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Repercussion of Large Scale Hydro Dam Deployment: The Case of Congo Grand Inga Hydro Project

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Table S1. Overview of electricity transmission line parameters for the area-wide open trade scenario.

	Region 1	Region 2	Length	Capacity	Utilisation
			[km]	[GW]	[%]
1	West-West	West-South	2581.50	0.35	77
2	West-South	South Nigeria	451.37	1.08	55
3	West-North	North Nigeria	990.68	4.63	90
4	West-North	Sudan Eritrea	2125.10	0.68	69
5	West-North	Central	1101.80	0.43	75
6	South Nigeria	North Nigeria	580.07	1.03	71
7	South Nigeria	Central	1244.90	0.21	84
8	Sudan Eritrea	Ethiopia	1149.30	0.32	60
9	Ethiopia	Somalia Djibouti	1166.40	0.09	60
10	Ethiopia	Kenya Uganda	1357.50	0.17	67
11	Kenya Uganda	Tanzania	789.55	0.74	73
12	Kenya Uganda	Congo	2805.60	0.26	85
13	Tanzania	South East	2058.10	0.39	78
14	Central	Congo	1152.90	0.31	67
15	Congo	South West	591.38	0.59	68
16	South West	South Africa	3237.90	0.00	45
17	South West	South East	2418.10	0.27	82
18	South Africa	South East	1077.30	3.32	69
19	South East	Indian Ocean	2351.70	0.26	71

Table S2. Sub-Saharan Africa sub-regions.

Region	Country
West-West	Senegal, Gambia, Cape Verde Islands, Guinea Bissau, Guinea, Sierra Leone, Liberia, Mali, Mauritania and Western Sahara
West-South	Ghana, Cote d'Ivoire, Benin, Burkina Faso and Togo
West-North	Niger and Chad
South-Nigeria	
North-Nigeria	
Ethiopia	
Sudan-Eritrea	Sudan and Eritrea
Somalia	Djibouti and Somalia
Kenya-Uganda	Kenya and Uganda

Tanzania	Rwanda, Burundi, Tanzania
Central	Central African Republic, Cameroon, Equatorial Guinea, Sao Tome and Principe, Democratic Republic of the Congo [Kinshasa], Republic of the Congo [Brazzaville] and Gabon
DR of the Congo	
South West	Angola, Namibia and Botswana
South Africa	Republic of South Africa and Lesotho
South East	Malawi, Mozambique, Zambia, Zimbabwe and Swaziland
Indian Ocean	Comoros Islands, Mauritius, Mayotte, Madagascar and Seychelles

Table S3. Financial assumptions for energy system components [114–121].

	2030				2040			
Technology	Capex (€/kW)	Opex fix (€/(kW·a))	Opex var (€/kWh)	Lifetime (a)	Capex (€/kW)	Opex fix (€/(kW·a))	Opex var (€/kWh)	Lifetime (a)
PV optimally-tilted	550	8	0	35	370	5.6	0	40
PV single-axis tracking	620	9	0	35	410	6.2	0	40
PV rooftop	813	12	0	35	610	9.2	0	40
Wind onshore	1000	20	0	25	940	18.8	0	25
CSP (solar field)	528	11	0	25	528	11	0	25
Hydro run-of-river	2560	115.2	0.005	60	2560	76.8	0.005	50
Hydro dam	1650	66	0.003	60	1650	49.5	0.003	50
Geothermal energy	4860	87	0	30	4441	88.9	0	40
Water electrolysis	380	13	0.0012	30	310	12.4	0.0012	30
Methanation	234	5	0.0015	30	190	3.8	0.0015	30
CO_2 scrubbing	356	14	0.0013	30	286	11.4	0.0013	30
CCGT	775	19.4	0.001	30	775	19.4	0.001	35
OCGT	475	14.25	0.001	30	475	14.3	0.001	35
Steam turbine	700	14	0	30	640	12.8	0	30
Hot heat burner	100	2	0	30	100	2	0	30
Heating rod	20	0.4	0.001	30	20	0.4	0.001	30
Biomass CHP	2500	175	0.001	30	2500	175	0.001	30
Biogas CHP	370	14.8	0.001	30	325	13	0.001	30
Waste incinerator	5240	235.8	0.007	20	4870	219.2	0.0069	30
Biogas digester	680	27.2	0	20	632	25.3	0	25
Biogas upgrade	250	20	0	20	220	17.6	0	20
	Capex (€/kWh)	Opex fix (€/(kWh·a))	Opex var (€/kWh)	Lifetime (a)	Capex (€/kWh)	Opex fix (€/(kWh·a))	Opex var (€/kWh)	Lifetime (a)
Battery	150	10	0.0002	10/20	100	2.5	0.0002	20
PHS	70	11	0.0002	50	70	11	0.0002	50
A-CAES	31	0.4	0.0012	40	29.75	0.39	0.0012	55
TES	24	2	0	20	20	0.3	0	30
Gas storage	0.05	0.001	0	50	0.05	0.001	0	50
	Capex (€/(kW_{NTC}*km))	Opex fix (€/(kW_{NTC}·km·a))	Opex var (€/kWh_{NTC})	Lifetime (a)	Capex (€/(kW_{NTC}*km))	Opex fix (€/(kW_{NTC}·km·a))	Opex var (€/kWh_{NTC})	Lifetime (a)

HVDC line on ground	0.612	0.0075	0	50	1.044	0.003	0	50
HVDC line submarine	0.992	0.0010	0	50	0.992	0.0010	0	50
HVDC converter pair	180	1.8	0	50	180	1.8	0	50

	2030			2040		
Technology	Efficiency (%)	Energy/Power Ratio (h)	Self-Discharge (%/h)	Efficiency (%)	Energy/Power Ratio (h)	Self-Discharge (%/h)
Battery	90	6	0	97	6	0
PHS	85	8	0	92	8	0
A-CAES	70	100	0.1	83	100	0.001
TES	90	8	0.2	90	8	0.002
Gas storage	100	80*24	0	100	80*24	0

Table S4. Efficiencies and energy to power ratio of storage technologies. Assumption taken from [114].

Table S5. Efficiency assumptions for energy system components for the 2030 reference year.

	2030		2040	
	η_{el} (%)	η_{th} (%)	η_{el} (%)	η_{th} (%)
CSP (solar field)		51		51
Steam turbine	42		43	
Hot heat burner		95		95
Heating rod		99		99
Water electrolysis		84		84
Methanation		77		77
CO_2 scrubbing		78		78
CCGT	58			60
OCGT	43			43
Geothermal	24			24
Biomass CHP	40	45	40	47
Biogas CHP	42	43	42	43
Waste incinerator	34		37	
Biogas upgrade		98		98

Assumption taken from [114,115].

Table S6. Efficiency assumptions for HVDC transmission according to [121].

	Power losses
HVDC line	1.6%/1000 km
HVDC converter pair	1.4%

Table S7. SSA end-user grid electricity costs (in €/MWh) for year 2030 and 2040. Assumptions for most of the countries were taken from [69].

	2030			2040		
Region	Residential	Commercial	Industry	Residential	Commercial	Industry
West-West	180	184	187	221	224	226
West-South	170	186	203	217	241	265
West-North	176	162	148	225	210	194
South Nigeria	46	81	117	74	119	163
North Nigeria	46	81	117	74	119	163
Sudan Eritrea	167	124	81	225	178	130
Ethiopia	180	144	107	242	199	155
Somalia	185	151	117	249	207	165
Kenya Uganda	218	241	195	270	312	263
Tanzania	148	156	164	200	210	220
Central	157	165	173	212	222	233
Congo	73	114	155	119	164	209
South West	113	96	78	163	139	115
South Africa	71	57	43	114	92	70
South East	120	122	124	168	170	172
Indian Ocean	135	132	130	177	173	170

Table S8. Overview of prosumer electricity costs, installed capacities, and energy utilisation for Sub-Saharan Africa in 2030.

Prosumer parameters	**Residential**	**Commercial**	**Industrial**
Electricity price (€/kWh)	0.0929	0.0926	0.0899
PV LCOE (€/kWh)	0.0255	0.0341	0.0339
Self-consumption PV LCOE (€/kWh)	0.0302	0.0387	0.0380
Self-consumption PV and Battery LCOE (€/kWh)	0.0569	0.0625	0.0590
Self-consumption LCOE (€/kWh)	0.0566	0.0622	0.0588
Benefit (€/kWh)	0.0363	0.0304	0.0311
Installed capacities	Residential	Commercial	Industrial
PV (GW)	23.5	13.8	24.0
Battery storage (GWh)	31.8	15.7	24.7
Generation	Residential	Commercial	Industrial
PV (TWh)	40.2	23.6	41.3
Battery storage (TWh)	10.3	5.1	7.9
Excess (TWh)	5.0	2.3	3.5
Utilization	Residential	Commercial	Industrial
Self-consumption of generated PV electricity (%)	84.7	88.0	89.4
Self-coverage market segment (%)	32.9	22.8	44.3
Self-coverage operators (%)	13.5	11.9	10.9

Table S9. Overview of prosumer electricity costs, installed capacities, and energy utilization for Sub-Saharan Africa in 2040.

Prosumer parameters	Residential	Commercial	Industrial
Electricity price (€/kWh)	0.1502	0.1551	0.1561
PV LCOE(€/kWh)	0.0258	0.0343	0.0339
Self-consumption PV LCOE (€/kWh)	0.0318	0.0415	0.0408
Self-consumption PV and Battery LCOE (€/kWh)	0.0475	0.0606	0.0588
Self-consumption LCOE (€/kWh)	0.0472	0.0602	0.0585
Benefit (€/kWh)	0.1030	0.0949	0.0975
Installed capacities	Residential	Commercial	Industrial
PV (GW)	72.3	47.1	78.9
Battery storage (GWh)	157.4	105.5	169.4
Generation	Residential	Commercial	Industrial
PV (TWh)	121.9	80.2	135.9
Battery storage (TWh)	49.2	33.0	53.4
Excess (TWh)	18.5	10.9	18.5
Utilization	Residential	Commercial	Industrial
Self-consumption of generated PV electricity (%)	81.3	82.7	83.0
Self-coverage market segment (%)	34.8	23.3	42.0
Self-coverage operators (%)	24.6	24.6	23.2

Table S10. Upper limits of installable capacities in SSA regions in units of GW_{th} for CSP and GW_{el} for all other technologies.

Region	area	Limits [GW]					
	[1000 km²]	Solar CSP	Solar PV	Wind	Hydro RoR	Hydro dams	PHS
Total area	25,304.9	230,137.9	115,068.9	8591.8	8.3	23.6	2.4
West-West	2947.3	28,919.8	14,459.9	1079.7	0.0	0.5	0.0
West-South	1005.5	9049.7	4524.9	337.9	0.3	3.0	0.0
West-North	2207.8	19,869.9	9935.0	741.8	0.0	0.0	0.0
South Nigeria	853.3	7679.5	3839.6	286.7	0.0	0.0	0.0
North Nigeria	938.5	8446.9	4223.4	315.3	0.7	2.3	0.0
Sudan-Eretria	2627.1	23,644.2	11,822.1	882.7	0.6	4.2	0.0
Ethiopia	1127.1	10,144.2	5072.1	378.7	0.6	2.3	0.0
Somalia Djibouti	660.7	5945.9	2973.0	222.0	0.0	0.0	0.0
Kenya-Uganda	818.7	7368.2	3684.1	275.1	0.3	1.6	0.0
Tanzania	999.3	8993.3	4496.6	335.7	0.5	0.6	0.0
Central	1737.1	15,634.3	7817.2	583.7	0.7	0.9	0.0
Congo	2345.4	21,108.7	10,554.3	788.1	2.1	0.8	0.0
South West	3114.1	28,026.6	14,013.3	1046.3	0.4	1.4	0.0
South Africa	1250.3	11,252.4	5626.2	420.1	0.1	0.9	2.4
South East	2080.6	18,725.6	9362.8	699.1	1.9	5.1	0.0
Indian Ocean	592.1	5328.7	2664.4	198.9	0.1	0.0	0.0

Table S11. Lower limits of installed capacities in SSA regions. Data were taken from [33].

Region	Installed capacity (MW)				
	Solar PV	Wind	Hydro RoR	Hydro dams	PHS
Total area	1424.9	805.3	5541.9	15749.2	1580.0
West-West	109.7	26.0	29.4	347.8	0.0
West-South	45.4	0.0	269.3	2009.7	0.0
West-North	4.7	0.0	0	0.0	0.0
South Nigeria	22.3	6.0	0	0.0	0.0
North Nigeria	23.3	6.2	434.6	1536.8	0.0
Sudan-Eretria	8.4	0.0	425.5	2722.2	0.0
Ethiopia	15.0	171.2	423.2	1464.4	0.0
Somalia Djibouti	2.9	0.0	0	0.0	0.0
Kenya-Uganda	44.8	19.3	176.9	1093.3	0.0
Tanzania	31.7	0.0	320.2	374.5	0.0
Central	13.4	0.0	445.1	629.9	0.0
Congo	3.8	0.0	1402.3	566.3	0.0
South West	31.4	0.2	274.2	949.0	0.0
South Africa	1035.1	570.2	69	612.3	1580.0
South East	25.8	0.3	1238.4	3420.3	0.0
Indian Ocean	7.3	6.0	33.8	22.7	0.0

Table S12. Regional biomass costs, calculated based on mix of biomass sources in the region. Solid waste costs are based on assumption of a 100 €/ton gate fee paid to the MSW incinerator.

Region	Biomass costs (€/MWh$_{th}$)		
	Solid waste	Solid biomass	Biogas sources
Total area	–20.3	7.7	3.3
West-West	–20.3	5.3	2.7
West-South	–20.3	5.5	1.0
West-North	–20.3	5.3	2.0
South Nigeria	–20.3	10.5	0.6
North Nigeria	–20.3	10.5	0.6
Sudan Eretria	–20.3	5.3	6.0
Ethiopia	–20.3	14.0	1.6
Somalia	–20.3	9.7	3.4
Kenya			
Uganda	–20.3	5.3	5.2
Tanzania	–20.3	5.3	1.0
Central	–20.3	5.3	4.1
Congo	–20.3	15.9	1.9
South West	–20.3	5.3	1.3

South Africa	–20.2	10.0	9.0
South East	–20.3	5.4	5.1
Indian Ocean	–20.3	5.4	8.0

Table S13. Regional biomass [71] and geothermal energy potentials [78].

Region	Biomass potential (TWh_{LHV}/a)			Geothermal Potentials (TWh_{th}/a)
	Solid waste	Solid biomass	Biogas sources	
Total area	41.5	258.5	55.6	358.0
West-West	1.4	9.4	2.2	0.0
West-South	2.1	8.4	2.7	0.0
West-North	1.2	11.7	1.3	2.6
South Nigeria	3.2	32.0	3.8	72.5
North Nigeria	2.7	27.1	3.3	18.8
Sudan Eretria	1.1	12.8	4.8	0.0
Ethiopia	5.0	43.1	5.0	0.0
Somalia	0.0	4.3	0.0	0.0
Kenya Uganda	2.4	4.4	3.7	4.4
Tanzania	1.1	0.0	1.1	0.0
Central	1.7	9.3	2.2	252.1
Congo	3.7	31.3	3.3	6.3
South West	1.6	8.4	1.1	1.3
South Africa	7.9	35.6	9.1	0.0
South East	5.1	11.8	8.0	0.0
Indian Ocean	1.3	9.1	3.7	0.0

Table S14. Overview of storage capacities, throughput, and full cycles per year for the four scenarios for Sub-Saharan Africa in 2030.

			I3 Announced cost	I3 Expected cost	GI 0%	GI 50%	GI 100%	GI 35% (Inflection point)
Storage capacities	Battery SC	(GWh_{el})	72.20	72.20	72.20	72.20	72.20	72.20
	Battery system	(GWh_{el})	167.46	167.22	158.87	159.76	164.89	159.37
	PHS	(GWh_{el})	3.16	3.16	3.16	3.16	3.16	3.16
	A-CAES	(GWh_{el})	418.35	416.82	405.44	406.27	416.67	406.98
	Gas	(GWh_{el})	18,475.66	18,483.24	18,601.62	18,548.60	18,732.04	18,549.24
Throughput of storages	Battery SC	(TWh_{el})	23.31	23.31	23.31	23.31	23.31	23.31
	Battery system	(TWh_{el})	53.75	53.68	51.21	51.51	52.79	51.42
	PHS	(TWh_{el})	0.83	0.83	0.84	0.84	0.82	0.84
	A-CAES	(TWh_{el})	10.25	10.21	10.09	10.11	10.23	10.13

	Gas	(TWh_{el})	44.78	44.79	44.20	44.16	44.64	44.15
	Battery SC	(-)	322.87	322.87	322.87	322.87	322.87	322.87
	Battery system	(-)	321.00	321.03	322.30	322.44	320.14	322.63
Full cycles per year	PHS	(-)	261.26	261.31	265.85	265.57	259.74	265.74
	A-CAES	(-)	24.50	24.50	24.88	24.88	24.54	24.89
	Gas	(-)	2.42	2.42	2.38	2.38	2.38	2.38

Table S15. Overview of storage capacities, throughput, and full cycles per year for the all scenarios for Sub-Saharan Africa in 2040.

			I3 Announced cost	**I3 Expected cost**	**GI 0%**	**GI 50%**	**GI 100%**	**GI -5% (Inflection point)**
Storage capacities	Battery SC	(GWh_{el})	432.30	432.30	432.30	432.30	432.30	432.30
	Battery system	(GWh_{el})	1155.07	1155.07	1107.06	1106.54	1107.85	1106.42
	PHS	(GWh_{el})	0.02	0.02	0.20	0.21	0.17	0.20
	A-CAES	(GWh_{el})	0.18	0.18	1.54	1.59	1.33	1.66
	Gas	(GWh_{el})	29,189.84	29,190.36	28,194.26	28,162.59	28,232.81	28,132.82
Throughput of storages	Battery SC	(TWh_{el})	135.67	135.67	135.67	135.67	135.67	135.67
	Battery system	(TWh_{el})	363.15	363.15	348.76	348.59	349.00	348.55
	PHS	(TWh_{el})	0.37	0.37	0.39	0.39	0.40	0.39
	A-CAES	(TWh_{el})	0.01	0.01	0.12	0.12	0.11	0.13
	Gas	(TWh_{el})	49.29	49.29	47.11	47.01	47.22	46.96
Full cycles per year	Battery SC	(-)	313.83	313.83	313.83	313.83	313.83	313.83
	Battery system	(-)	314.40	314.40	315.03	315.03	315.03	315.03
	PHS	(-)	237.16	236.75	249.93	247.70	250.30	247.42
	A-CAES	(-)	81.76	81.62	77.46	75.44	79.56	75.45
	Gas	(-)	1.69	1.69	1.67	1.67	1.67	1.67

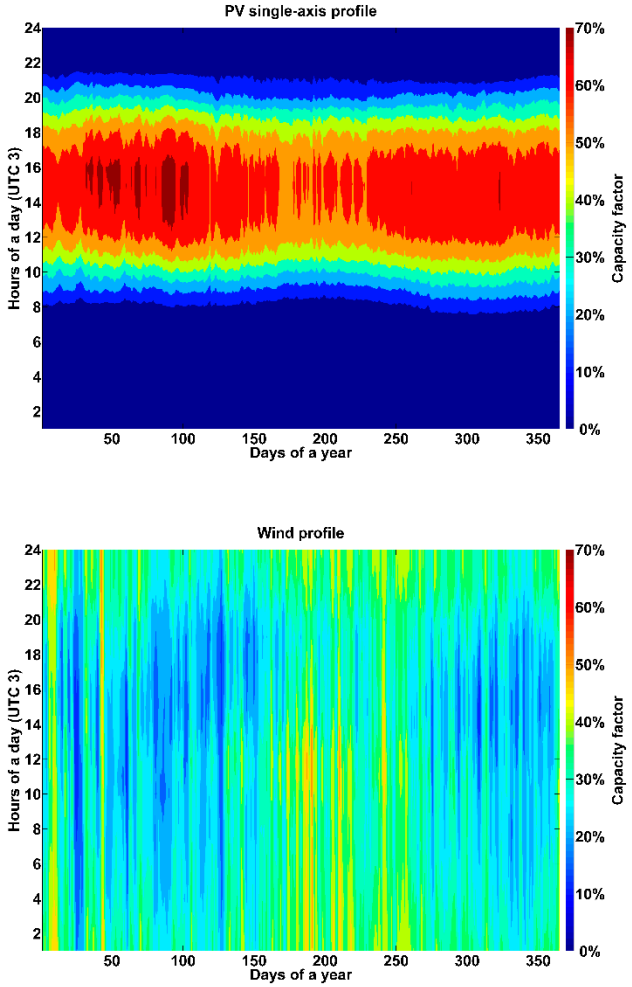


Figure S1. Solar PV single-axis tracking (left) and wind power (right) generation profiles for SSA.

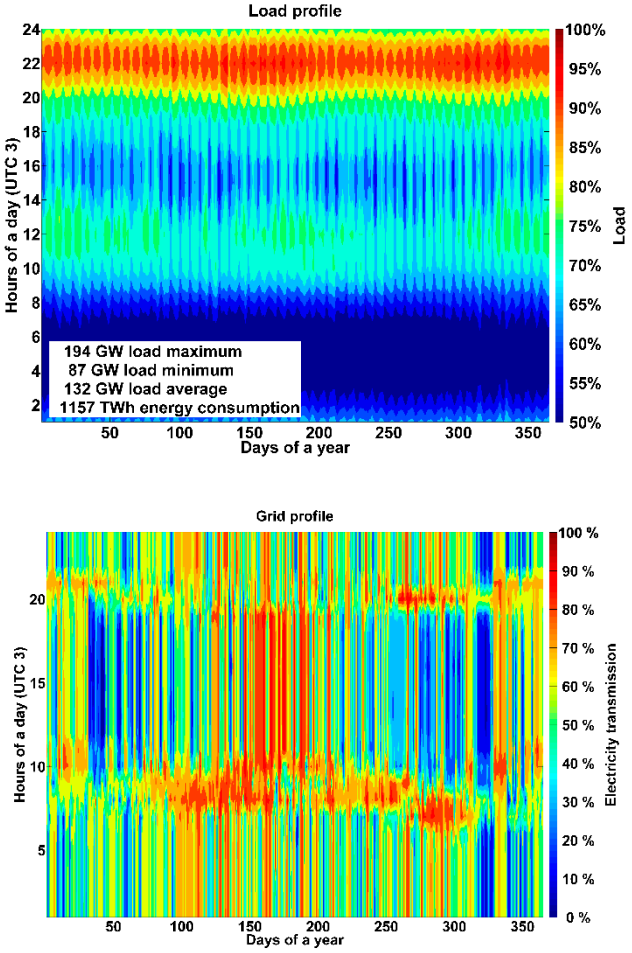
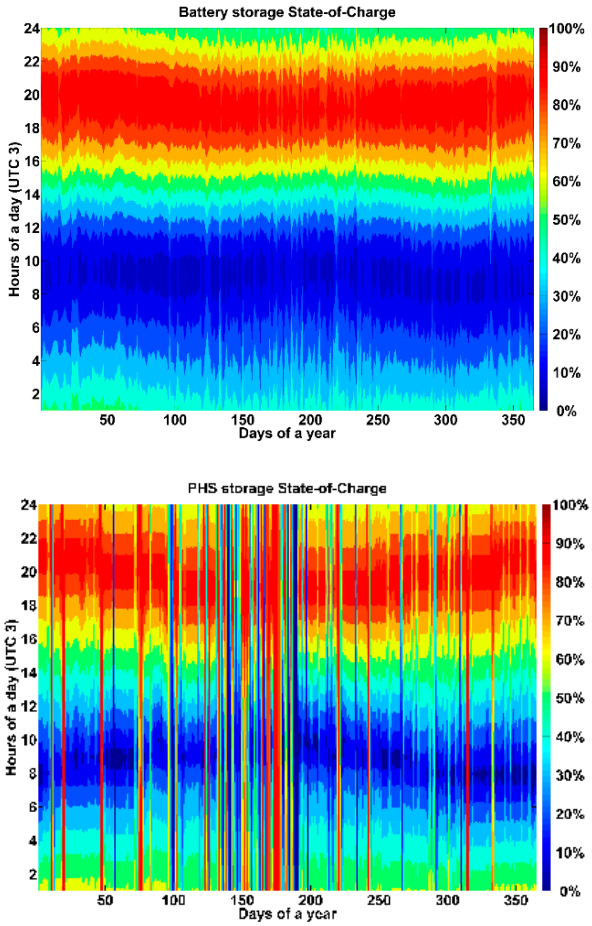


Figure S2. Aggregated load curve (left) and grid profile (right) for SSA.


Battery storage State-of-Charge
Hours of a day (UTC 3)
Days of a year
PHS storage State-of-Charge
Hours of a day (UTC 3)
Days of a year

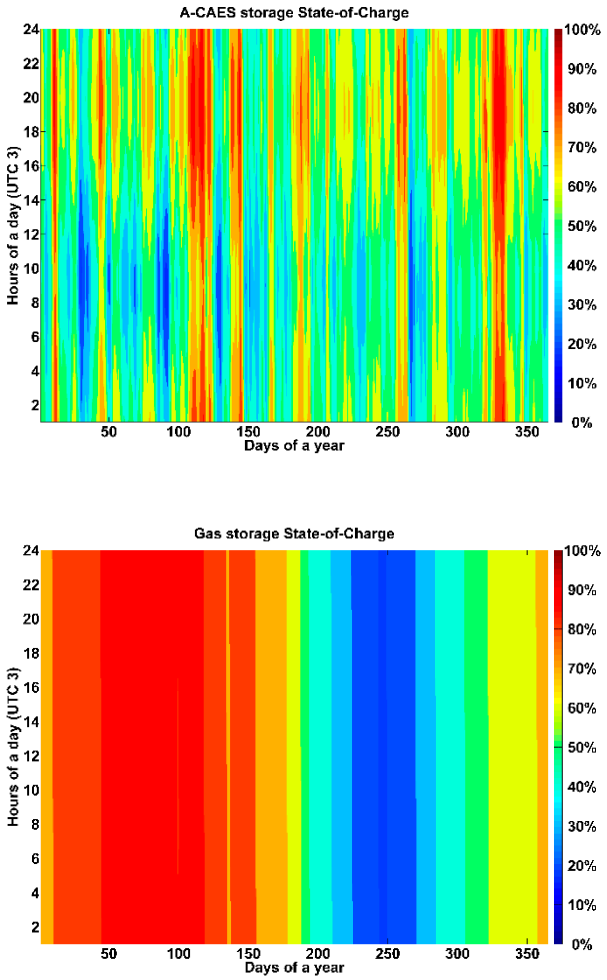


Figure S3. Aggregated state-of-charge for storage technologies in the reference scenario for the 2040: battery (top left), PHS (top right), A-CAES (bottom left), and gas storage (bottom right).

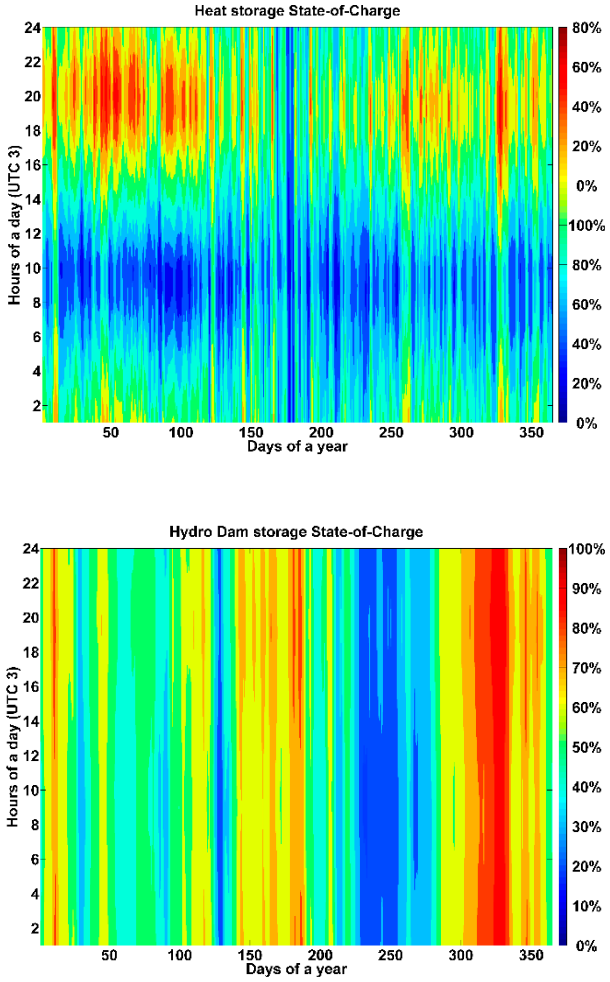
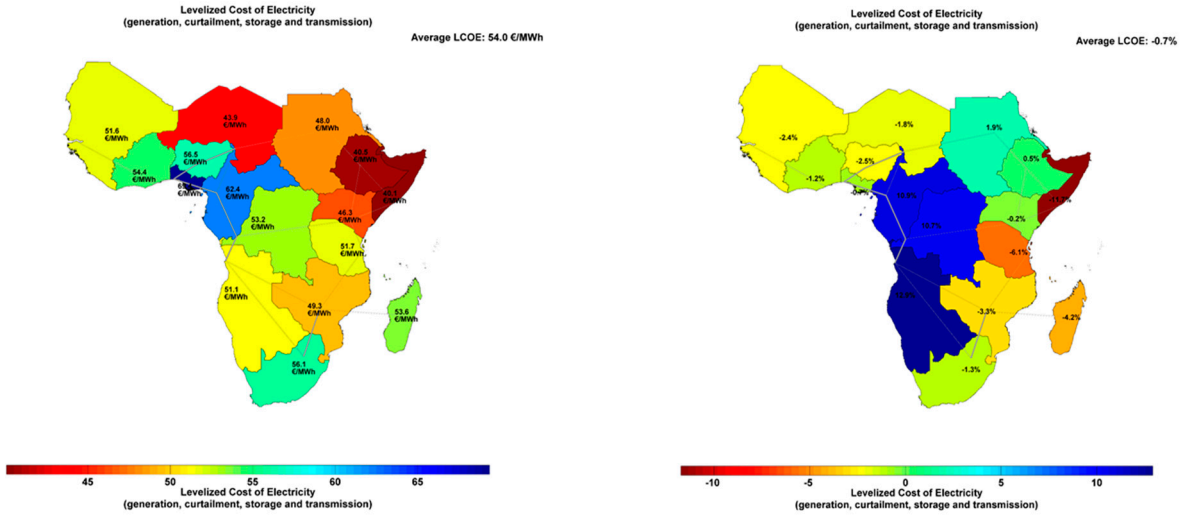


Figure S4. State-of-charge for heat and hydro dam storage in the reference scenario by 2040.



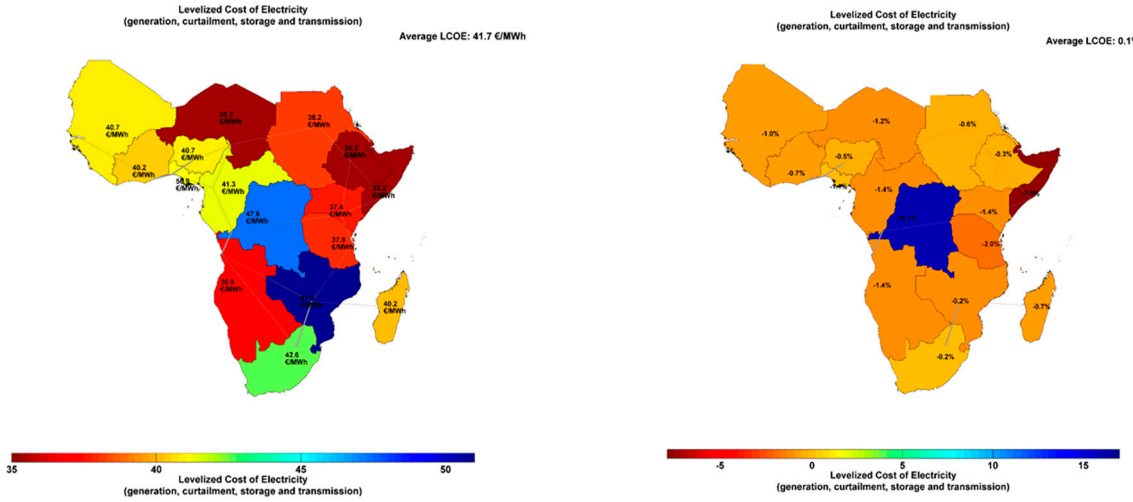


Figure S5. Scenario GI 0% in absolute total LCOE (left) and the relative difference to the reference scenario (right) for the years 2030 (top) and 2040 (bottom).

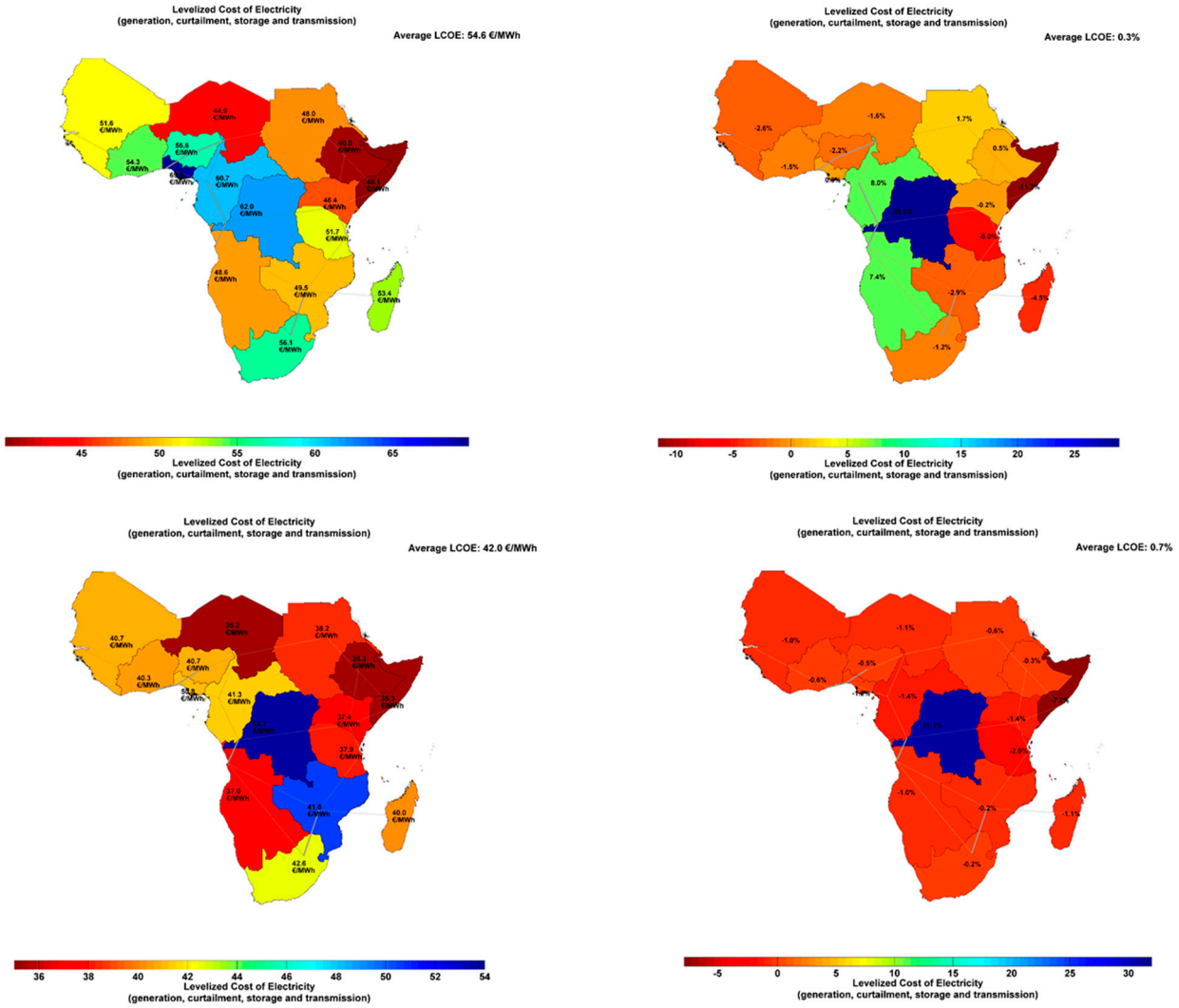


Figure S6: Scenario GI 50% in absolute total LCOE (left) and the relative difference to the reference scenario (right) for the years 2030 (top) and 2040 (bottom).

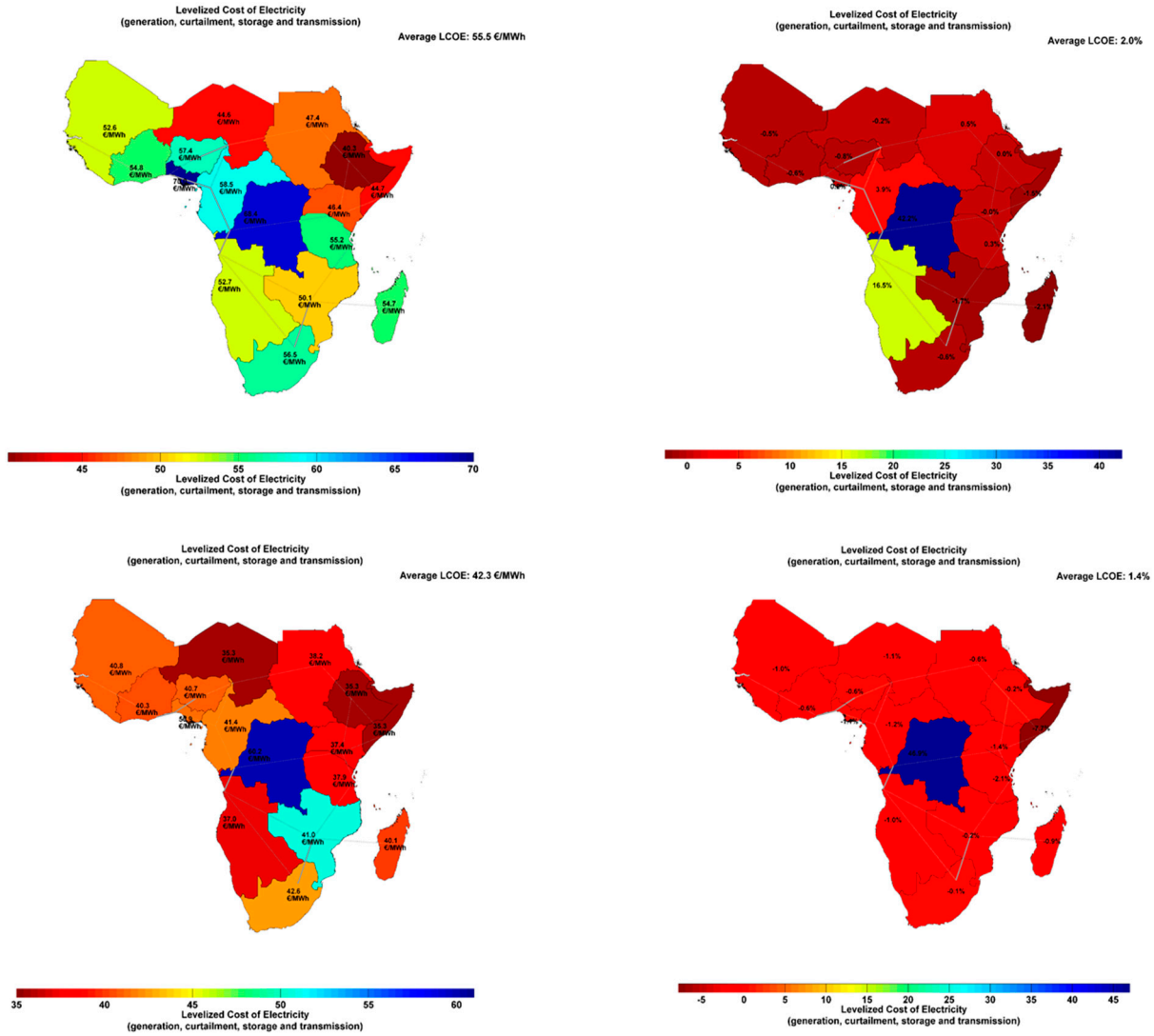
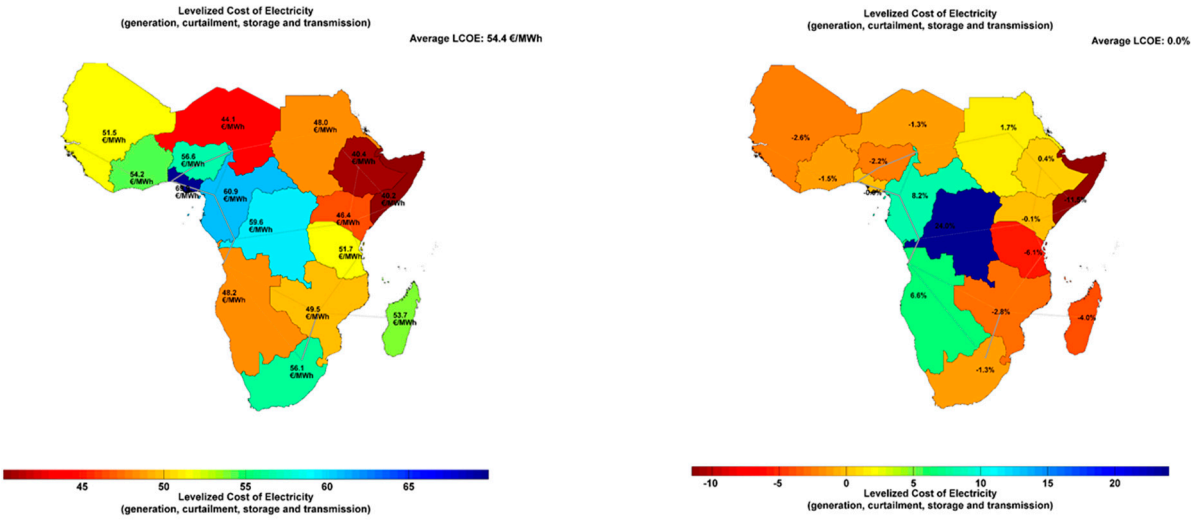


Figure S7: Scenario GI 100% absolute total LCOE (left) and the relative difference to the reference scenario (right) for the years 2030 (top) and 2040 (bottom).



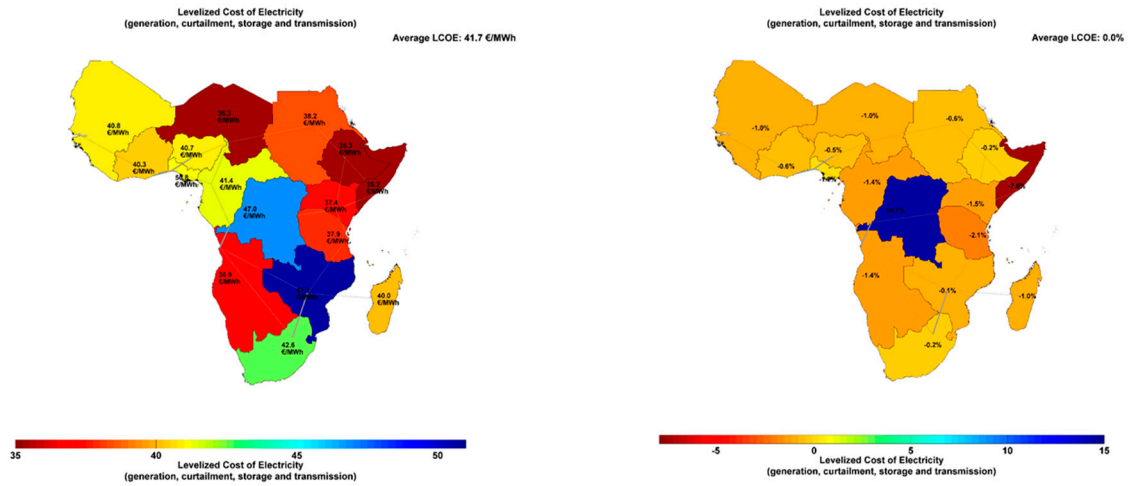


Figure S8: The +35% and –5% scenarios (near inflection point) in absolute total LCOE (left) and the relative difference to the reference scenario (right) for the years 2030 (top) and 2040 (bottom).

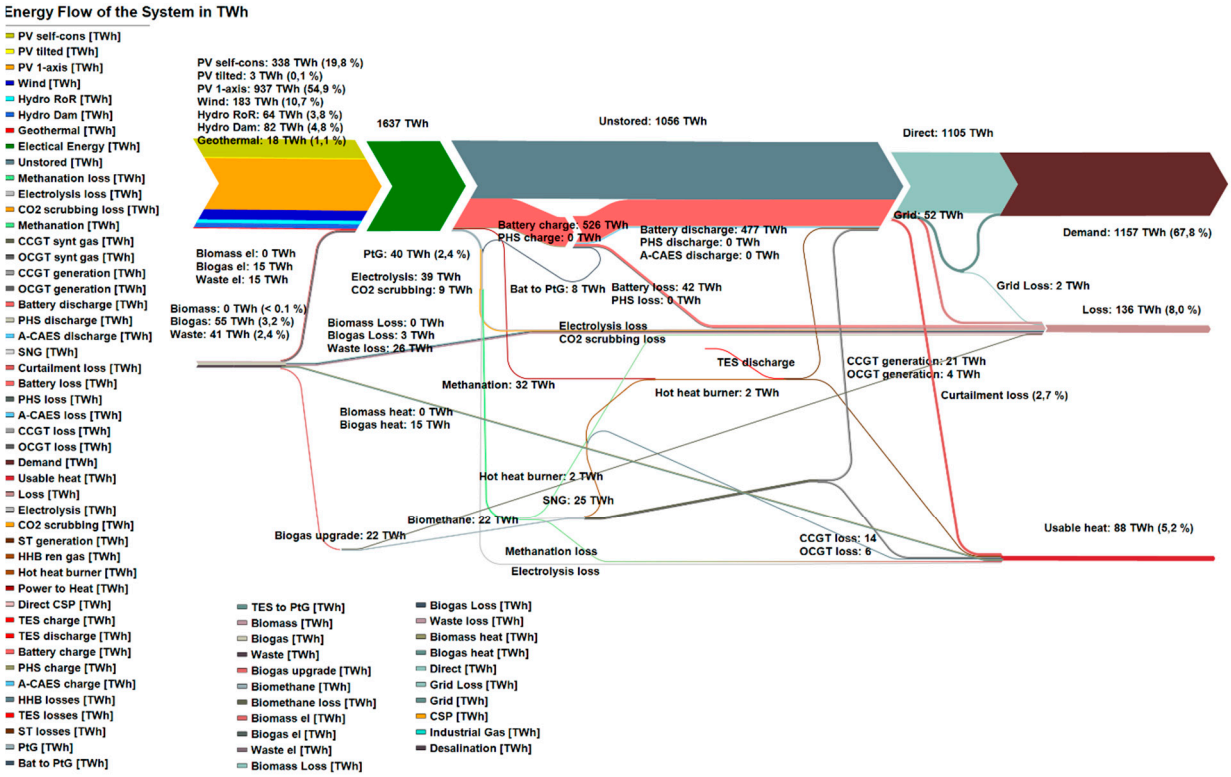


Figure S9. Energy flow of the system for the GI 0% scenarios for the year 2040.

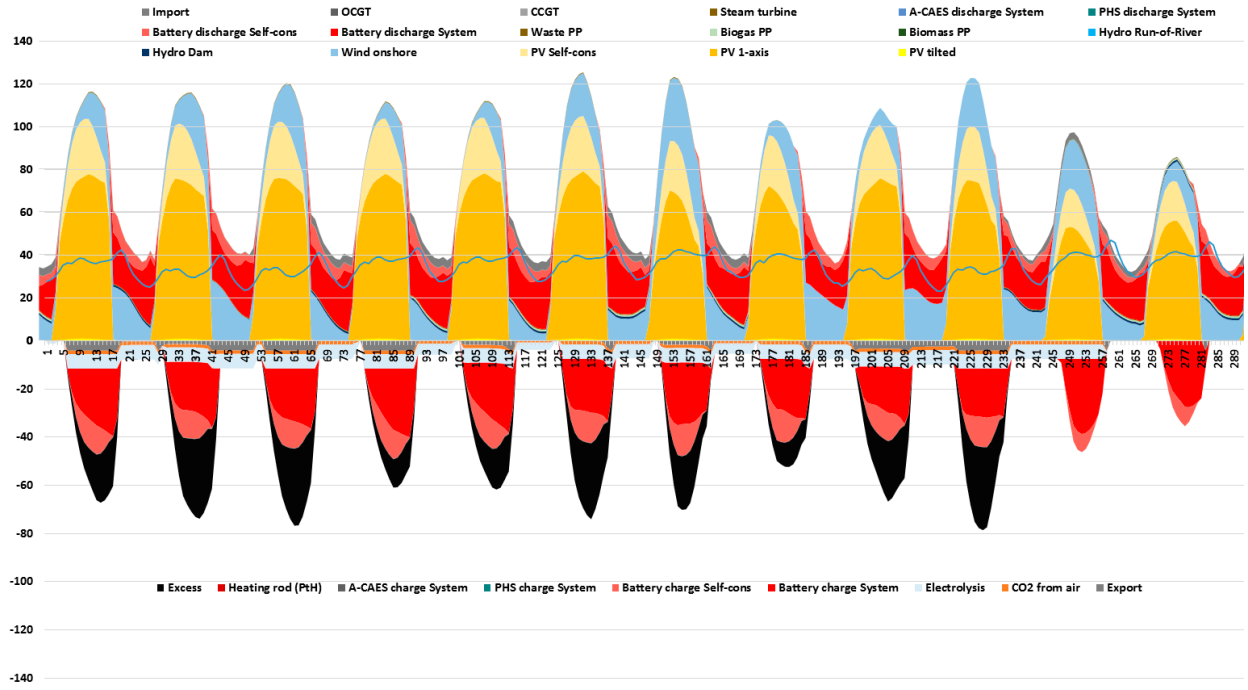


Figure S10. Hourly generation profile for the ZAFLS sub-region

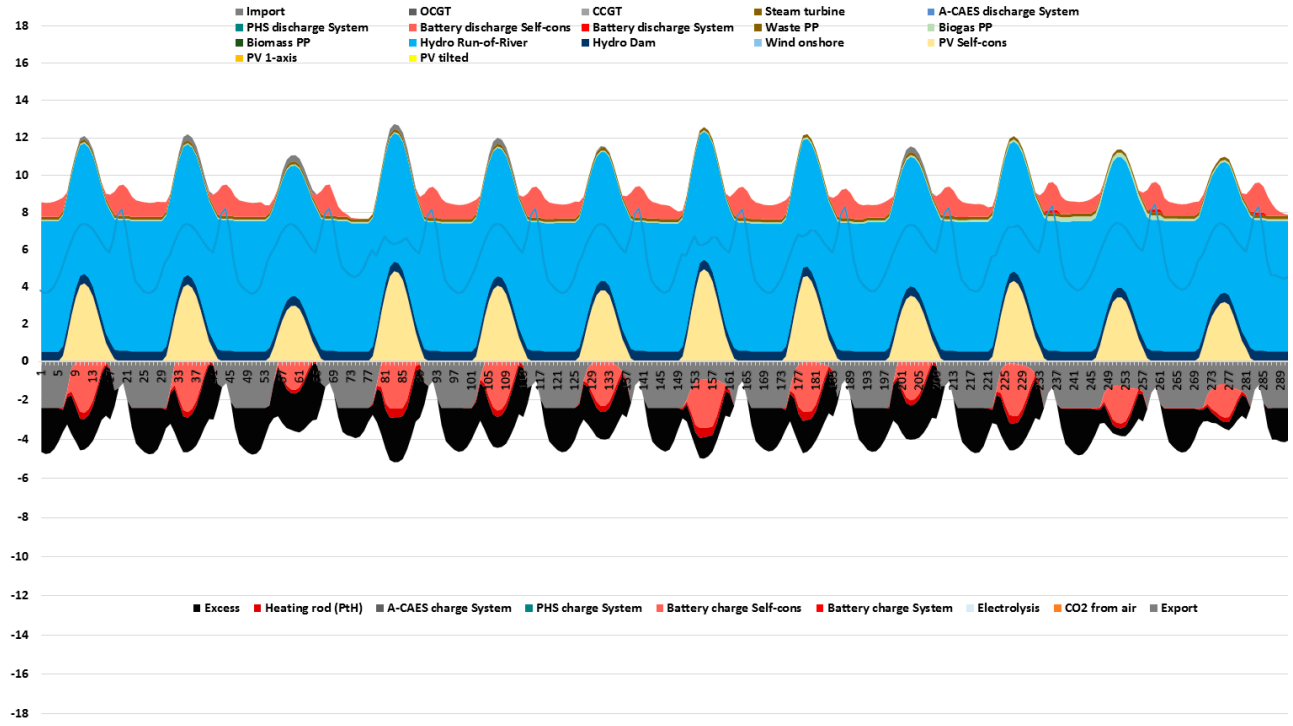


Figure S11. Hourly generation profile for the COG sub-region

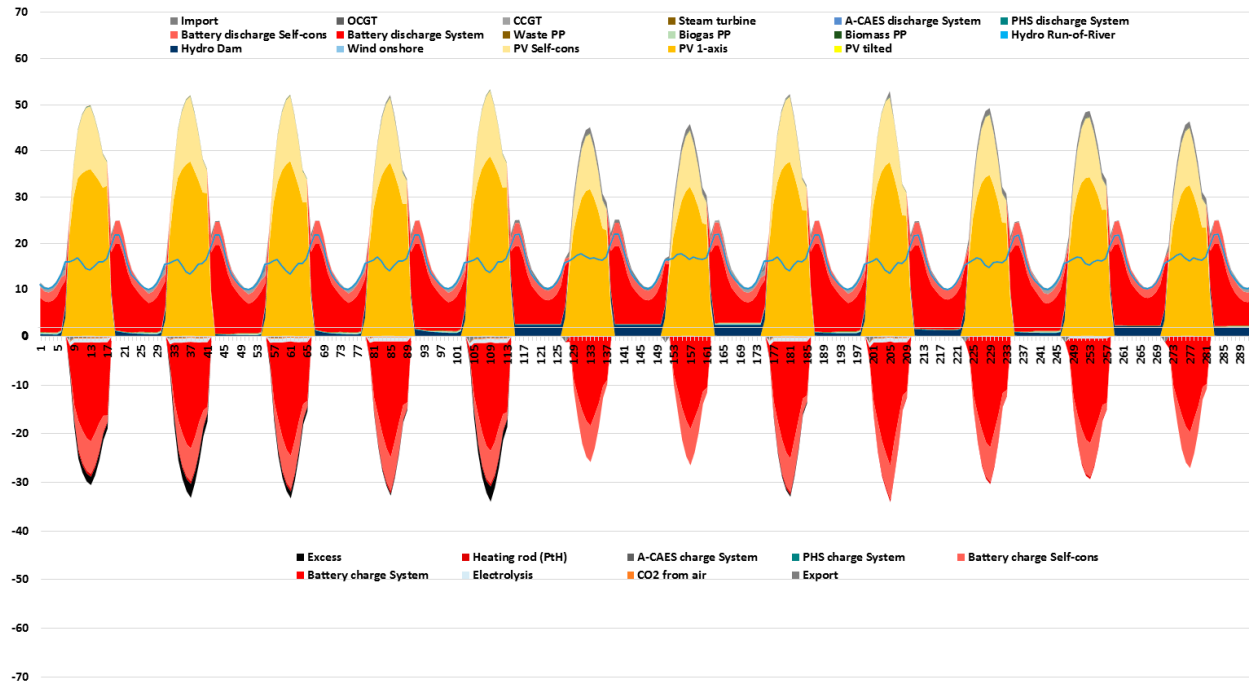


Figure S12. Hourly generation profile for the North Nigeria sub-region

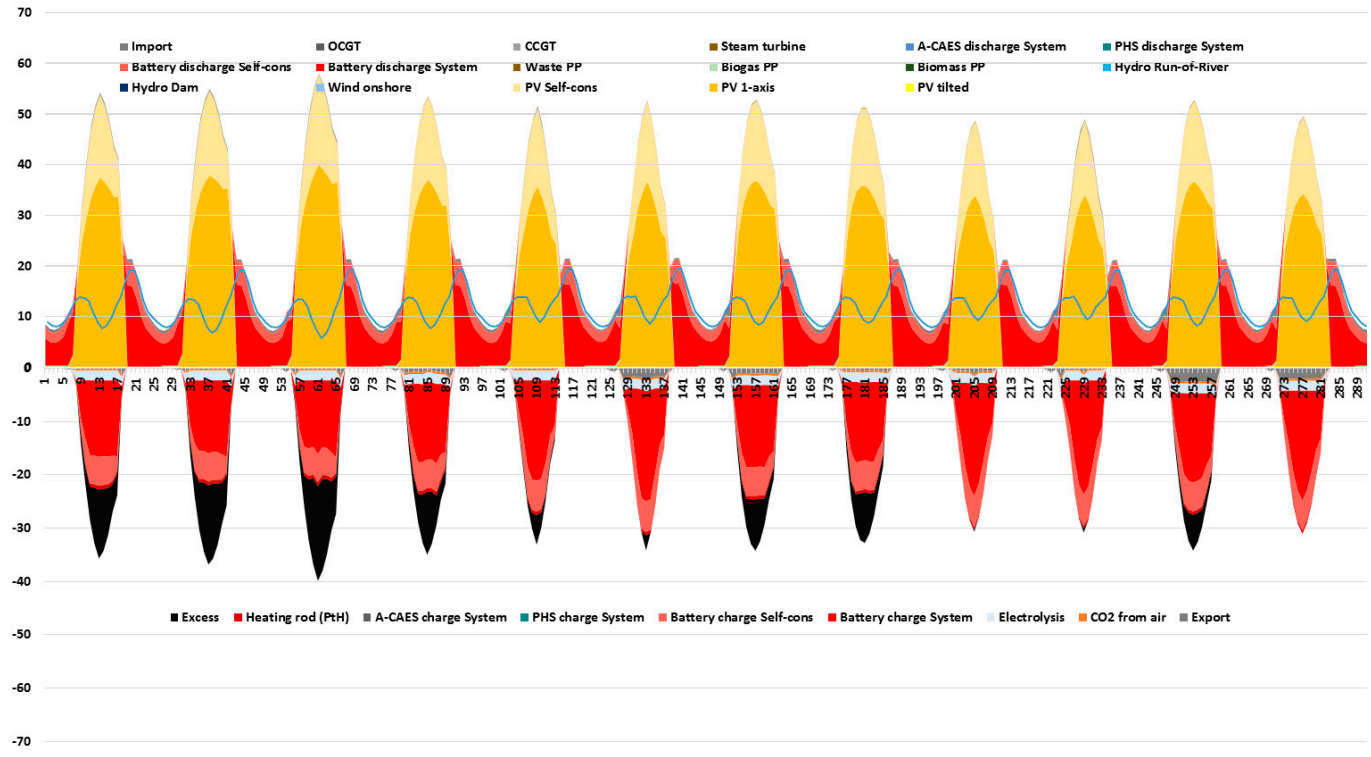


Figure S13. Hourly generation profile for the South Nigeria sub-region