

Supplementary Material for:

A Cost Optimized Fully Sustainable Power System for Southeast Asia and the Pacific Rim

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Table S1: Efficiencies and energy to power ratio of storage technologies.

Technology	Efficiency [%]	Energy/Power Ratio [h]	Self-Discharge [%/h]
Battery	90	6	0
PHS	85	8	0
A-CAES	70	100	0.001
TES	90	8	0.002
Gas storage	100	80*24	0

Table S2: Efficiency assumptions for energy system components for the 2020 and 2030 reference years.

	η_{el} [%]	η_{th} [%]
CSP (solar field)		51
Steam turbine	42	
Hot heat burner		95
Heating rod		99
Water electrolysis		84
Methanation		77
CO ₂ scrubbing		78
CCGT	58	
OCGT	43	
Geothermal	24	
Biomass CHP	40	45
Biogas CHP	42	43
Waste incinerator	34	
Biogas upgrade		98

Table S3: Efficiency assumptions for HVDC transmission.

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

Table S4: Regional grid electricity prices.

Region	Electricity costs [€/MWh]		
	Residential	Commercial	Industrial
Total area	157	151	149
New Zealand	221	135	182
Australia East	183	162	130
Australia West	183	162	130
Indonesia Papua + Papua New Guinea	325	310	302
Sumatra	100	106	113
Java + Timor-Leste	100	106	113
Indonesia East	100	106	113
Malaysia West + Singapore	112	103	100
Malaysia East + Brunei	112	103	100
Philippines	217	192	203
Myanmar	182	182	182
Thailand	124	125	125
Laos	78	116	98
Vietnam	78	116	98
Cambodia	235	238	241

Table S5: Regional biomass potentials and geothermal energy potentials.

Region	Biomass potential [TWh _{th} /a]			Geothermal Potential [TWh _{th} /a]
	Solid waste	Solid biomass	Biogas sources	
Total area	66.4	532.0	140.8	504.7
New Zealand	2.3	15.1	9.6	4.1
Australia East	14.2	50.3	36.1	28.1
Australia West	2.2	17.7	5.6	0.0
Indonesia Papua + Papua New Guinea	0.5	21.2	0.5	1.5
Sumatra	4.2	56.6	5.0	272.4
Java + Timor-Leste	13.5	101.8	16.1	0.8
Indonesia East	2.7	51.5	3.2	41.9
Malaysia West + Singapore	0.5	13.9	0.5	70.5
Malaysia East + Brunei	2.0	11.3	2.1	0.0
Philippines	5.3	71.1	15.4	0.0
Myanmar	2.5	38.9	4.9	57.5
Thailand	8.6	10.2	26.7	26.8
Laos	0.5	4.3	0.6	0.0
Vietnam	6.1	59.9	13.2	1.1
Cambodia	1.2	8.1	1.1	0.0

Table S6: Regional biomass costs.

Region	Biomass costs [€/MWh]		
	Solid waste	Solid biomass	Biogas sources
Total area	-10.4	10.08	3.74
New Zealand	-10.7	15.97	0.00
Australia East	-10.03	8.54	3.59
Australia West	-10.03	13.05	3.59
Indonesia Papua + Papua New Guinea	-10.15	15.17	4.38
Sumatra	-10.15	11.55	4.38
Java + Timor-Leste	-10.15	7.62	4.38
Indonesia East	-10.15	13.06	4.38
Malaysia West + Singapore	-10.17	13.59	1.52
Malaysia East + Brunei	-10.17	16.01	1.52
Philippines	-10.17	7.72	7.87
Myanmar	-10.17	5.37	5.77
Thailand	-10.17	7.49	9.09
Laos	-10.17	5.26	0.00
Vietnam	-10.13	5.46	5.00
Cambodia	-10.17	5.36	3.74

Table S7: Lower limits of installed capacities in Southeast Asian sub-regions.

Region	Installed capacity [MW]			
	Solar PV	Wind	Hydro RoR and dams	PHS
Total area	4698.7	5242.7	45924.5	4319.5
New Zealand	23.5	682.9	5107.0	0.0
Australia East	3233.5	3316.8	5827.5	2391.1
Australia West	12.2	489.6	132.0	0.0
Indonesia Papua + Papua New Guinea	0.6	0.0	76.5	0.0
Sumatra	0.0	0.0	635.0	0.0
Java + Timor-Leste	46.1	1.5	5189.0	0.0
Indonesia East	0.0	0.3	391.0	0.0
Malaysia West + Singapore	114.2	0.2	2389.0	0.0
Malaysia East + Brunei	6.0	0.0	1914.5	0.0
Philippines	45.2	331.5	1966.0	684.6
Myanmar	23.0	0.0	2862.0	0.0
Thailand	1172.0	282.6	2367.0	1243.8
Laos	3.0	0.0	269.0	0.0
Vietnam	11.8	137.2	15969.0	0.0
Cambodia	7.7	0.0	830.0	0.0

Table S8: Upper limits on installable capacities in Southeast Asian regions in units of GW_{th} for CSP and GW_{el} for all other technologies.

Region	Area	Limits [GW]					
	[1000 km ²]	Solar CSP	Solar PV	Wind	Hydro RoR	Hydro dams	PHS
Total area	12640	195331	57450	4291	40	41	13
New Zealand	268	4070	1197	89	4	4	0
Australia East	4193	64147	18867	1409	5	5	5
Australia West	3513	53755	15810	1181	0	0	0
Indonesia Papua + Papua New Guinea	394	13495	3969	296	0	0	0
Sumatra	602	7344	2160	161	1	1	0
Java + Timor-Leste	202	2341	689	51	4	4	0
Indonesia East	719	10985	3231	241	1	0	0
Malaysia West + Singapore	206	2020	594	44	2	2	0
Malaysia East + Brunei	123	3158	929	69	2	1	0
Philippines	300	4561	1341	100	3	1	1
Myanmar	677	10248	3014	225	2	4	0
Thailand	515	7881	2318	173	2	2	2
Laos	231	3528	1038	78	0	3	0
Vietnam	515	5005	1472	110	13	13	0
Cambodia	183	2794	822	61	1	1	0

Table S9: Annual industrial gas demand and water demand for year 2030.

	Annual gas demand		Annual electricity demand for gas synthesis	Annual water desalination demand	Annual electricity demand for water desalination
	[Bcm]	[TWh _{th}]	[TWh _{el}]	[Mil. m³]	[TWh _{el}]
Total	53.9	572.4	969.6	9667.3	36.1
New Zealand	0.9	9.3	5.4	0.0	0.0
Australia East	19.3	204.9	344.7	5162.9	19.7
Australia West	11.7	124.1	230.0	56.9	0.3
Indonesia Papua + Papua New Guinea	0.0	0.0	0.0	0.0	0.0
Sumatra	3.7	39.8	71.0	0.0	0.0
Java + Timor-Leste	6.6	69.9	117.7	2060.7	9.0
Indonesia East	2.6	27.4	49.2	0.0	0.0
Malaysia West + Singapore	4.3	45.4	86.1	0.0	0.0
Malaysia East + Brunei	1.7	18.4	32.5	0.0	0.0
Philippines	0.1	0.8	0.0	2327.9	7.0
Myanmar	0.3	3.5	4.4	0.0	0.0
Thailand	2.2	23.1	19.6	0.0	0.0
Laos	0.0	0.0	0.0	0.0	0.0
Vietnam	0.5	5.7	8.9	58.9	0.2
Cambodia	0.0	0.0	0.0	0.0	0.0

Table S10: Total LCOE components in all sub-regions of Southeast Asia.

Region-wide	LCOE primary	LCOC	LCOS	LCOT	LCOE total	
	[€/MWh]	[€/MWh]	[€/MWh]	[€/MWh]	[€/MWh]	
Area average	44.4	1.9	20.4	0.0	66.7	
New Zealand	47.5	0.7	8.3	0.0	56.5	
Australia East	40.4	3.8	10.9	0.0	55.1	
Australia West	35.8	2.4	12.5	0.0	50.7	
Indonesia Papua + Papua New Guinea	42.4	0.1	18.5	0.0	61.0	
Sumatra	51.2	0.0	6.7	0.0	58.0	
Java + Timor-Leste	45.5	0.5	16.2	0.0	62.2	
Indonesia East	46.3	0.7	4.5	0.0	51.4	
Malaysia West + Singapore	40.5	3.1	39.9	0.0	83.5	
Malaysia East + Brunei	38.0	2.1	32.8	0.0	72.9	
Philippines	47.9	0.5	16.0	0.0	64.3	
Myanmar	46.7	5.7	15.1	0.0	67.5	
Thailand	44.3	2.9	30.1	0.0	77.3	
Laos	42.6	0.4	15.5	0.0	58.4	
Vietnam	46.7	1.1	21.7	0.0	69.5	
Cambodia	47.9	1.4	25.7	0.0	75.0	

Country-wide	LCOE primary	LCOC	LCOS	LCOT	LCOE total	export (-)/import (+)
	[€/MWh]	[€/MWh]	[€/MWh]	[€/MWh]	[€/MWh]	[%]
Area average	44.3	1.9	19.9	0.2	66.2	1.1
New Zealand	47.5	0.7	8.3	0.0	56.5	0.0
Australia East	40.4	3.8	10.9	0.0	55.1	0.0
Australia West	35.8	2.4	12.5	0.0	50.7	0.0
Indonesia Papua + Papua New Guinea	42.4	0.1	18.5	0.0	61.0	0.0
Sumatra	51.0	0.0	4.6	0.6	56.2	-2.3
Java + Timor-Leste	44.7	0.0	15.5	0.6	60.9	4.5
Indonesia East	46.4	0.0	1.6	1.7	49.7	-13.0
Malaysia West + Singapore	40.5	3.1	39.0	0.3	82.8	0.5
Malaysia East + Brunei	37.7	2.4	30.6	0.7	71.5	-1.3
Philippines	47.9	0.5	16.0	0.0	64.3	0.0
Myanmar	46.7	5.7	15.1	0.0	67.5	0.0
Thailand	44.3	2.9	30.1	0.0	77.3	0.0
Laos	42.6	0.4	15.5	0.0	58.4	0.0
Vietnam	46.7	1.1	21.7	0.0	69.5	0.0
Cambodia	47.9	1.4	25.7	0.0	75.0	0.0

Area-wide	LCOE primary	LCOC	LCOS	LCOT	LCOE total	export (-)/import (+)
	[€/MWh]	[€/MWh]	[€/MWh]	[€/MWh]	[€/MWh]	[%]
Area average	45.6	1.1	15.9	1.0	63.5	0.0
New Zealand	47.5	0.7	8.3	0.0	56.5	0.0
Australia East	40.4	3.8	10.9	0.0	55.1	0.0
Australia West	35.8	2.4	12.5	0.0	50.7	0.0
Indonesia Papua + Papua New Guinea	42.5	0.1	18.2	0.1	60.9	0.3
Sumatra	56.0	0.1	5.8	2.4	64.3	-18.4

Java + Timor-Leste	45.0	0.3	15.2	0.3	60.8	-0.1
Indonesia East	50.1	0.2	5.6	2.8	58.7	-33.9
Malaysia West + Singapore	41.6	0.7	25.4	2.1	69.9	14.0
Malaysia East + Brunei	39.9	0.2	17.1	2.4	59.7	22.1
Philippines	47.9	0.5	16.0	0.0	64.3	0.0
Myanmar	53.2	0.4	7.8	3.5	64.9	-34.3
Thailand	44.3	0.4	23.2	1.7	69.6	12.4
Laos	43.2	0.4	5.4	2.1	51.1	-0.5
Vietnam	47.4	0.8	19.5	0.3	68.1	-1.2
Cambodia	44.6	1.7	26.6	1.3	74.2	0.8

Integrated scenario	LCOE primary	LCOC	LCOS	LCOT	LCOE total	export (-)/import (+)
	[€/MWh]	[€/MWh]	[€/MWh]	[€/MWh]	[€/MWh]	[%]
Area average	39.1	1.0	10.5	0.5	51.1	3.6
New Zealand	47.1	0.7	5.6	0.0	53.4	0.0
Australia East	33.8	1.7	3.7	0.0	39.2	0.0
Australia West	28.8	1.7	1.4	0.0	32.0	0.0
Indonesia Papua + Papua New Guinea	42.4	0.1	18.4	0.0	60.9	0.0
Sumatra	46.0	0.2	2.7	1.0	50.0	-8.1
Java + Timor-Leste	35.4	0.5	11.4	0.2	47.4	0.0
Indonesia East	39.5	0.6	2.0	1.3	43.5	-15.1
Malaysia West + Singapore	36.5	1.1	18.5	0.9	57.1	6.6
Malaysia East + Brunei	36.3	0.8	12.8	1.5	51.4	14.0
Philippines	46.5	0.5	17.7	0.1	64.8	-0.2
Myanmar	52.5	0.1	8.4	3.0	64.0	-26.0
Thailand	43.0	0.5	23.0	1.5	68.0	10.6
Laos	43.5	0.3	4.6	2.2	50.6	1.2
Vietnam	47.7	0.8	19.4	0.3	68.2	-2.2
Cambodia	43.6	1.6	26.6	1.2	73.1	0.3

Table S11: Prosumers electricity costs, installed capacities and electricity utilization for Southeast Asia.

Prosumers parameters	Residential	Commercial	Industrial
Electricity price [€/kWh]	0.130	0.132	0.125
PV LCOE [€/kWh]	0.028	0.037	0.038
Self-consumption PV LCOE [€/kWh]	0.035	0.044	0.051
Self-consumption PV and Battery LCOE [€/kWh]	0.063	0.073	0.068
Self-consumption LCOE [€/kWh]	0.063	0.073	0.067
Benefit [€/kWh]	0.067	0.059	0.058
Installed capacities	Residential	Commercial	Industrial
PV [GW]	65	37	47
Battery storage [GWh]	81	46	44
Generation	Residential	Commercial	Industrial
PV [TWh]	101	59	73
Battery storage [TWh]	26	14	14
Excess [TWh]	16	8	10
Utilization	Residential	Commercial	Industrial
Self-consumption of generated PV electricity [%]	80.8	83.9	84.2
Self-coverage market segment [%]	12.5	12.0	10.8
Self-coverage operators [%]	62.8	59.9	54.2

Table S12: Important system parameters for the region-wide open trade scenario for 2030 for Southeast Asia and Eurasia.

		Southeast Asia		Eurasia	
		with A-CAES	without A-CAES	with A-CAES	without A-CAES
Total annualized levelized cost	[b€]	102.6	102.66	91.08	91.73
Total LCOE	[€/MWh _{el}]	62.54	62.58	62.61	63.06
LCOS	[€/MWh _{el}]	18.01	18.09	16.77	17.53
Electricity demand	[TWh _{el}]	1629.55	1629.55	1449.88	1449.88
Curtailement losses	[TWh _{el}]	77.03	76.76	113.00	126.08
Storage losses	[TWh _{el}]	82.90	86.03	191.08	235.30
Curtailement losses (rel.)	[%]	4.7	4.7	7.8	8.7
Storage losses (rel.)	[%]	5.1	5.3	13.2	16.2
Excess energy	[TWh]	77.03	76.76	113.00	126.01
Generated electricity	[TWh]	1791.04	1790.92	1770.96	1804.39
PV total	[GW]	562.03	565.33	206.94	209.93
Wind onshore	[GW]	92.75	88.92	327.16	339.32
PV supply share in generation	[%]	49.57	55.83	15.73	15.66
Wind supply share in generation	[%]	14.53	11.87	53.62	54.59
Battery storage capacity	[GWh _{el}]	289.64	317.95	15.20	67.77
PHS storage capacity	[GWh _{el}]	800.00	805.03	9.01	9.01
A-CAES storage capacity	[GWh _{el}]	302.77	0.00	1783.47	0.00
Gas storage capacity	[GWh]	38589	37323	87184	91069
Electrolyser capacity	[GW _{el}]	7.77	8.74	32.52	43.45
Total storage output	[TWh _{el}]	347.38	348.60	144.05	144.71
Battery output	[TWh _{el}]	96.27	101.88	4.67	17.19
PHS output	[TWh _{el}]	226.91	227.81	1.63	1.27
A-CAES output	[TWh _{el}]	6.62	0.00	41.20	0.00
Gas output	[TWh _{el}]	53.25	54.13	83.55	106.61
Battery storage share	[%]	27.7	29.2	3.2	11.9
PHS storage share	[%]	65.3	65.4	1.1	0.9
A-CAES storage share	[%]	1.9	0.0	28.6	0.0
Gas storage share	[%]	15.3	15.5	58.0	73.7

Table S13: Overview on storage capacities, throughput, full cycles and utilization of A-CAES potential per year for the four scenarios for Southeast Asia.

			Region- wide	Country- wide	Area- wide	Integrated
Storage capacities	Battery SC	[TWh _{el}]	0.2	0.2	0.2	0.2
	Battery system	[TWh _{el}]	0.6	0.6	0.5	0.6
	PHS	[TWh _{el}]	0.0	0.0	0.0	0.0
	A-CAES	[TWh _{el}]	0.8	0.8	0.2	0.3
	Gas	[TWh _{th}]	39.2	37.4	30.3	43.1
Throughput of storage technologies	Battery SC	[TWh _{el}]	54.2	54.2	54.2	54.2
	Battery system	[TWh _{el}]	190.6	189.5	166.8	190.9
	PHS	[TWh _{el}]	2.3	2.3	2.3	1.3
	A-CAES	[TWh _{el}]	19.2	17.7	5.0	7.2
	Gas	[TWh _{th}]	102.2	98.5	83.1	23.5
Full cycles per year	Battery SC	[-]	316.1	316.1	316.1	316.1
	Battery system	[-]	322.4	322.5	329.3	328.9
	PHS	[-]	266.4	266.4	271.9	212.1
	A-CAES	[-]	22.7	22.7	24.5	26.7
	Gas	[-]	2.6	2.6	2.7	0.5
Utilization of A-CAES potential	Storage used	[TWh]	0.8	0.8	0.2	0.3
	Storage available	[TWh]	605,800	605,800	605,800	605,800

Table S14: Overview on storage capacities, throughput, full cycles and utilization of A-CAES potential per year for the four scenarios for Eurasia.

			Region- wide	Country- wide	Area- wide	Integrated
Storage capacities	Battery SC	[TWh _{el}]	0	0	0	0
	Battery system	[TWh _{el}]	0.015	0.015	0.009	0
	PHS	[TWh _{el}]	0.009	0.009	0.009	0.009
	A-CAES	[TWh _{el}]	1.8	0.5	0	0
	Gas	[TWh _{th}]	87.2	69.9	62.9	70.3
Throughput of storage technologies	Battery SC	[TWh _{el}]	0	0	0	0
	Battery system	[TWh _{el}]	4.7	4.7	3.1	0.1
	PHS	[TWh _{el}]	1.6	1.5	1.5	0.9
	A-CAES	[TWh _{el}]	41.2	11.6	0	0
	Gas	[TWh _{th}]	147.6	107.9	89.7	11.4
Full cycles per year	Battery SC	[-]	0	0	0	0
	Battery system	[-]	307.0	307.0	354.5	260.0
	PHS	[-]	181.0	163.3	161.5	100.1
	A-CAES	[-]	23.1	23.3	0	0
	Gas	[-]	1.7	1.5	1.4	0.2
Utilization of A-CAES potential	Storage used	[TWh]	1.8	0.5	0	0
	Storage available	[TWh]	369,000	369,000	369,000	369,000

Table S15: Electricity transmission lines parameters for the area-wide scenario for Southeast Asia.

Region 1	Region 2	Length [km]	Capacity [GW]	Utilization [%]
Indonesia Sumatra	Indonesia Java+Timor Leste	1588	0.8	82
Indonesia Sumatra	Malaysia West+Singapore	342	5.6	74
Indonesia Java+Timor Leste	Indonesia Kalimantan Sulawesi	768	0.1	79
Indonesia Kalimantan Sulawesi	Malaysia East+Brunei	224	2.6	76
Malaysia West+Singapore	Malaysia East+Brunei	1013	0.7	64
Malaysia West+Singapore	Thailand	1431	1.9	68
Myanmar	Thailand	1129	4.3	72
Thailand	Laos	528	1.1	62
Thailand	Cambodia	590	2.1	62
Laos	Vietnam	508	0.9	57
Vietnam	Cambodia	234	2.4	57

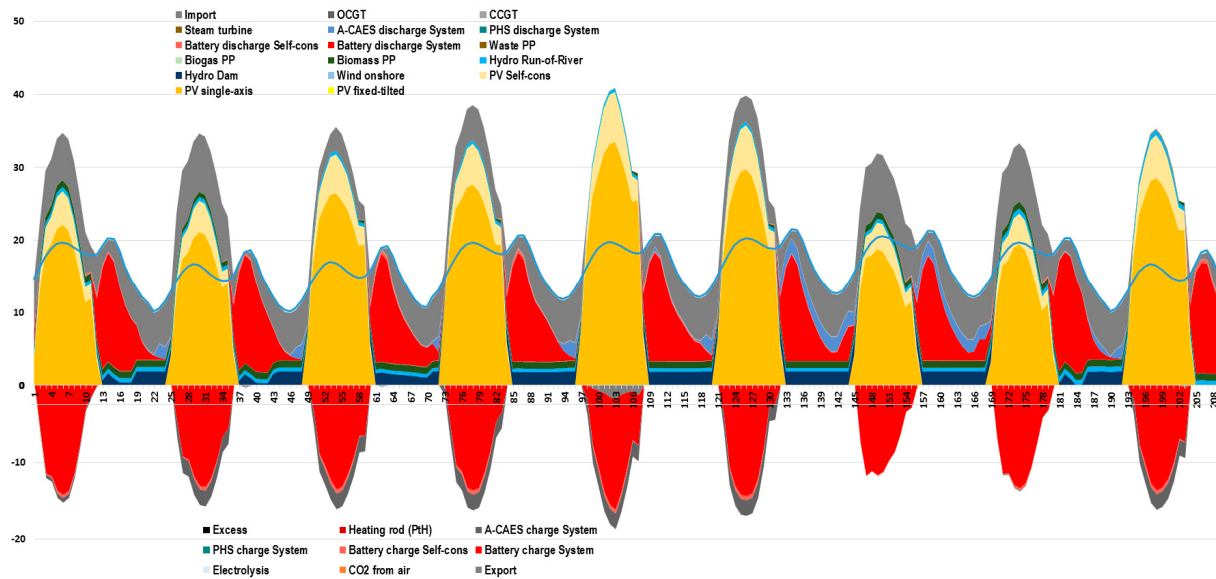


Figure S1: Hourly generation profile for a net importer region, Malaysia West + Singapore.

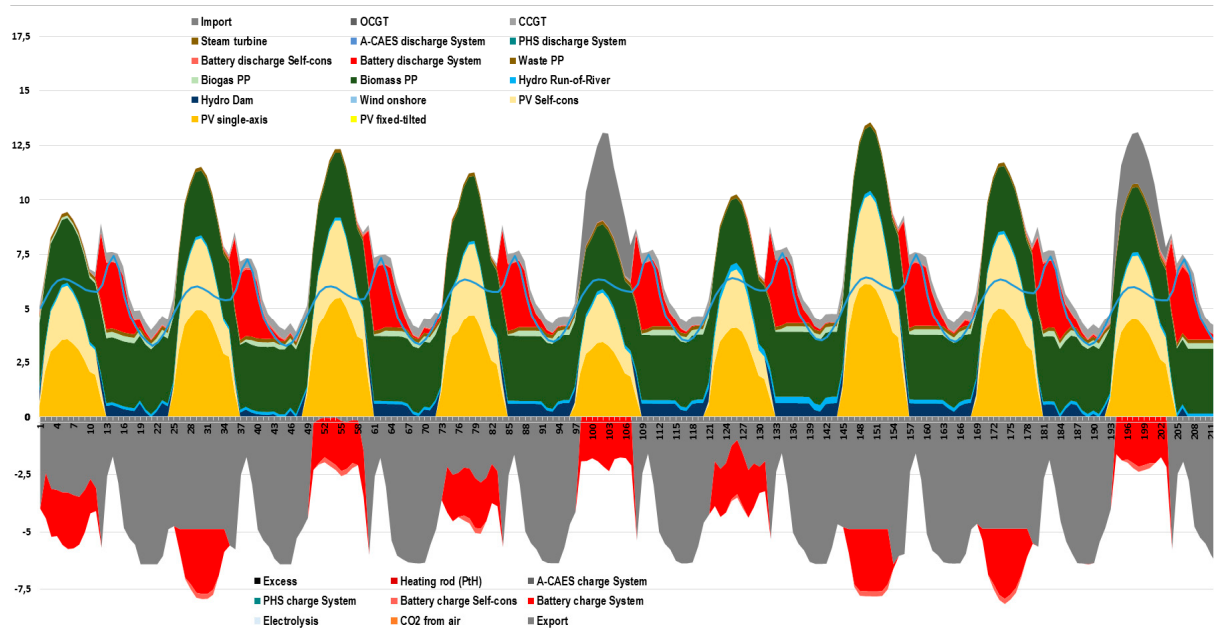


Figure S2: Hourly generation profile for net exporter region, Sumatra.

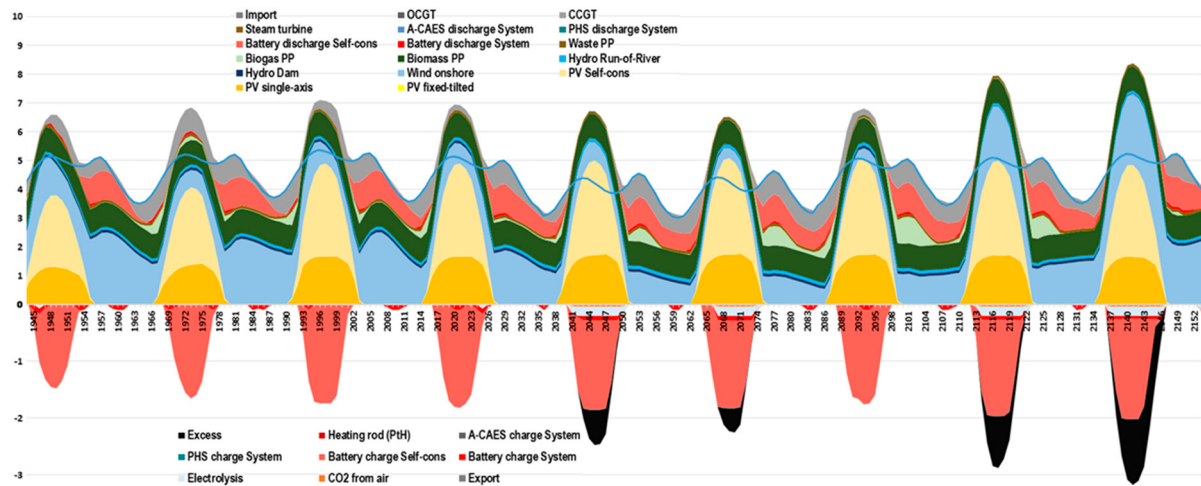


Figure S3: Hourly generation profile for Australia-West.

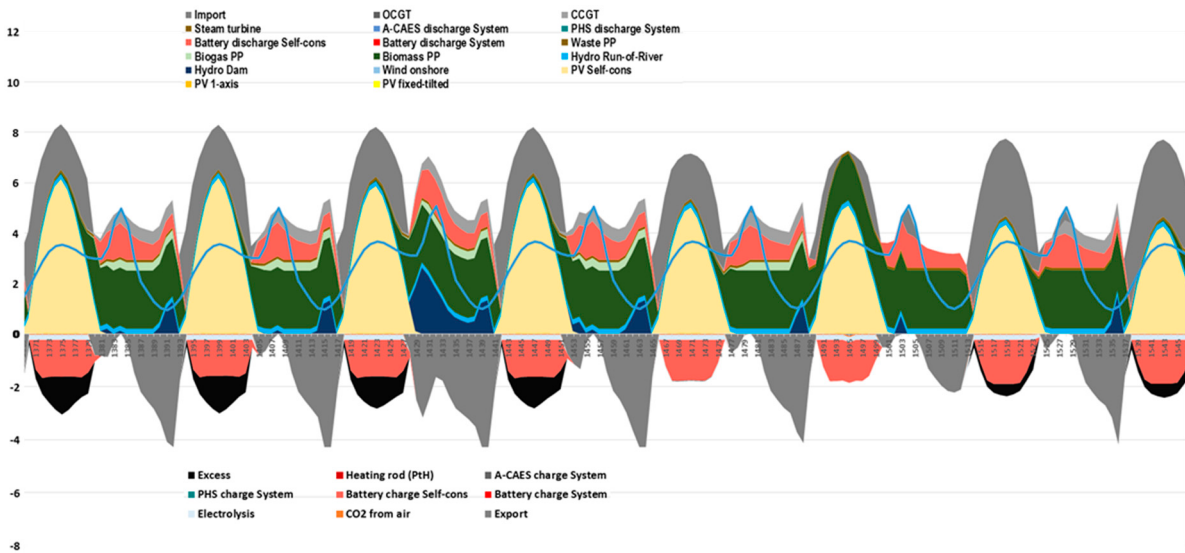


Figure S4: Hourly generation profile for Myanmar.

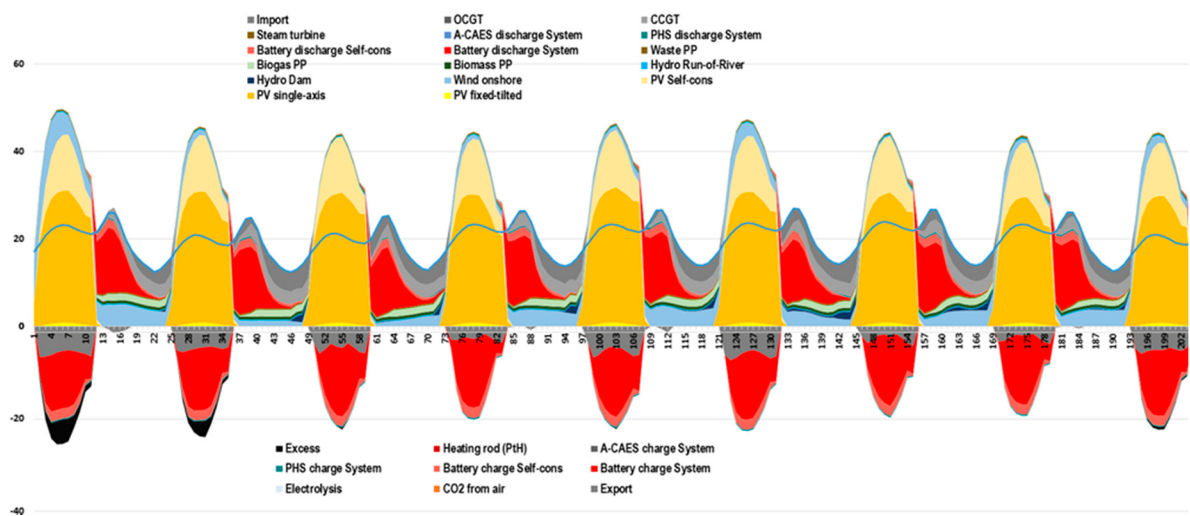


Figure S5: Hourly generation profile for Thailand.

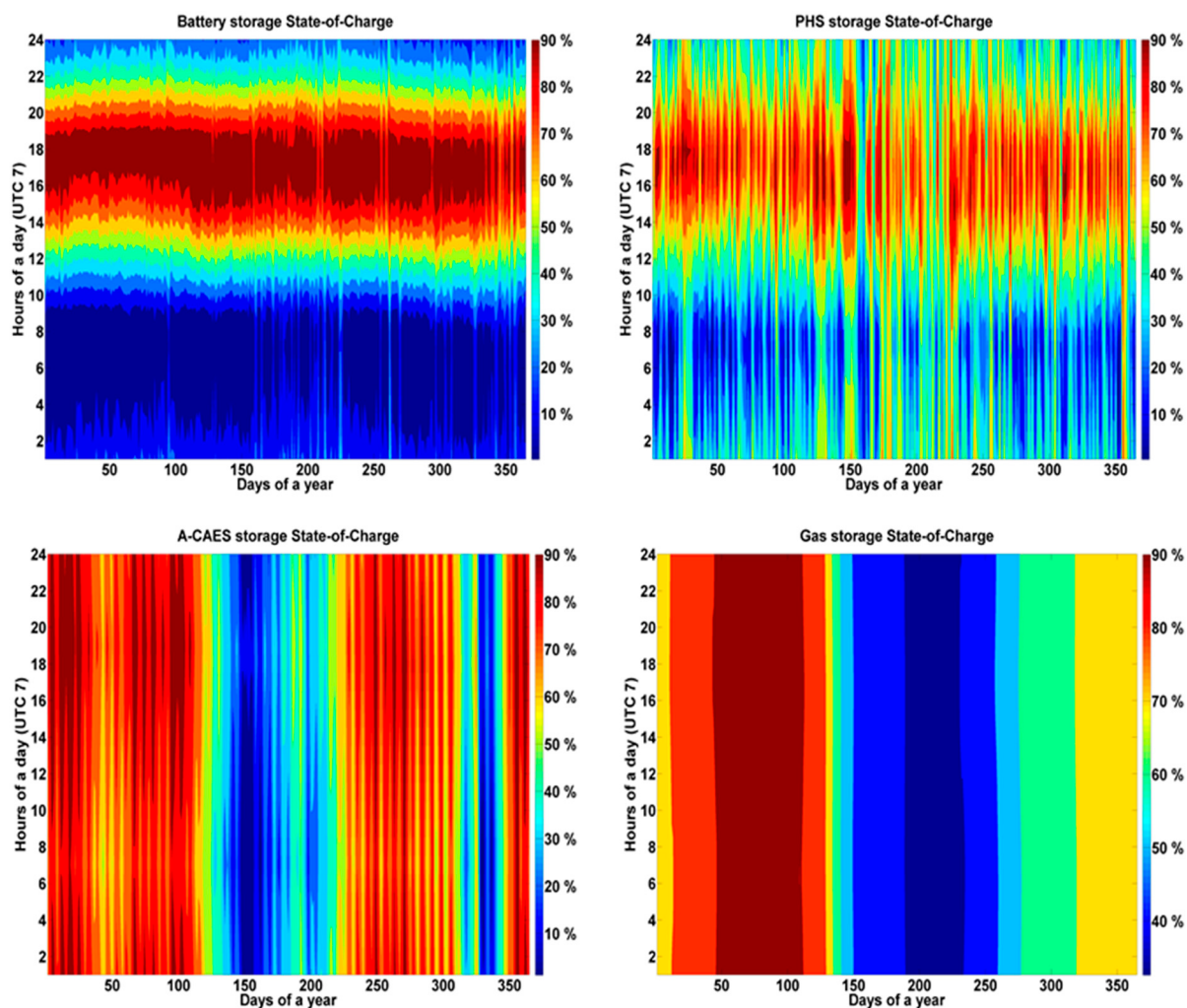


Figure S6: Aggregated yearly state-of-charge for storage technologies, battery (top left), PHS (top right), A-CAES (bottom left), gas storage (bottom right).

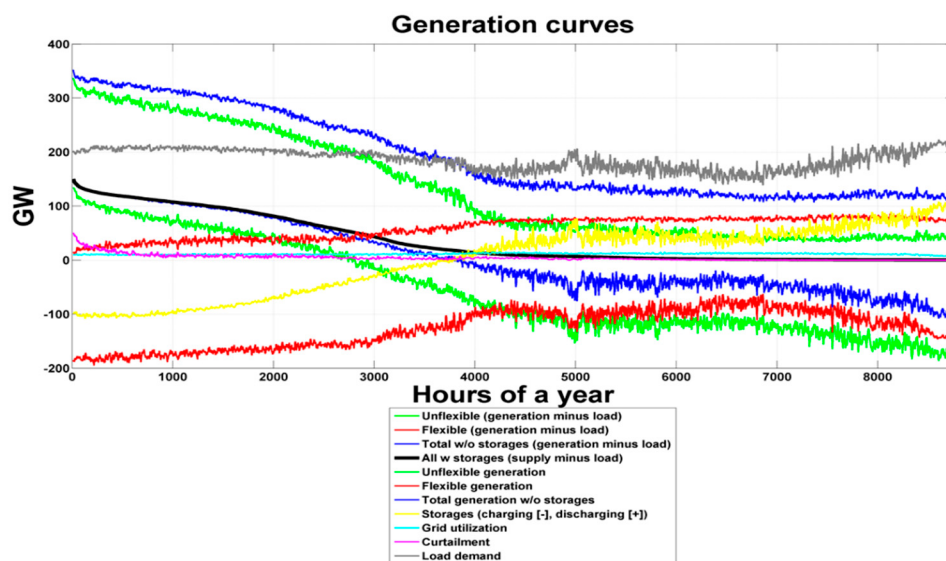
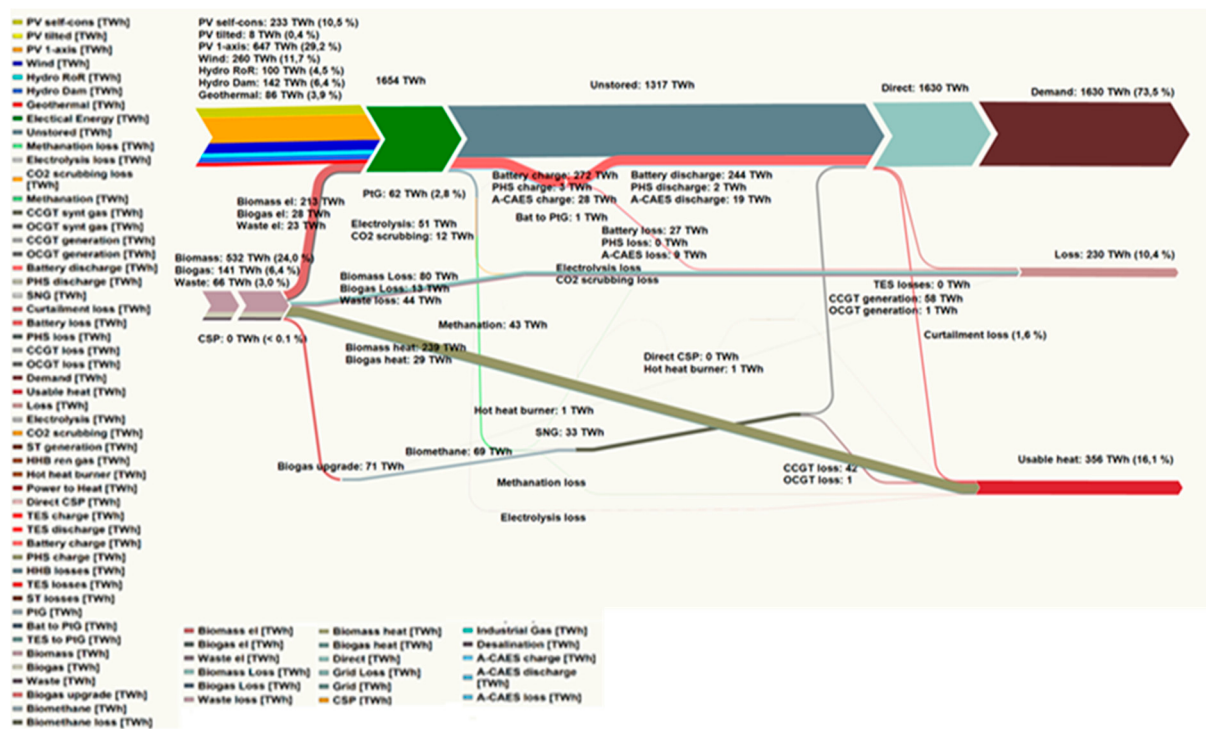
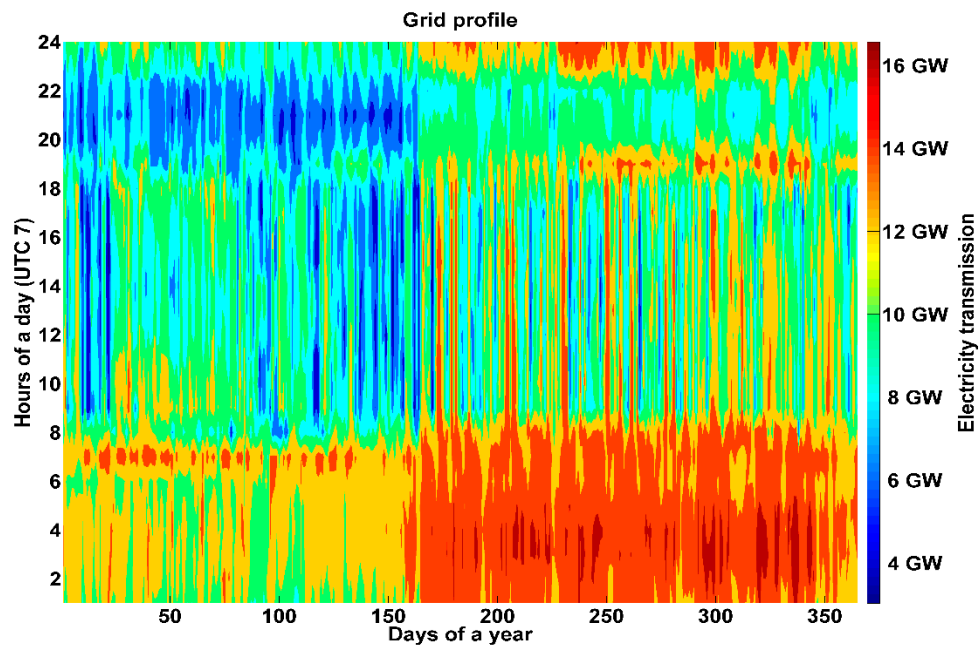


Figure S7. Electricity generation curves for a whole year for area-wide open trade scenario for Southeast Asia.



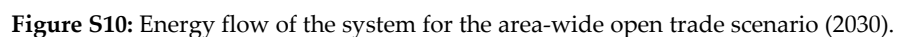


Figure S10: Energy flow of the system for the area-wide open trade scenario (2030).