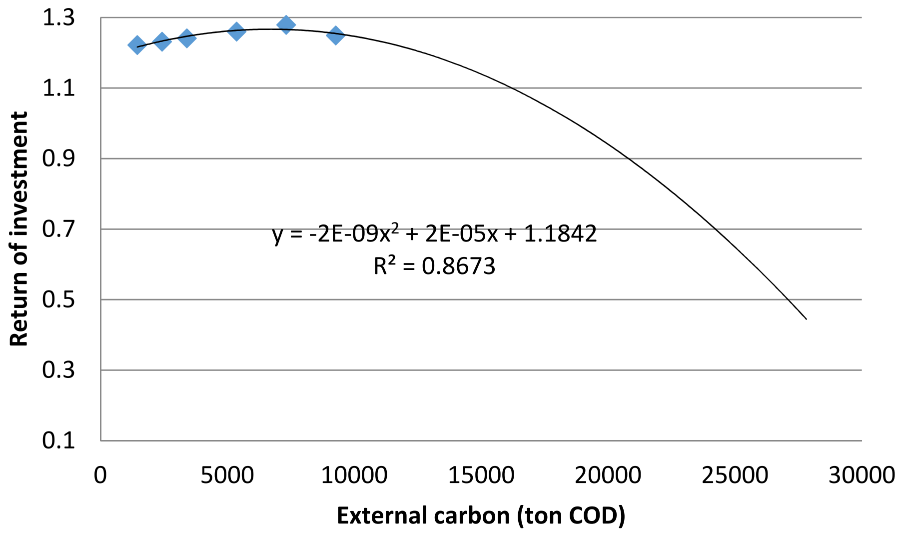


Figure S5. Energy outputs of different external carbon inputs.

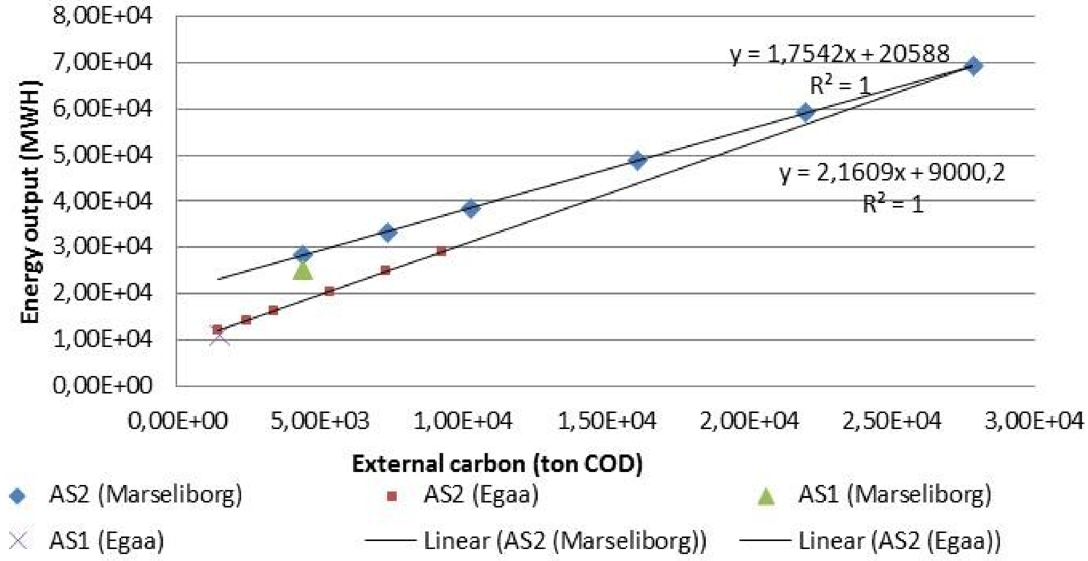


Figure S6. Farmers' benefit structure in the different scenarios.

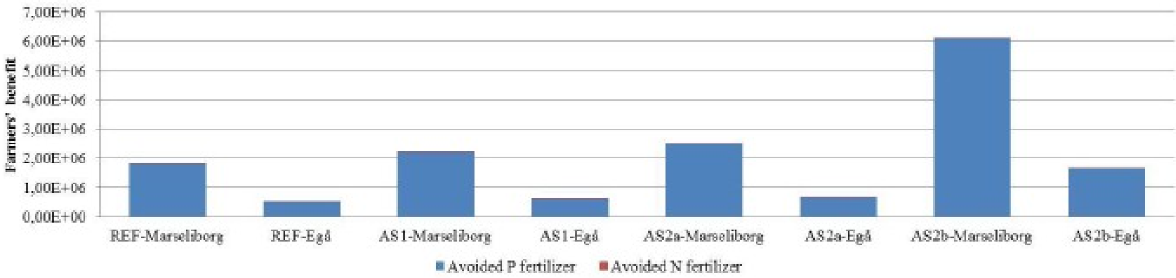


Figure S7. Social benefit structure of WWTPs in the different scenarios.

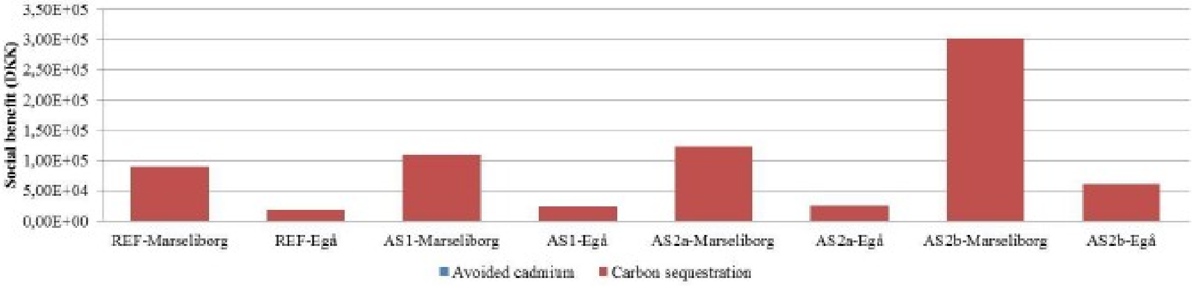


Figure S8. Social cost structure of WWTPs in the different scenarios.

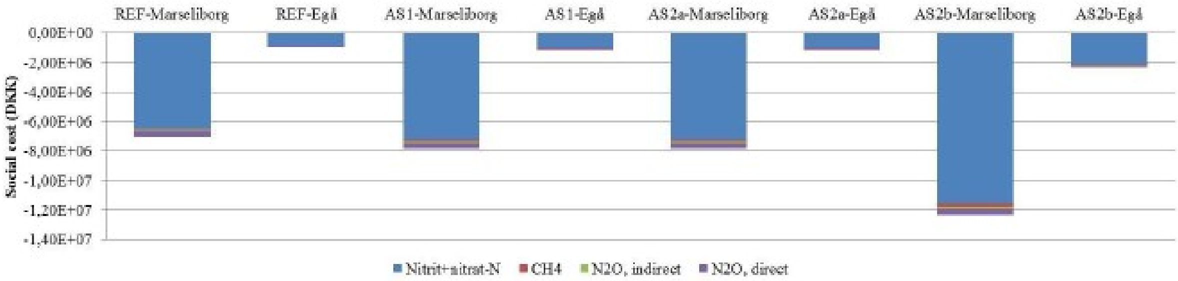


Figure S9. Radar graph of system level environmental performances for the reference and alternative scenarios (aggregated visualization of total results in Figure 4a-f) together with the whole benefit; i.e. net revenue. All value normalised in the range 0-1.

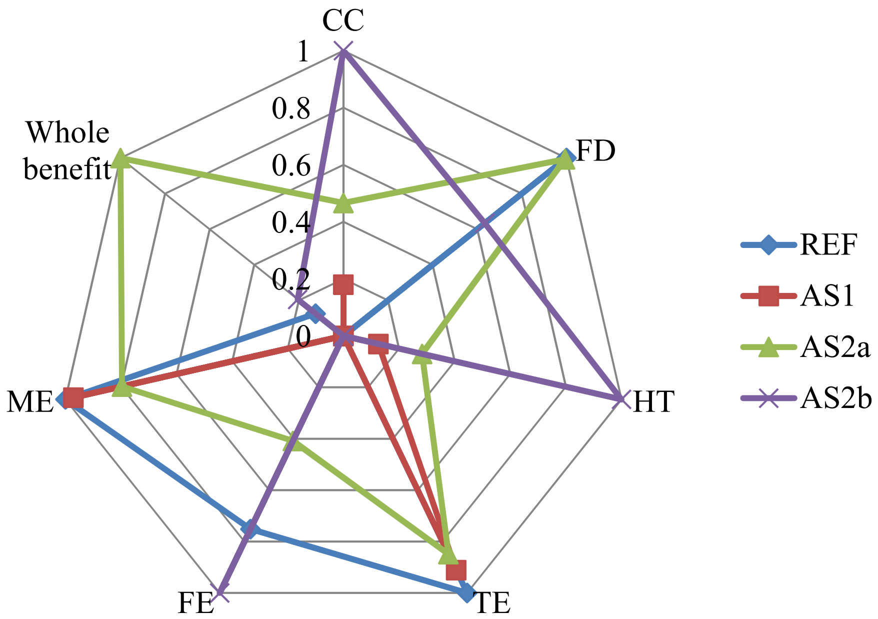
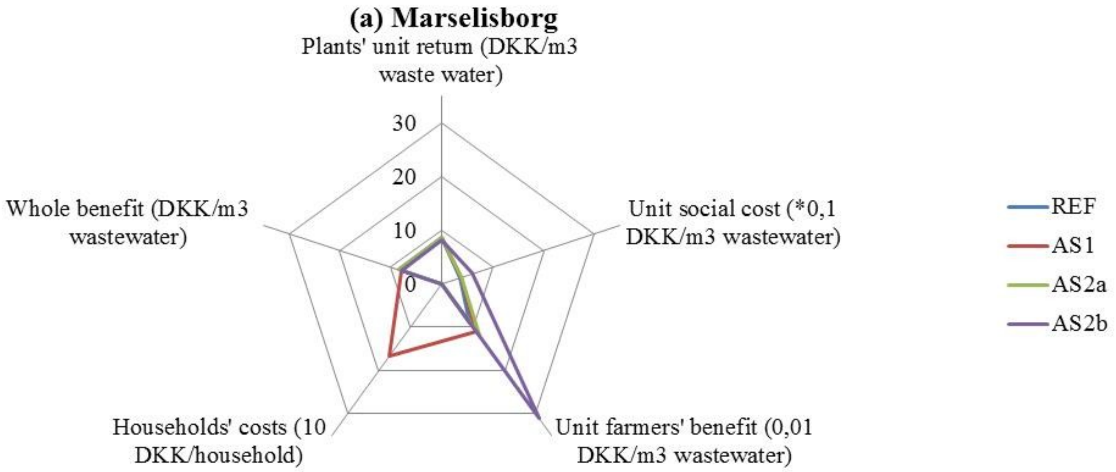
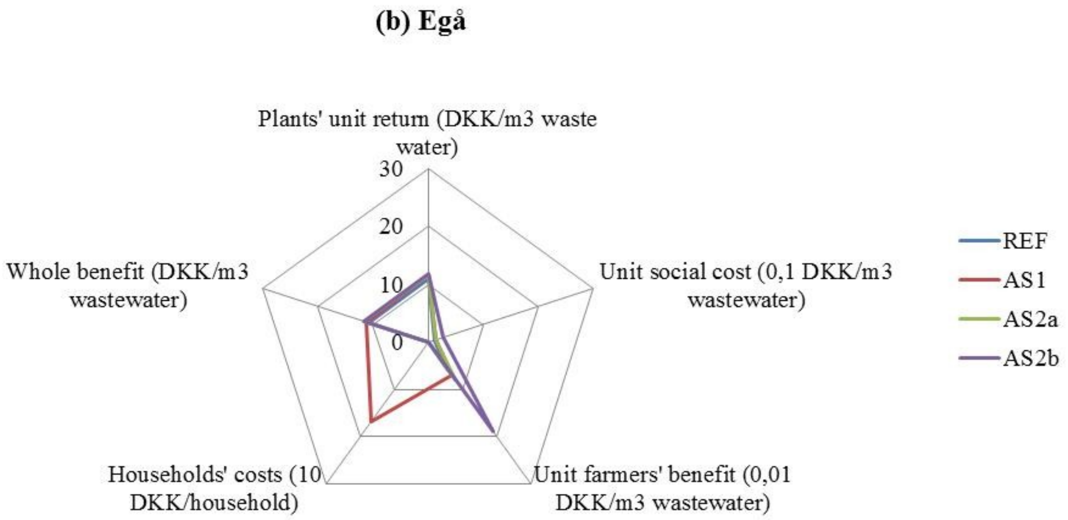


Figure S10: Radar graph of economic performances of Marselisborg (a) and Egaa (b) in different scenarios**.**





Concerning the cost-benefit performance, our analysis has revealed that the Marselisborg WWTP shows the largest return on investment in AS1, while Egaa shows largest return on investment in the AS2b (Supplementary Materials, Figure S10). The main reason for this difference between the two WWTPs is that the amount of final sludge produced in AS1 is less compared to the AS2 scenarios due to around 30% of the organic matter is removed in the aerobic biotank in AS1. Secondary, in the calculation setup of the presented analysis, Marselisborg WWTP receives a higher amount of external carbon compared to Egaa WWTP.

References

AarhusVand, 2015. Business plan 2015 of AarhusVand Available at: http://www.vpu-aarhus.dk/globalassets/filer/om-os/publikationer/business-plan-2015.pdf

Energinet, 2013. Energinet.dk's analysis assumptions 2013-2035. Available at: http://energinet.dk/

Energistyrelsen, 2011. Presumptions for socioeconomic analysis within the energy sector, "in Danish". Available at http://www.ens.dk/

Eurostat. Available at: http://ec.europa.eu/eurostat/data/database

Jacobsen, B.H., B. Hasler, and L.B. Hansen, 2009. Economic midterm evaluation of the Water action plan III, 41 pp

Mogensen, L., Kristensen, T., Nguyen, T.L.T., Knudsen, M.T., Hermansen, J.E., 2014. Method for calculating carbon footprint of cattle feeds – including contribution from soil carbon changes and use of cattle manure. J. Clean. Prod. 73, pp 40-51.

NATIONS, F.A.A.O.O.T.U., 2015. World fertilizer trends and outlook to 2018.

Nielsen, O.-K., Plejdrup, M.S., Winther, M., Nielsen, M., Gyldenkærne, S., Mikkelsen, M.H., Albrektsen, R., Thomsen, M., Hjelgaard, K., Fauser, P., Bruun, H.G., Johannsen, V.K., Nord-Larsen, T., Vesterdal, L., Møller, I.S., Caspersen, O.H., Rasmussen, E., Petersen, S.B., Baunbæk, L. & Hansen, M.G. 2015. Denmark's National Inventory Report 2015. Emission Inventories 1990-2013 - Submitted under the United Nations Framework Convention on Climate Change and the Kyoto Protocol. Aarhus University, DCE – Danish Centre for Environment and Energy, 911pp. Scientific Report from DCE –Danish Centre for Environment and Energy. http://dce2.au.dk/pub/SR171.pdf

Niero, M., Pizzol, M., Bruun, H.G., Thomsen, M., 2014. Comparative life cycle assessment of wastewater treatment in Denmark including sensitivity and uncertainty analysis. Journal of Cleaner Production, 68, pp 25-35.

Petersen, B.M., Knudsen, M.T., Hermansen, J.E., Halberg, N., 2013. An approach to include soil carbon changes in life cycle assessments. J. Clean. Prod. 52, pp 217-224.

Pizzol, M., Scotti, M., Thomsen, M., 2013. Network analysis as a tool for assessing environmental sustainability: applying the ecosystem perspective to a Danish water management system. Journal of Environmental Management 118, pp 21-31.

Riber, C., Petersen, C., Christensen, T.H., 2009. Chemical composition of material fractions in Danish household waste. Waste Management 29, pp 1251-1257

Seghetta, M., Romeo, D., D'Este, M., Alvarado-Morales, M., Angelidaki, I., Bastianoni S., Thomsen, M., 2016. Seaweed as innovative feedstock for energy and feed – evaluating the impacts through a Life Cycle Assessment. Submitted to Journal of Cleaner Production

Thomsen, M. 2014. Wastewater treatment and discharge. Aarhus University, DCE – Danish Centre for Environment and Energy, 79 pp. Scientific Report from DCE – Danish Centre for Environment and Energy No. 193 http://www.dmu.dk/Pub/SR193.pdf

Vestforbrænding, 2011. Grønt regnskab, p. 26 [In English: Green Accounts], I/S Vestforbrænding, Ejby Mosevej 219, 2600 Glostrup. www.vestfor.dk.