

A nexus approach for sustainable urban Energy-Water-Waste systems planning and operation

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Supporting Information Available including page S2-S18, Tables S1-S9, and Figures S1-S3.

Part A: Input parameters

Part B: Model details

Part C: Parameters and results of each scenario.

Part A: Input parameters

Table S1 Demand of water, electricity, and generation of waste from agent-based modeling simulation used in the paper

District	Year 2010			Year 2030		
	Municipal Solid Waste/ tons per year	Wastewater/ m ³ / per year	Electricity/ MJ per year	Municipal Solid Waste/ tons per year	Wastewater/ m ³ per year	Electricity/ MJ per year
ADENTAN	20478	1767915	701444744	57295	3655957	1419933233
ACCRA_METROPOLITAN	501903	45410179	13099107624	1404254	68040234	19739373536
ASHAIMAN	49936	4495392	1333549669	139714	9145552	2758981288
GA_CENTRAL	28936	3311607	1140866937	80959	5869462	2299731972
GA_SOUTH	100701	9606596	3161181684	281747	23731293	7539894152
GA_WEST	55913	5188252	1769876796	156437	8795310	3131242285
GA_EAST	33736	2982612	961389397	94389	6352081	2305134660
KPONE_KATAMANSO	26800	2326688	801923631	74983	6104232	2037046534
LA_DADE_KOTOPON	51154	5860209	1581228481	143122	7321424	2215000498
LA_NKWANTANANG_MADINA	28870	2621313	934051240	80774	4987392	2012372204
LEDZOKUKU_KROWOR	60859	5119854	1814202927	170275	7785275	2834580724
TEMA_METROPOLITAN	70797	6242827	1994314762	198080	10772097	3506701035
AKWAPIM_SOUTH	2491	537179	174445307	6969	670507	256417292
AWUTU_SENYA_EAST	25322	2910979	787987984	70847	6343494	2025888092
NSAWAM_ADOAGYIRI	21232	2346654	652593869	59404	2690797	743562714

Table S2 Waste distribution from statistical data used for calibration^{1,2}

Method of waste disposal	Count	Region	Waste Distribution								District									
			ACCRA METROPOLITAN	ASHAIMAN	GA CENTRAL	GA OUTH	GA WEST	GA EAST	KPO NEKATAMANSO	LA DADÉKOTOPON	LA NKWA NTA NAN G M ADIN A	LEDZOKU KRÖWOR	TEM A M ETRO POLI TAN	AKW APIM SOU TH	AWUTUS ENYAEAST	NSA WAM AD OAG YIRI	ADE NTA N	GAM A sum	Average percentage	
Solid waste (tons per year)																				
Total	5,467,054	1,036,370	501,903	49,936	28,936	100,701	55,913	33,736	26,800	51,154	28,870	60,859	70,797	2,491	25,322	21,232	20,478	1,079,128	1	
Collected	785,889	502,642	298,178	31,266	9,822	21,402	26,518	17,748	7,830	39,423	19,601	16,647	39,753	46	7,568	544	9,379	545,725	0.495	
Burned by households	584,820	134,654	13,402	1,460	12,248	38,077	14,982	8,294	5,245	2,103	3,273	7,321	4,745	301	10,979	2,773	5,550	130,753	0.125	
Public dump (container)	1,299,654	266,287	156,481	14,241	2,771	14,945	6,443	3,768	8,563	7,976	3,485	30,312	15,416	144	2,103	9,096	2,314	278,058	0.257	
Public dump (open space)	2,061,403	87,379	23,647	1,378	2,120	17,288	4,533	2,014	3,243	654	1,754	4,540	7,544	1,875	1,867	7,021	2,048	81,526	0.080	
Dumped indiscriminately	498,868	22,123	5,408	318	509	4,302	1,037	540	1,394	173	311	643	1,481	24	970	829	819	18,758	0.019	
Buried by households	182,615	14,003	1,412	146	1,354	4,210	2,150	1,049	280	135	342	330	298	60	1,547	863	287	14,463	0.013	
Other	53,805	9,282	3,375	1,127	112	477	250	323	245	690	104	1,066	1,560	41	288	106	82	9,846	0.009	
Liquid (tons per year, statistic data not trustable)																				
Total	5,467,054	1,036,370	501,903	49,936	28,936	100,701	55,913	33,736	26,800	51,154	28,870	60,859	70,797	2,491	25,322	21,232	20,478	1,079,128	1	
Through sewerage system	183,169	95,188	41,000	1,378	1,462	4,577	2,897	4,050	2,145	5,939	2,503	3,851	27,966	29	763	308	1843,02	100,711	0.0926	
Through drainage system into a gutter	594,404	191,228	135,248	8,407	1,928	7,217	5,615	3,180	1,954	15,337	3,290	10,063	9,800	353	605	1,964	2,662,14	207,623	0.188	
Through drainage system into a pit	167,555	55,807	20,012	1,253	2,463	8,402	4,634	4,986	1,961	1,866	2,922	2,495	2,987	76	815	443	1023,9	56,339	0.053	
Thrown onto the street/outside	1,538,550	127,782	33,064	4,457	5,369	21,857	12,595	4,797	7,816	2,738	6,068	9,896	3,778	311	6,319	3,383	2,866,92	125,315	0.120	
Thrown into gutter	1,020,096	351,349	236,463	30,563	4,119	11,608	8,940	5,288	2,695	20,145	7,558	20,435	18,817	910	2,867	5,933	2,150,19	378,491	0.345	
Thrown onto compound	1,924,986	208,821	33,436	3,776	13,441	46,476	21,060	11,218	10,056	4,899	6,424	13,376	7,035	786	13,849	9,134	9911,352	204,877	0.196	
Other	38,29	6,195	2,680	102	154	564	172	217	173	230	105	743	414	26	104	67	20	5,771	0.005	

Table S3 Economic and environmental costs of waste treatment and energy recovery technologies^{3,4}

Treatment technology*	Waste streams (ton or m ³ /day)	Life Span (years)	Electricity outputs (MJ/day)	Fixed capital investment (USD)	O&M costs (USD per ton or m ³)	GHG emissions (kg CO ₂ eq/ per ton or m ³)
Incineration	591.5 ton OFMSW	25	587919.7	58,192,172	0.0034	0.877
Pyrolysis	98.6 ton OFMSW	25	157808	10,826,653	0.1157	0.794
Gasification	106.85 ton OFMSW	25	250412.1	33,191,637	0.0333	0.824
Large-scale AD	2463.4 m ³ WW	20	14879.0	4,284,280	0.0394	6.3366
Large-scale AD	15.6 ton OFMSW and 2329.1 m ³ WW	20	15385.3	7,711,704	0.0139 (on basis per m ³ WW)	11.237
Large-scale AD	29.2 ton OFMSW	20	26481.2	4,284,280	0.0031	0.846
Large-scale AD	35 ton banana leaf	20	17220	5,141,136	0.0028	0.120
Large-scale AD	35 ton cassava leaf	20	17220	5,141,136	0.0028	0.121
Large-scale AD	35 ton corn	20	17220	5,141,136	0.0028	0.120
Small-scale AD	12.3 ton OFMSW	15	11378.3	438,194	0.0179	0.741
Small-scale AD	13.8 ton banana leaf	15	7418.2	525,833	0.0183	0.040
Small-scale AD	13.8 ton cassava leaf	15	7418.2	525,833	0.0183	0.044
Small-scale AD	13.8 ton corn	15	7418.2	525,833	0.0183	0.041

* Including 7 WW treatment methods (i.e., conventional waste water treatment plant, waste stabilization pond, aerated lagoon, decentralized activated sludge system, fecal sludge polymer separation drying plant, decentralized aerobic treatment plant, large-scale AD), 6 MSW treatment methods (i.e., large-scale AD, large-scale AD co-digestion, small-scale AD, incineration, pyrolysis, gasification), and 3 for agro-waste (large- and small- scale AD for banana, cassava, and corn as agro-waste feedstocks).

Table S4 Economic and environmental costs of traditional wastewater treatment technologies⁵⁻⁸

Treatment technology	Waste streams (wastewater m ³ /year)	Life Span (years)	Electricity outputs (MJ/day)	Fixed capital investment (USD)	O&M costs (USD per m ³)	GHG emissions (kg CO ₂ eq/ per m ³)
Conventional waste water treatment plant	3,467,500	20	0	53,398,778	1.5	0.01
Waste stabilization pond	1,374,225	20	0	14,145,810	0.19	6.14
Aerated lagoon	4,288,750	20	0	768,544	0.255	1.57
Decentralized activated sludge system	239,062	20	0	1,516,850	0.56	1.16
Fecal sludge polymer separation drying plant	153,000	20	0	4,816,845	0.206	80.41
Decentralized aerobic treatment plant	6,387.5	20	0	244,500	1.21	9.81

Table S5 Economic and environmental costs of energy generation technologies^{9–11}

Generation technology	Rated Capacity (MJ per year)	Capacity factor	Fixed capital investment (USD)	O&M costs (USD per MJ)	GHG emissions (kg CO₂ eq/MJ)
solar P-si-ground	157,680,000	0.2	72,081,785	0.00008	0.0337
Solar-thermal trough	394,200,000	0.412	288,011,509	0.0121	0.0273
hydro small	15,768,000	0.386	7,287,273	0.00359	0.00657
coal IGCC	3,942,000,000	0.75	3,118,121,818	0.00733	1.648
gas CCGT	1,971,000,000	0.56	339,200,683	0.00973	0.612
nuclear SPWR	2,365,200,000	0.875	1,269,564,033	0.00570	0.0256
wind onshore	23,652,000	0.367	6,526,731	0.00494	0.00970
hydro large	9,303,120,000	0.1	3,125,979,139	0.00199	0.00676
biofuel cassava	299,592,000	0.8	314,542,957	0.0307	0.0105
biofuel sugarcane	685,908,000	0.56	3,172,387,866	0.0473	0.0213
wind offshore	28,382,400	0.443	18,449,956	0.0140	0.00297
coal IGCC-CCS	3,942,000,000	0.75	4,482,420,045	0.00914	0.330
gas CCGT-CCS	1,971,000,000	0.56	523,801,485	0.0122	0.122

Table S6 Resource mass and energy balance of all technologies (units in kg or m³ or MJ)

Technology/ Resources	raw source water (m ³)	Electricity (MJ)	labor (hours)	potable water (m ³)	Sludge (m ³)	Influent wastewater (m ³)	liquid effluent (m ³)	sludge effluent (m ³)	municipal solid waste (kg)
waste water treatment plant	0	-1.07	-0.02	0	0	1	-1	0.00024	0
waste stabilisation pond	0	-0.05	-0.0025	0	1.49	1	-1	0.0015	0
aerated lagoon	0	-5.99	-0.0063	0	1.39	1	-1	0.0014	0
decentralized activated sludge system	0	-0.36	-0.004	0	0	1	-1	0.16	0
faecal sludge polymer separation drying plant	0	-1	-0.2	0	0.05	1	-0.86	0	0
decentralised aerobic treatment plant	0	-6.21	-0.5	0	0	1	-0.97	0.03	0
large AD co	0	6.6	-0.0055	0	0	1	-0.98	0	6.259
large AD WW	0	6.04	-0.016	0	0	1	-0.98	0	0
large AD MSW	0	0.907	-0.0014	0	0	0	0	0	1
large AD banana	0	0.492	-0.0011	0	0	0	0	0	0
large AD cassava	0	0.492	-0.0011	0	0	0	0	0	0
large AD corn	0	0.492	-0.0011	0	0	0	0	0	0
farm AD MSW	0	0.989	-0.0021	0	0	0	0	0	1
farm AD banana	0	0.536	-0.0012	0	0	0	0	0	0
farm AD cassava	0	0.536	-0.0012	0	0	0	0	0	0
farm AD corn	0	0.536	-0.0012	0	0	0	0	0	0
incinerator MSW	0	0.994	-0.00243	0	0	0	0	0	1
pyrolysis MSW	0.0816	1.6	-0.0073	0	0	0	0	0	1
gasification MSW	0.06	2.34	-0.00674	0	0	0	0	0	1
solar P-si-ground	0.000105	1	0	0	0	0	0	0	0
solar-thermal trough	-0.000358	1	0	0	0	0	0	0	0

hydro small	0	1	0	0	0	0	0	0	0
coal IGCC	-0.000433	1	0	0	0	0	0	0	0
gas CCGT	-0.000268	1	0	0	0	0	0	0	0
nuclear SPWR	-0.00122	1	0	0	0	0	0	0	0
wind onshore	-0.0000284	1	0	0	0	0	0	0	0
hydro large	0	1	0	0	0	0	0	0	0
biofuel cassava	-0.000433	1	0	0	0	0	0	0	0
biofuel sugarcane	-0.000274	1	0	0	0	0	0	0	0
wind offshore	-0.0000283	1	0	0	0	0	0	0	0
coal IGCC-CCS	-0.000697	1	0	0	0	0	0	0	0
gas CCGT-CCS	-0.000542	1	0	0	0	0	0	0	0

Table S7 Life cycle assessment of the current electricity generation in Ghana as benchmark (1 MJ 'Electricity, production mix Ghana')¹²

Impact category	Unit	Total	Electricity, oil	Electricity, natural gas	Electricity, hydropower	Electricity, production mix photovoltaic
Abiotic depletion	kg Sb eq	0.00071982	0.00019156	0.00052477	2.43E-06	1.07E-06
Acidification	kg SO ₂ eq	0.00046281	0.000427	3.35E-05	1.61E-06	7.27E-07
Eutrophication	kg PO ₄ --- eq	3.10E-05	2.04E-05	9.53E-06	6.21E-07	4.65E-07
Global warming (GWP100)	kg CO ₂ eq	0.09379272	0.03067303	0.06252064	0.000448787	0.00015027
Ozone layer depletion (ODP)	kg CFC-11 eq	5.77E-09	3.70E-09	2.02E-09	2.74E-11	2.84E-11
Human toxicity	kg 1,4-DB eq	0.02642007	0.01189998	0.01342921	0.000743622	0.00034727
Fresh water aquatic ecotox.	kg 1,4-DB eq	0.00281563	0.00227877	0.00022772	0.000199743	0.0001094
Marine aquatic ecotoxicity	kg 1,4-DB eq	19.982749	8.1589475	11.319308	0.26340317	0.24109083
Terrestrial ecotoxicity	kg 1,4-DB eq	0.00025338	0.00024402	5.11E-06	3.15E-06	1.10E-06
Photochemical oxidation	kg C ₂ H ₄	1.98E-05	1.68E-05	2.79E-06	9.91E-08	4.56E-08

Table S8 Feed-In Tariffs for Electricity generated from renewable energy sources, effective October 01, 2014 by Ghana PURC (GH¢/ kWh).

Electricity generated from renewable technology/ source	FIT (USD/ kWh)	Maximum capacity (MW)
Wind with grid stability systems	0.139	300
Solar PV with grid stability/storage systems	0.161	150
Hydro (\leqslant 10 MW)	0.134	No limit
Hydro (10 - 100 MW)	0.135	No limit
Landfill Gas, Sewage Gas and Biomass	0.140	No limit
Biomass (plantation as feed stock)	0.158	No limit

Table S9 Waste-to-Energy ratio by district in the scenario with FIT (data corresponding to Figure 5a).

Region	WTE percent	Waste energy recover	Total energy supply
ADENTAN	4%	61166586	1419933233
ACCRA_METROPOLITAN	1%	128348110	19739373536
ASHAIMAN	1%	31410316	2758981288
GA_CENTRAL	1%	33828939	2299731972
GA_SOUTH	1%	100035963	7539894152
GA_WEST	1%	45310662	3131242285
GA_EAST	4%	87238720	2305134660
KPONE_KATAMANSO	4%	82862439	2037046534
LA_DADE_KOTOPON	2%	33828939	2215000498
LA_NKWANTANANG_MADINA	3%	52342886	2012372204
LEDZOKUKU_KROWOR	1%	31163069	2834580724
TEMA_METROPOLITAN	1%	46202557	3506701035
AKWAPIM_SOUTH	25%	65253010	256417292
AWUTU_SENYA_EAST	2%	37414254	2025888092
NSAWAM_ADOAGYIRI	7%	49070584	743562714.5

Part B: Model details

Detailed explanations of optimization model using mixed-integer linear programming (MILP)

Objective function: $Z = \sum Wf(m, tm) VM(m, tm)$, where

$Wf(m, tm)$: weighting factors for metrics m including CAPEX, OPEX, GHG

$$\begin{aligned} VM(m, tm) = & \sum_j \sum_i VIJ(j, i, m) INV(j, i, m) \\ & + \sum_j \sum_i \sum_t VPJ(j, i, t, m) P(j, i, t, tm) \\ & + \sum_{i,i'} \sum_r \sum_t VQ(r, t, m) dist(i, i') Q(r, i, i', t, tm) \\ & + \sum_{i,i'} \sum_r VY(r, m) dist(i, i') Y(r, i, i', tm) \\ & + \sum_i \sum_r \sum_t VI(r, t, m) IM(r, i, t, tm) \end{aligned}$$

Value of weighting factors are [1, 20, 0.25] in the base case.

j – Technologies: electricity generation plants, waste treatment facilities

i – Districts: spatial zones/ cells

r – Resource: raw water, wastewater, process chemicals, solid waste, electricity, labor etc.

t – Minor time periods, e.g., hours in a day) and tm – Major time periods, e.g., years

Other symbols: costs for investment (VIJ), O&M (VPJ), resource transportation (VQ), pipe and grid expansions (VY) and resource import costs (VI).

Decision variables:

$INV_{j, i, tm}$ (investment of technology j in district i during time period tm)

$P_{j, i, t, tm}$ (production rate of technology j in district i during time period t, tm)

$Q_{r, i, i', t, tm}$ (flow of resource r from district i to i' during time period t, tm)

$IM_{r, i, t, tm}$ (import of resource r to district i during time period t, tm)

$Y_{r, i, i', tm}$ (distance based connection expansion [binary],

e.g., water pipeline, electrical grid, for resource r in district i during time period t, tm)

Constraints:

Technology and Investment balance/ limits, $N(j, i, tm) = N(j, i, tm-1) + INV(j, i, tm)$.

Resource balance and capacity limits- mass and energy balance,

$$D(r, i, t, tm) = MU * P(j, i, t, tm) + Q(r, i', i, t, tm) - Q(r, i, i', t, tm) + IM(r, i, t, tm)$$

Production limits based on capacities, $P(j, i, t, tm) \leq N(j, i, tm) CF(j) CAP(j)$.

Flow limits based on pipe and grid connections and capacities- geometric distance related.

Other realistic factors, e.g., pipe leakage/transmission loss and existing infrastructure set as pre-allocation matrix.

Part C: Parameters and results of each scenario:

Base Case: no land use constraints: weighting factors are [1, 20, 0.25]

Natural Resources Constraints: weighting factors are [1, 20, 0.25] (Job Creation: 2,134)

Land use constraints added as *NE*, which constrains the allowed technology expansion (cells by techs)

Regional Cells: [ADENTAN, ACCRA_METROPOLITAN, ASHAIMAN, GA_CENTRAL, GA_SOUTH, GA_WEST, GA_EAST, KPONE_KATAMANSO, LA_DADE_KOTOPON, LA_NKWANTANANG_MADINA, LEDZOKUKU_KROWOR, TEMA_METROPOLITAN, AKWAPIM_SOUTH, AWUTU_SENYA_EAST, NSAWAM_ADOAGYIRI, VOLTA_RIVER]

Technologies: [waste_water_treatment_plant, waste_stabilisation_pond, aerated_lagoon, decentralized_activated_sludge_system, faecal_sludge_polymer_separation_drying_plant, decentralised_aerobic_treatment_plant, large_AD_co, large_AD_WW, large_AD_MSW, large_AD_banana, large_AD_casava, large_AD_corn, farm_AD_MSW, farm_AD_banana, farm_AD_casava, farm_AD_corn, incinerator_MSW, pyrolysis_MSW, gasification_MSW, solar_P-si-ground, solarthermal_trough, hydro_small, coal_IGCC, gas_CCGT, nuclear_SPWR, wind_onshore, hydro_large, biofuel_cassava, biofuel_sugarcane, wind_offshore, coal_IGCC-CCS, gas_CCGT-CCS]

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- [1,1,1,1,1,1,1,1,0,0,0,1,0,0,0,1,1,1,1,1,0,1,1,1,0,0,0,1,1,0,1,1]

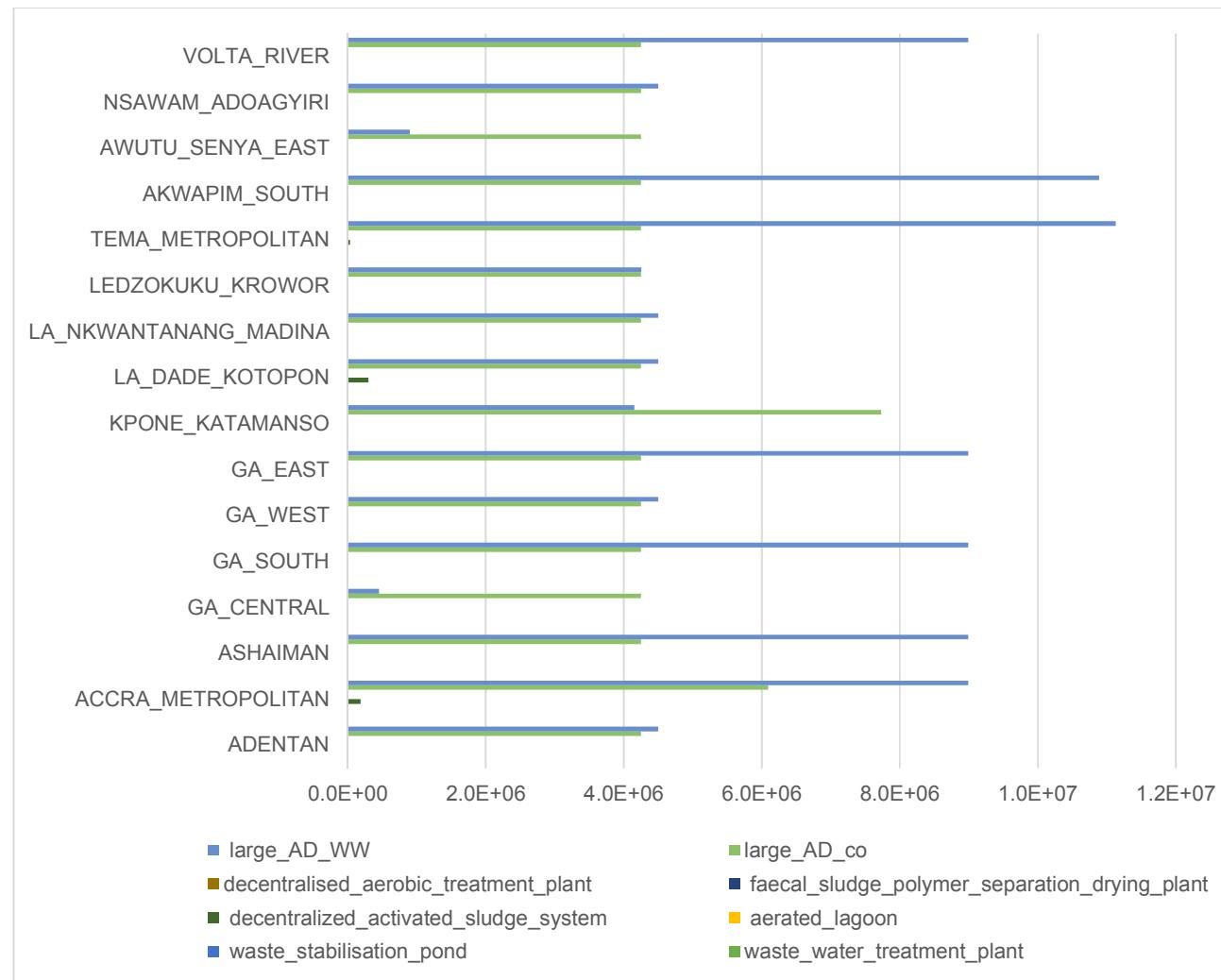


Figure S1. Model suggested wastewater treatment technologies in each region (by wastewater handling capacity in m^3).

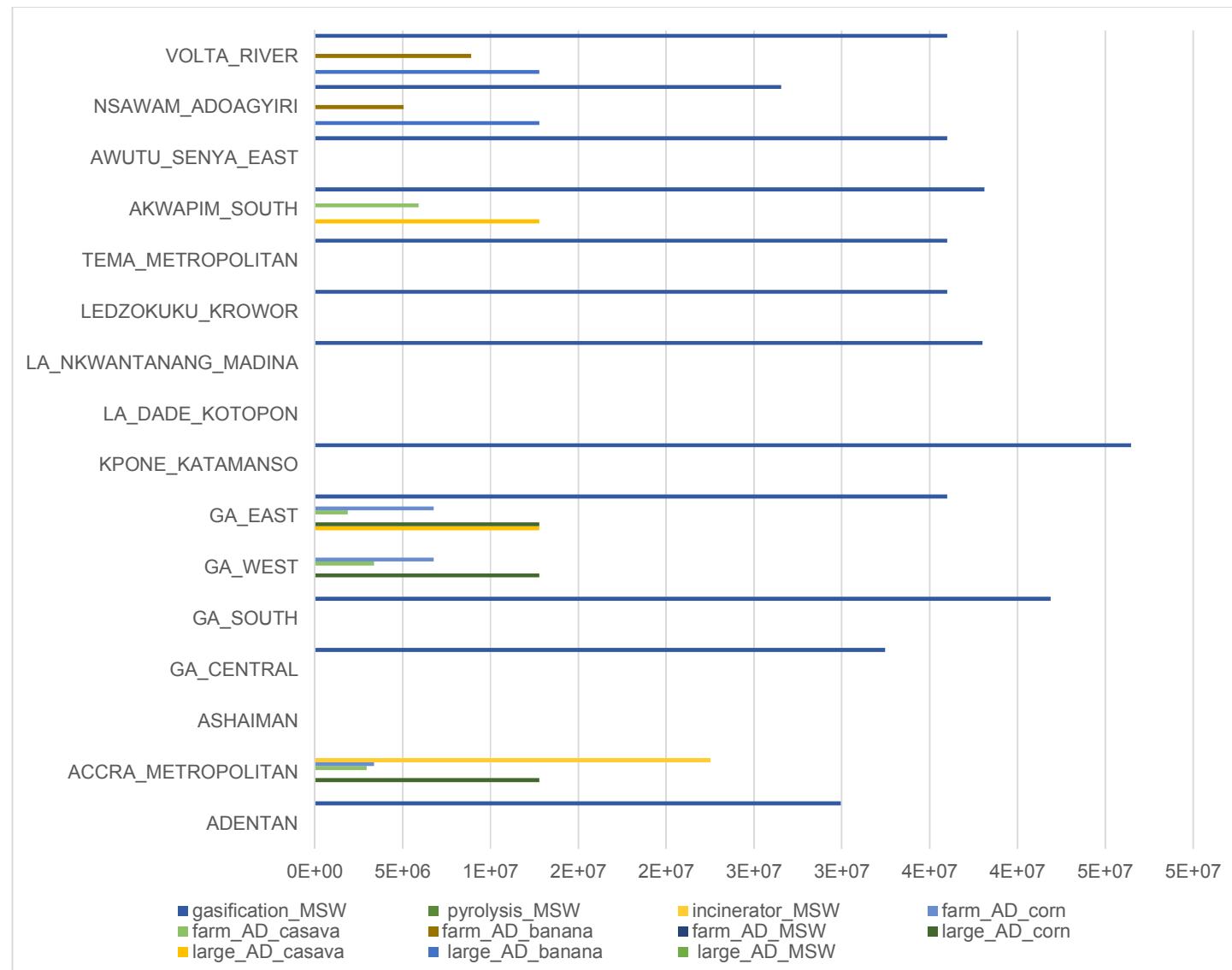


Figure S2. Model suggested MSW and agro-waste treatment technologies in each region (by solid waste handling capacity in kg).

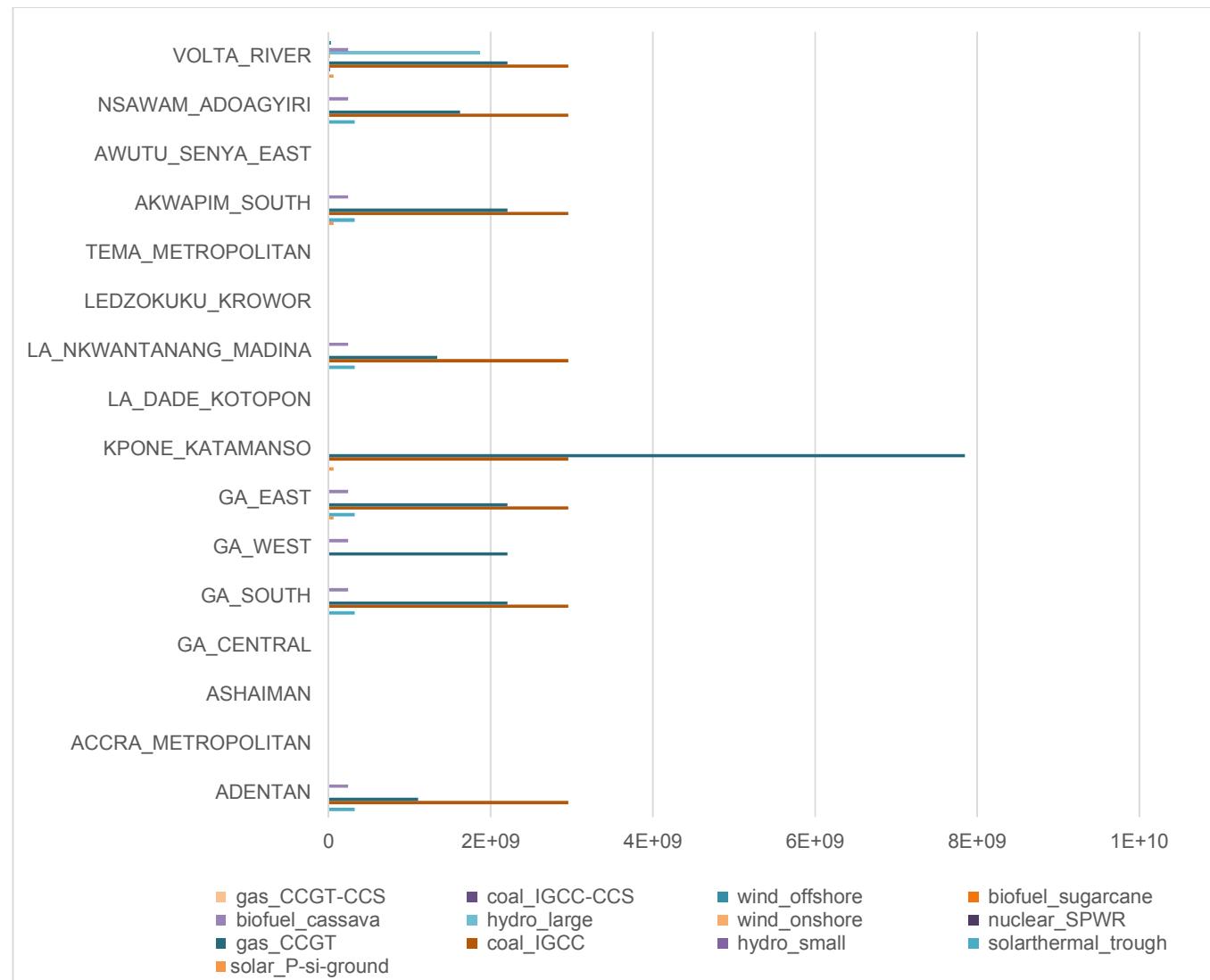


Figure S3 Model suggested power generation technologies in each region (by generation capacity in MJ).

Policy Intervention: Feed-In Tariff imposed and OPEX changed thereafter (Job Creation: 1,799)

Climate change impacts: carbon trading price changes- weighting factors are [1, 20, [0.25-10]] (Job Creation: 1,749 - 2,156)

However, it is notably that the carbon price introduced in the optimization model in our study is based on the current scenario; whereas the carbon prices vary significantly with time horizon which would lead to coal-driven systems less economically competitive in mid/long term. Despite the research advances in the environmental impact evaluation, there is no consensus on reliable approach for monetization systems for environmental indicators.¹³

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