Complementarity of hydro, wind and solar power as a base for a 100% RE energy supply: South America as an example

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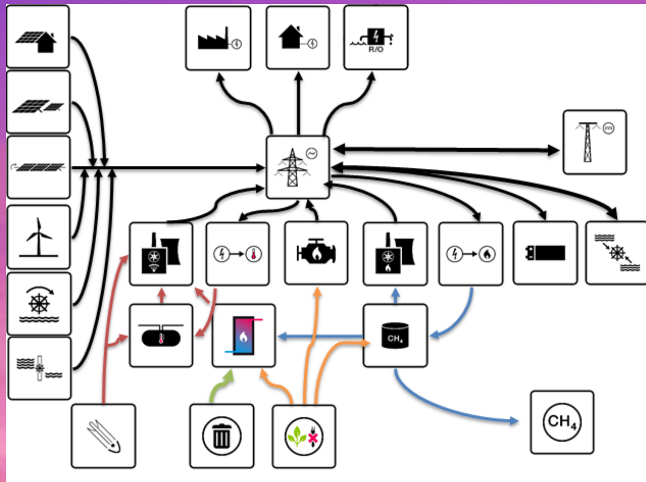

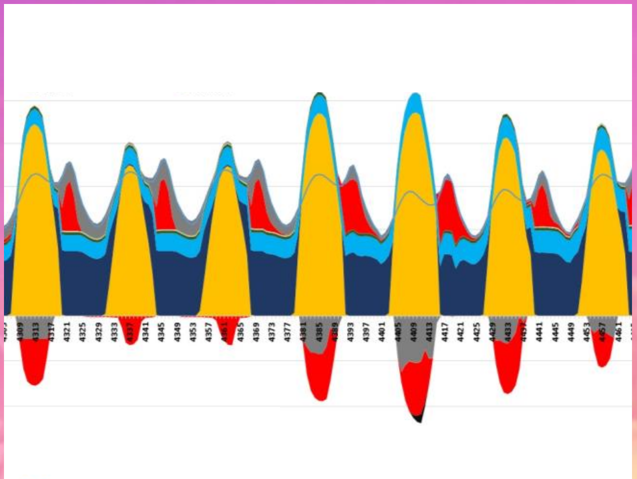

Complementarity of hydro, wind and solar power as a base for a 100% RE energy supply: South America as an example

NEO CARBON ENERGY

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Agenda

- Motivation
- Methodology and Data
- Results for the Energy System
- Results for Hourly Operation
- Alternatives
- Summary

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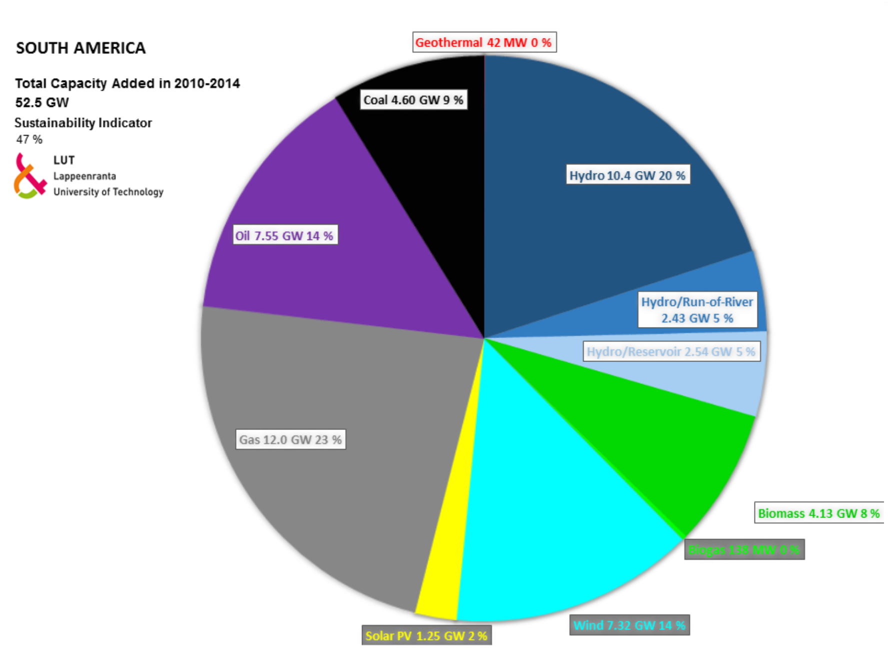
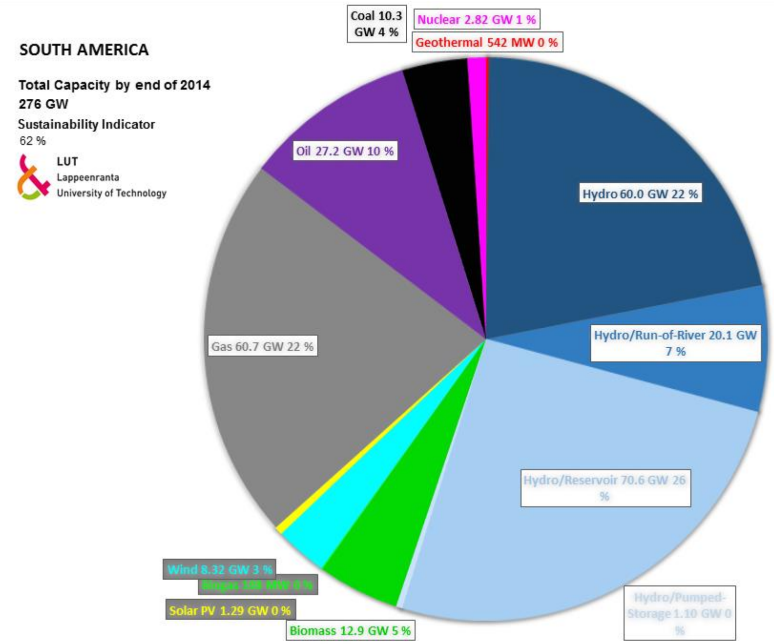
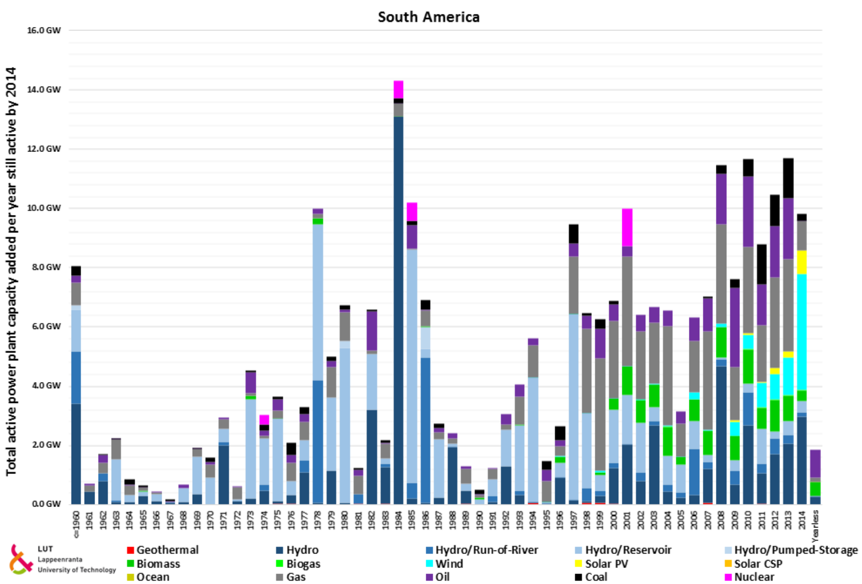
South America's RE potential

- Vast potential of non-hydro renewables enabling low cost RE technologies
- Strong renewables new markets emerging in all sectors with growing investments
- Feed-in tariffs, public competitive bidding, tax incentives, and quotas are driving deployment of renewables in South America
- Growing electricity demand (2.5%/y) and growing population
- Need to reduce vulnerability to a changing hydrological profile
- Increase economic and energy security
- Promising possibility to build cost competitive independent 100% RE system using current technologies

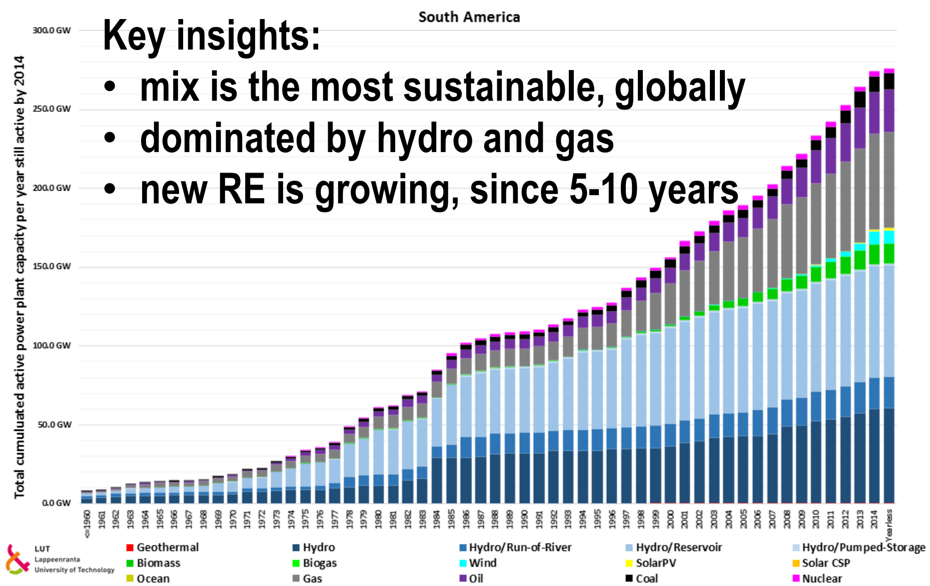
Current status of the power plant mix







Key insights:
- mix is the most sustainable, globally
- dominated by hydro and gas
- new RE is growing, since 5-10 years



Agenda

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Key Objective

Definition of an optimally structured energy system based on 100% RE supply

- optimal set of technologies, best adapted to the availability of the regions' resources,
- optimal mix of capacities for all technologies and every sub-region of South America,
- optimal operation modes for every element of the energy system,
- least cost energy supply for the given constraints.

LUT Energy model, key features

- linear optimization model
- hourly resolution
- multi-node approach
- flexibility and expandability

Input data

- historical weather data for: solar irradiation, wind speed and hydro precipitation
- synthesized load data
- efficiency/ yield characteristics of RE plants
- efficiency of energy conversion processes
- capex, opex, lifetime for all energy resources
- min and max capacity limits for all RE resources
- nodes and interconnections configuration

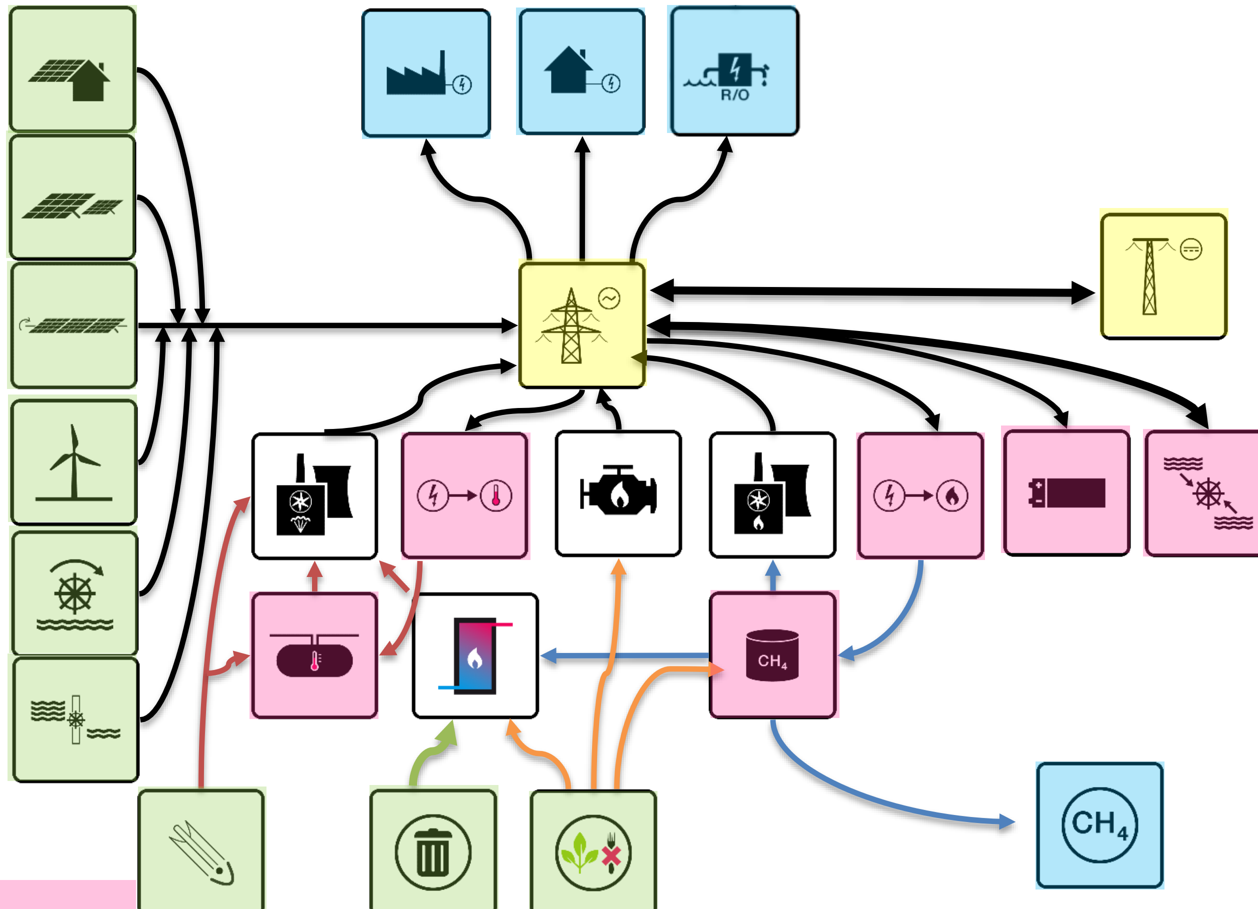
Methodology

Full system

Renewable energy sources
- PV ground-mounted (optimally tilted)
- PV rooftop
- Wind onshore
- Hydro run-of-river
- Hydro dam
- CSP
- Waste
- Biogas
- Biomass

Electricity transmission
- node-internal AC transmission
- interconnected by HVDC lines

Storage options
- Batteries
- Pumped hydro storages
- Thermal energy storage, Power-to-Heat
- Gas storage based on Power-to-Gas
  - Water electrolysis
  - Methanation
  - CO_2 from air
  - Gas storage



Energy Demand
- Electricity
- Water Desalination
- Industrial Gas

Scenarios assumptions

15 regions
- Central America
- Central South America
- 5 regions in Brazil (based on consumption centers and Brazil's grid distribution)
- 3 regions in Argentina

Key data
- ~445 mio population (2030)
- ~1813 TWh electricity demand (2030)
- ~267 GW peak load (2030)
- ~18 mio km^2 area
- ~420 bio m^3/a water demand (2030)
- ~145 mio m^3/a water desalination demand (2030)

Scenarios assumptions

Grid configurations

- **Regional-wide open trade**
  (no interconnections between regions)
- **Country-wide open trade**
  (no interconnections between countries)
- **Area-wide open trade**
  (country-wide HVDC grids are interconnected)
- **Area-wide open trade with water desalination and industrial gas production**

Assumption	Scenarios: Regional-wide open trade	Country-wide open trade	Area-wide open trade	Area-wide open trade Des-Gas
PV self-consumption	X	X	X	X
Water Desalination				X
Industrial gas demand				X

Scenarios assumptions

Financial assumptions (year 2030)

Generation costs

Technology	Capex [€/kW]	Opex fix [€/(kW·a)]	Opex var [€/kWh]	Lifetime [a]
PV fixed-tilted	550	8	0	35
PV rooftop	813	12	0	35
PV 1-axis	620	9	0	35
Wind onshore	1000	20	0	25
Hydro Run-of-River	2560	115.2	0.005	60
Hydro Dam	3000	30	0	60
Water electrolysis	380	13	0.001	30
Methanation	234	5	0	30
CO_2 scrubbing	356	14	0.0013	30
CCGT	775	19	0.002	30
OCGT	475	14	0.011	30
Biomass PP	2500	175	0.001	30
Wood gasifier CHP	1500	20	0.001	40
Biogas CHP	370	14.8	0.001	20
Steam Turbine	700	14	0	30

Technology	Capex [€/(m³·a)]	Opex fix [€/(m³·a)]	Opex var [€/(m³)]	Lifetime [a]
Water Desalination	2.23	0.097	0	30

Technology	Energy/Power Ratio [h]
Battery	6
PHS	8
Gas Storage	80*24

	Efficiency [%]
Battery	90
PHS	92
Gas Storage	100
Water Electrolysis	84
CO_2 Scrubbing	78
Methanisation	77
CCGT	58
OCGT	43
Biomass PP	40
MCW Incinerator	34
Biogas CHP	40
Steam Turbine	42
CSP collector	51

Scenarios assumptions

Financial assumptions (year 2030)

Storage and transmission costs

Technology	Capex [€/kWh]	Opex fix [€/(kWh·a)]	Opex var [€/kWh]	Lifetime [a]
Battery	150	10	0.0002	10
PHS	70	11	0.0002	50
Gas Storage	0.05	0	0	50

Technology	Capex [€/(m^3·h)]	Opex fix [€/(m^3·h·a)]	Opex var [€/(m^3·h)]	Lifetime [a]
Water Storage	65	1	0	50

Technology	Capex [€/(m^3·h·km)]	Opex fix [€/(m^3·h·km·a)]	Opex var [m^3·h·km]	Lifetime [a]
Horizontal pumping	15	2.3	0.0004	30
Vertical pumping	23	2.4	0.0036	30

Technology	Capex [€/(kW·km)]	Opex fix [€/(kW·km·a)]	Opex var [€/kW]	Lifetime [a]
Transmission Line	0.612	0.0075	0	50

Technology	Capex [€/kW]	Opex fix [€/(kW·a)]	Opex var [€/kW]	Lifetime [a]
Converter Station	180	1.8	0	50

WACC = 7%

Scenarios assumptions

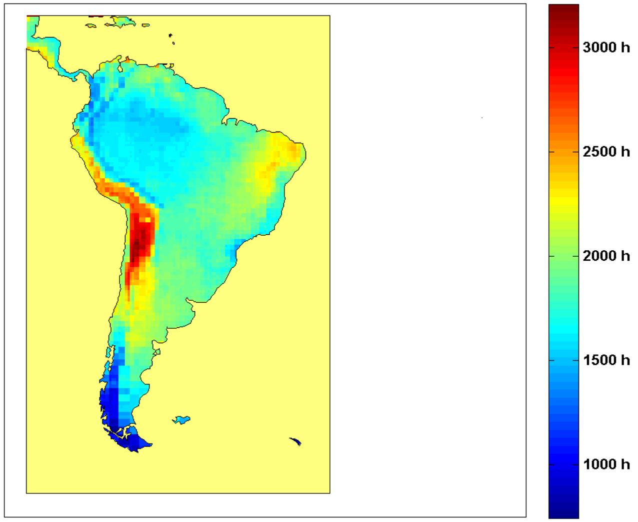
Full load hours

Region	PV fixed-tilted FLH	PV 1-axis FLH	CSP FLH	Wind FLH
Central America	1633	2141	1854	1557
Colombia	1520	1835	1322	799
Venezuela	1573	1981	1558	980
Ecuador	1510	1942	1323	1939
Peru	1820	2414	1944	1815
Central South America	1775	2341	2098	2813
Brazil South	1470	1877	1774	2012
Brazil São Paulo	1544	1984	1844	1653
Brazil Southeast	1588	2069	1858	1541
Brazil North	1499	1904	1662	823
Brazil Northeast	1668	2296	2024	3371
Argentina Northeast	1497	1957	1908	2877
Argentina East	1532	2008	1973	3824
Argentina West	1799	2425	2338	4801
Chile	1909	2641	2528	4513

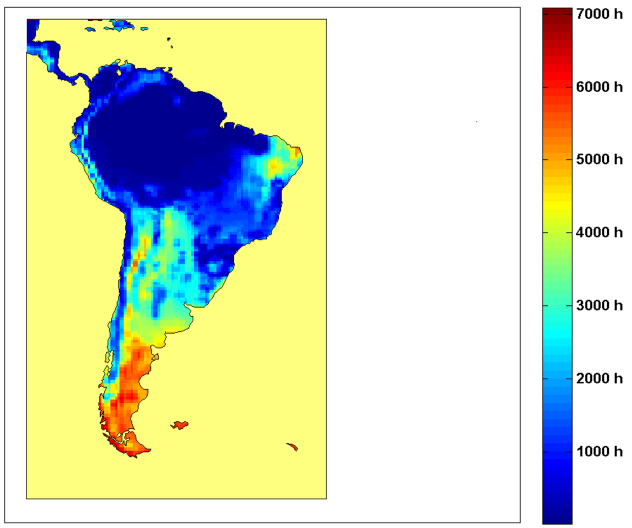
FLH of region computed as weighed average of regional sub-areas (about 50 km x 50 km each):

- 0%-10% best “sub-areas” of region – 0.3
- 10%-20% best “sub-areas” of region – 0.3
- 20%-30% best “sub-areas” of region – 0.2
- 30%-40% best “sub-areas” of region – 0.1
- 40%-50% best “sub-areas” of region – 0.1

PV (1-axis tracking) full load hours



Wind (E101 at 150m) full load hours

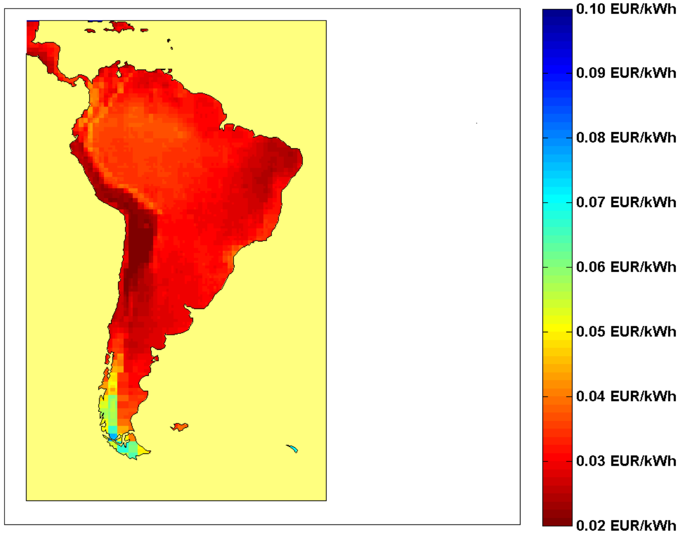


Data: based on NASA (Stackhouse P.W., Whitlock C.H., (eds.), 2009. SSE release 6.0) reprocessed by DLR (Stetter D., 2012. Dissertation, Stuttgart)

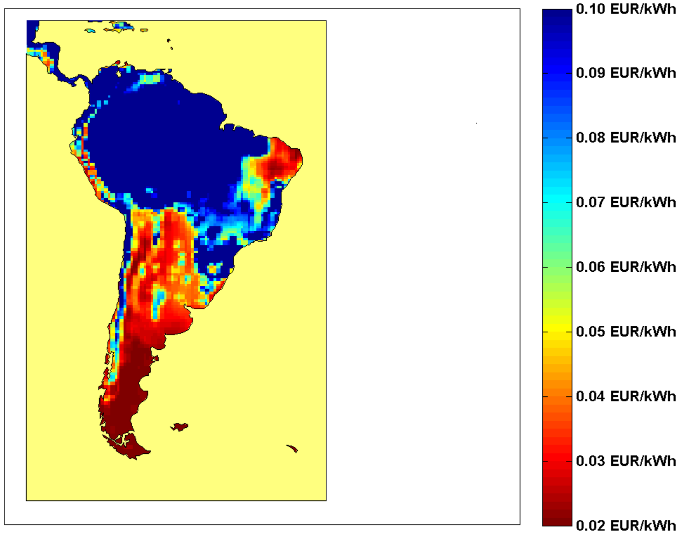
Scenarios assumptions

PV and Wind LCOE (weather year 2005, cost year 2030)

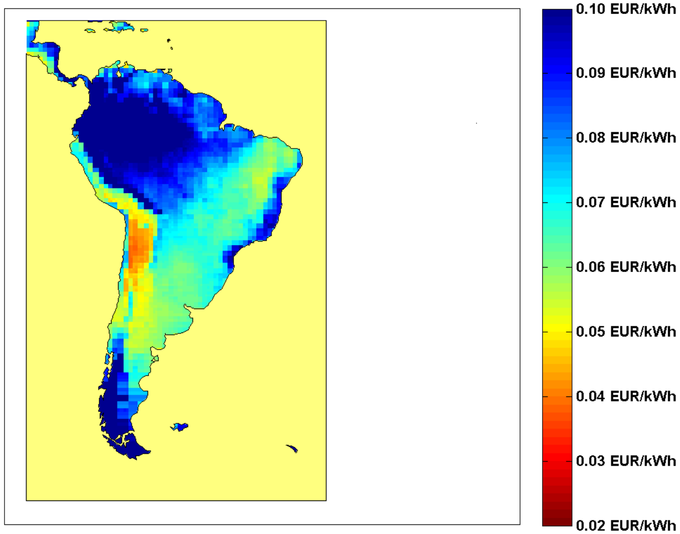
PV (1-axis tracking) LCOE



Wind (E101 at 150m) LCOE



CSP LCOE



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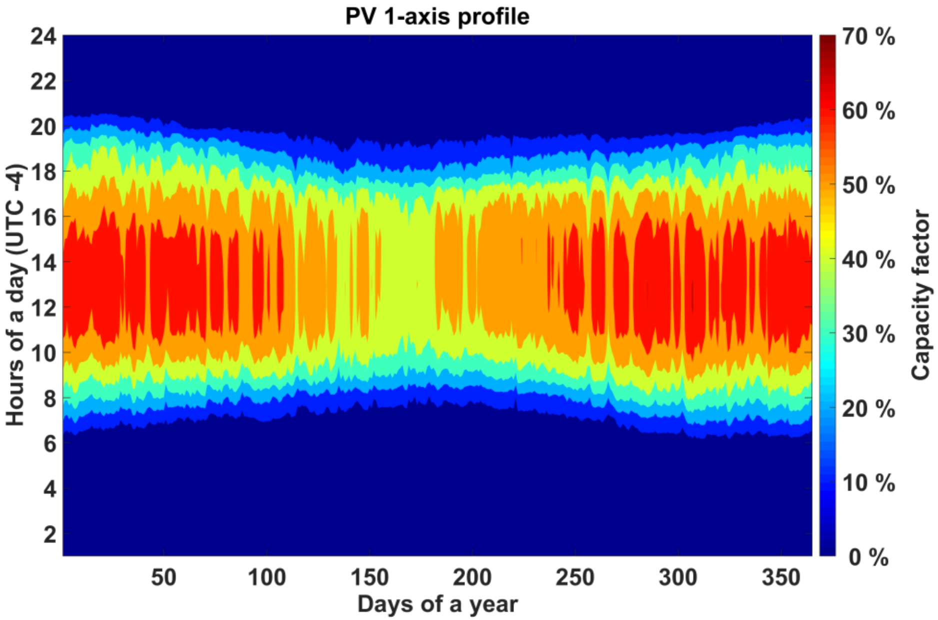
Scenarios assumptions

Generation profile (area aggregated)

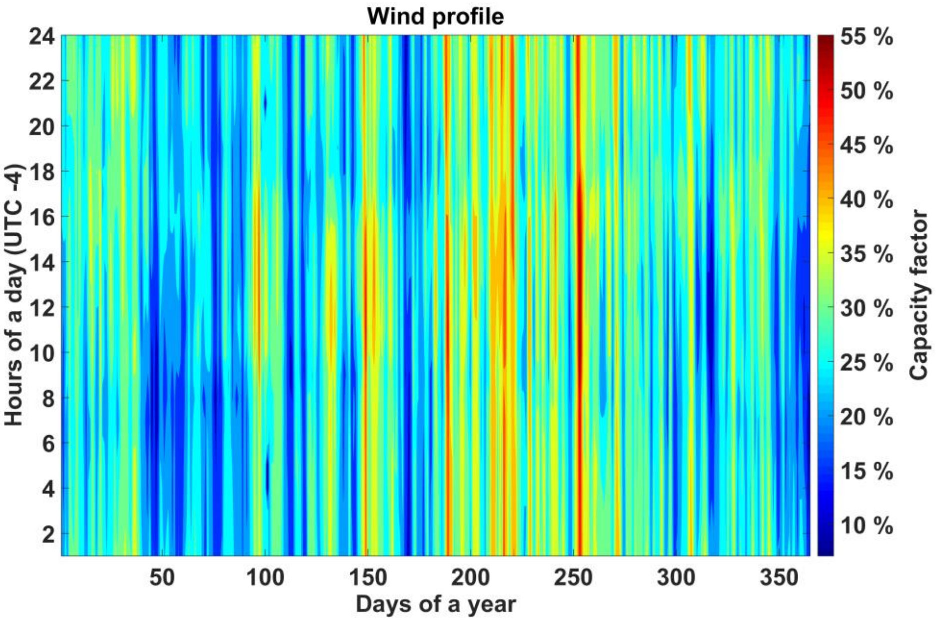
PV generation profile

Aggregated area profile computed using earlier presented weighed average rule.



Wind generation profile

Aggregated area profile computed using earlier presented weighed average rule.

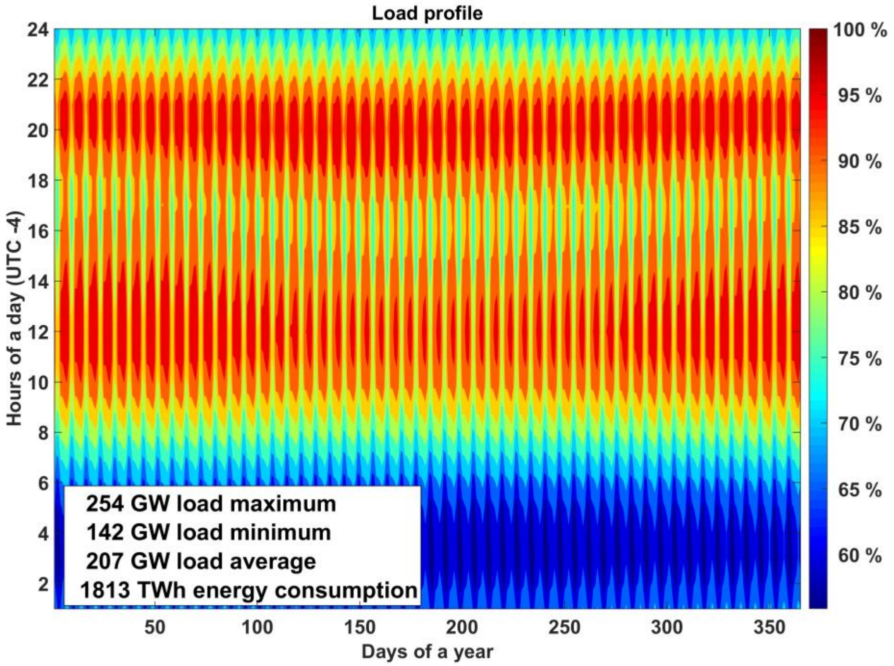


Scenarios assumptions

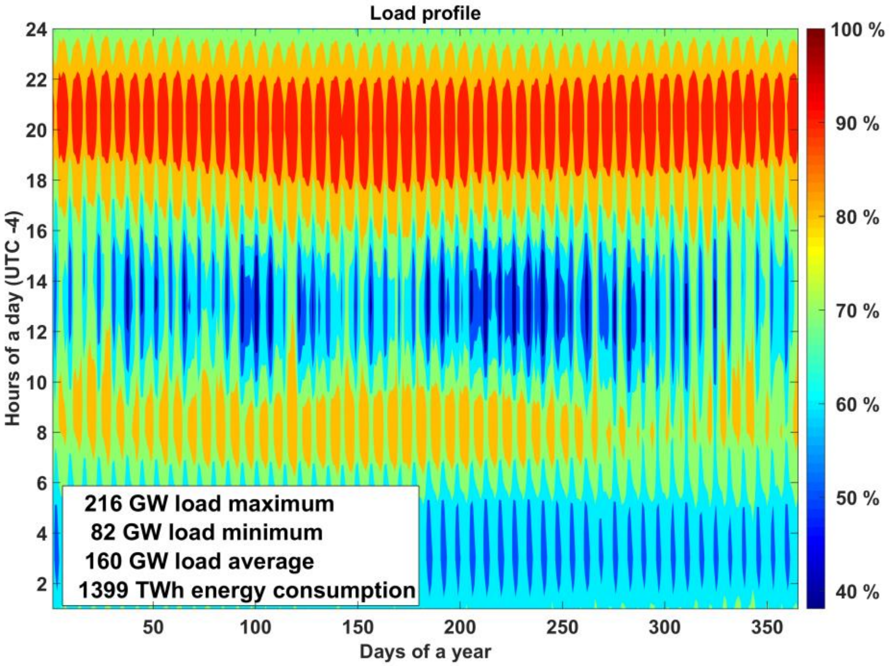
Load (area aggregated)

Synthesized load curves for each region

Total load for South America (2030)



Total load for South America (2030) - excluding PV prosumers



Agenda

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Results

2030 Scenario	Total LCOE [€/kWh]	LCOE primary [€/kWh]	LCOC [€/kWh]	LCOS [€/kWh]	LCOT [€/kWh]	Total ann. cost [bn €]	Total CAPEX [bn €]	RE capacities [GW]	Generated electricity [TWh]
Region-wide	0.062	0.042	0.003	0.017	0	112	939	762	2207
Country-wide	0.059	0.041	0.003	0.014	0.001	106	894	701	2026
Area-wide	0.055	0.042	0.002	0.008	0.003	100	865	630	1918
Area-wide Des-Gas*,**	0.048	0.038	0.001	0.007	0.002	149	1316	1094	2981

Total LCOE*** prosumer [€/kWh]	LCOE primary prosumer [€/kWh]	LCOS prosumer [€/kWh]	Total ann. Cost prosumer [bn €]	Total CAPEX prosumer [bn €]	RE capacities prosumer [GW]	Generated electricity prosumer [TWh]
0.089	0.045	0.044	27	250	268	428

* additional demand 98% gas and 2% desalination

** LCOS does not include the cost for the industrial gas (LCOG)

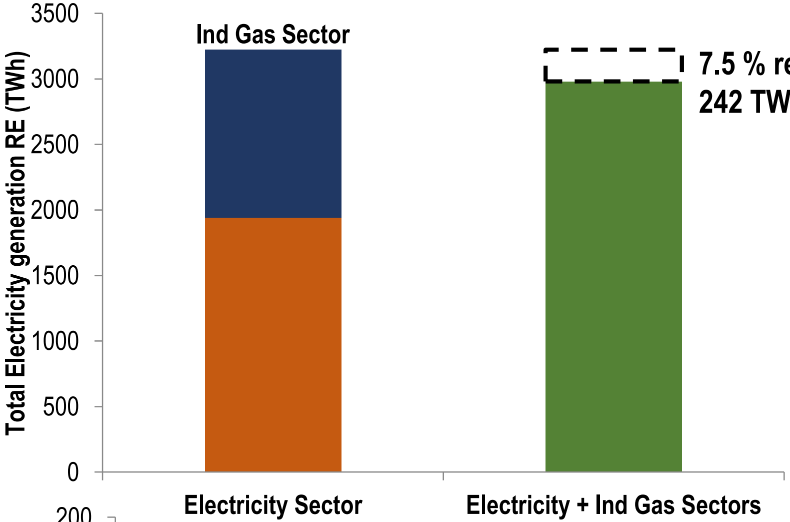
*** fully included in table above

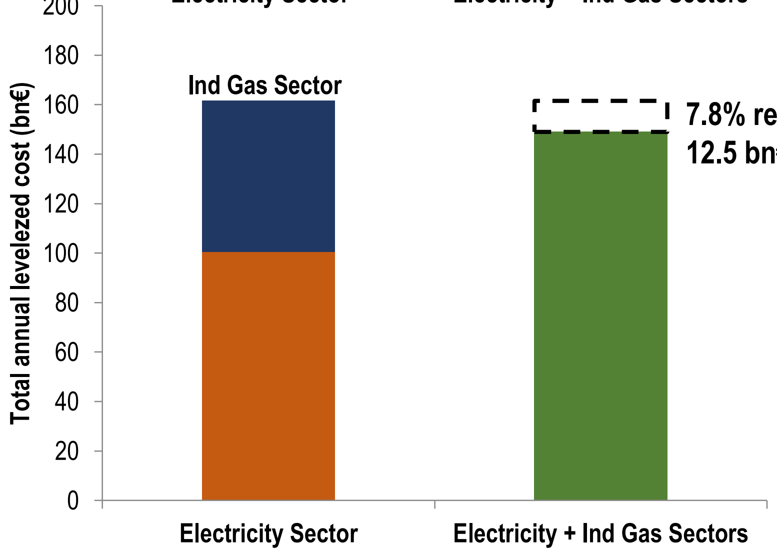
LCOW: 1.13 €/m^3

LCOG: 0.088 €/kWh,gas

Results

Benefits of electricity and industrial gas sectors integration – Area-wide desalination gas





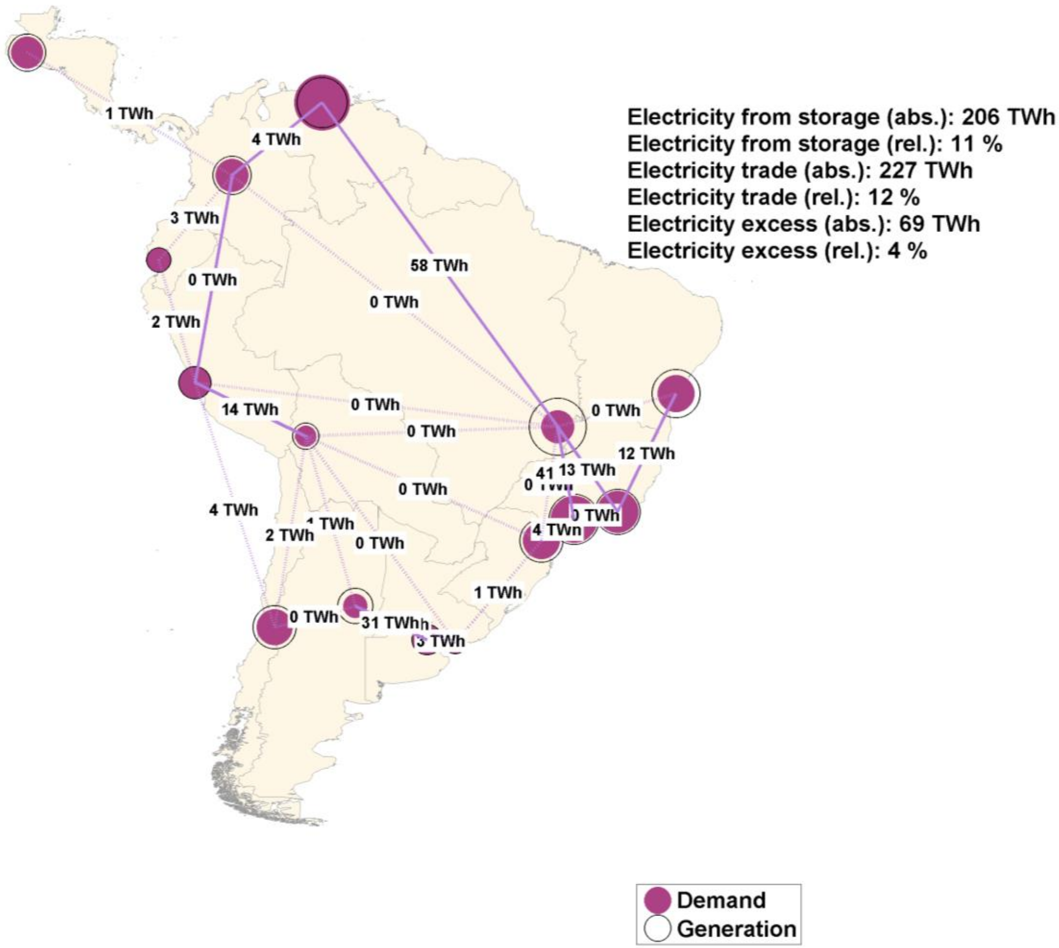
Key insights:

- integration benefits: decrease in total electricity demand and total annual levelized cost
- descrease in total electricity curtailment losses of 31% (39 TWh absolute) and in total capex by 9.6% (140 bn€ absolute)

Results

Import / Export (year 2030)

Area-wide open trade

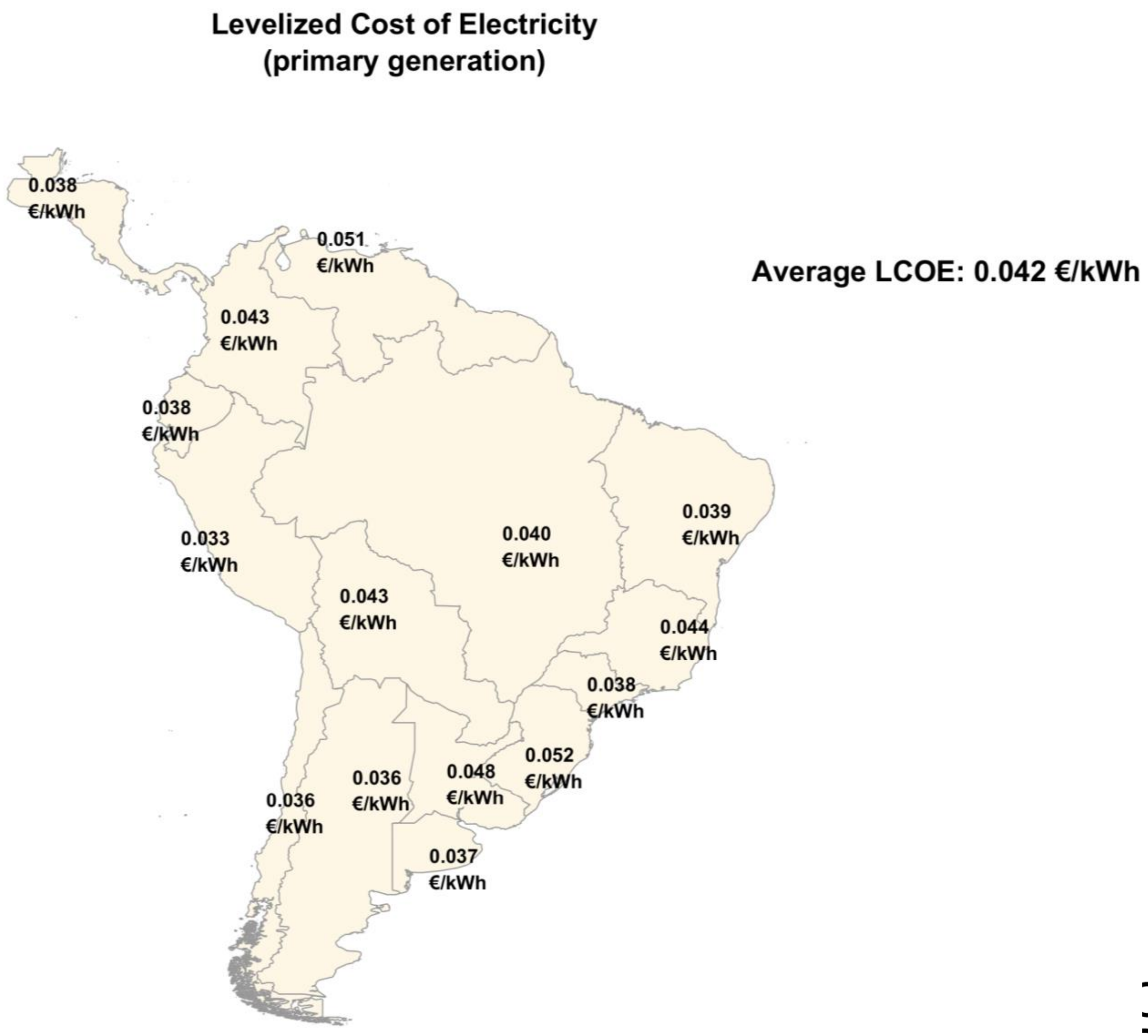


Key insights:

- **Net Importers: CAM, VE, EC, PE, AR-NE, AR-E, BR-SP, BR-SE**
- **Net Exporters: BR-N, BR-NE, BR-S,CSA, CL, AR-W, CO**
- **CO and BR-SP have the highest grid utilization**

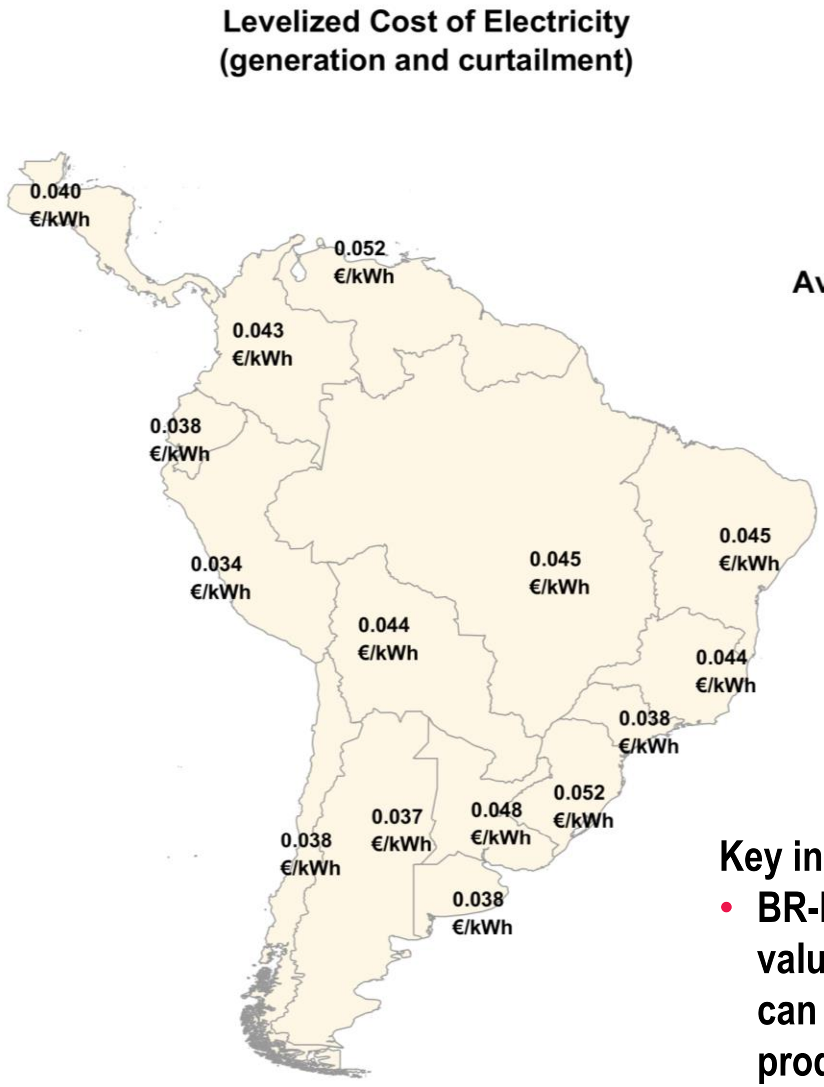
Results

Total LCOE (year 2030) – area-wide open trade



Results

Total LCOE (year 2030) – area-wide open trade



Average LCOE: 0.043 €/kWh

Key insights:

- BR-N and BR-NE have the highest values for LCOC: surplus energy can be used for industrial gas production

Results

Total LCOE (year 2030) – area-wide open trade

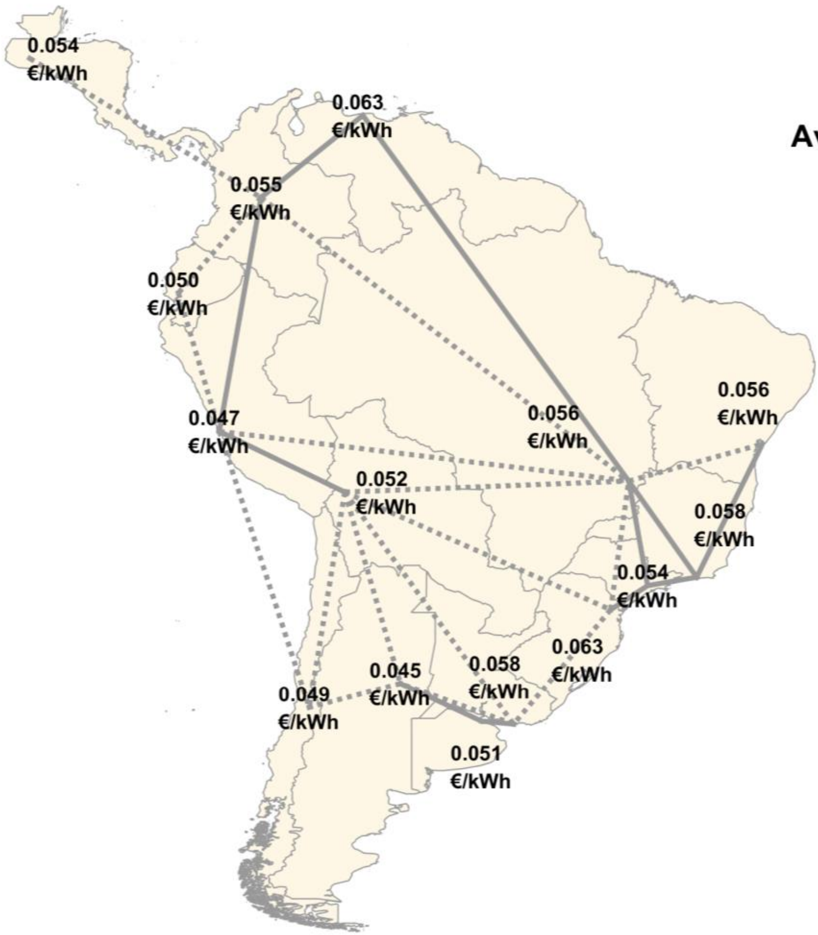
Levelized Cost of Electricity
(generation, curtailment and storage)

Average LCOE: 0.052 €/kWh

Results

Total LCOE (year 2030) – area-wide open trade

Levelized Cost of Electricity
(generation, curtailment, storage and transmission)



Average LCOE: 0.055 €/kWh

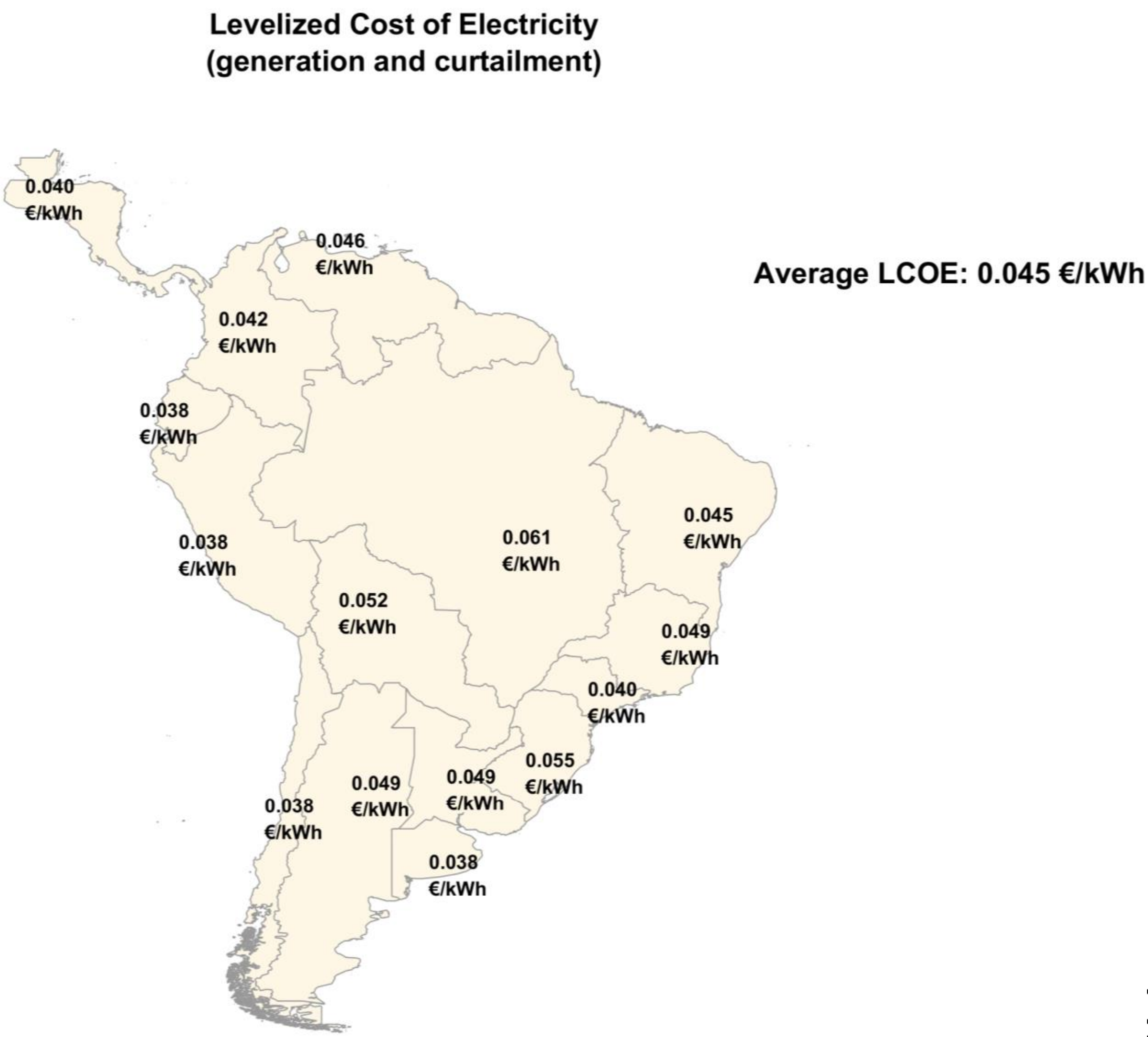
Results

Total LCOE (year 2030) – region-wide open trade

Average LCOE: 0.042 €/kWh

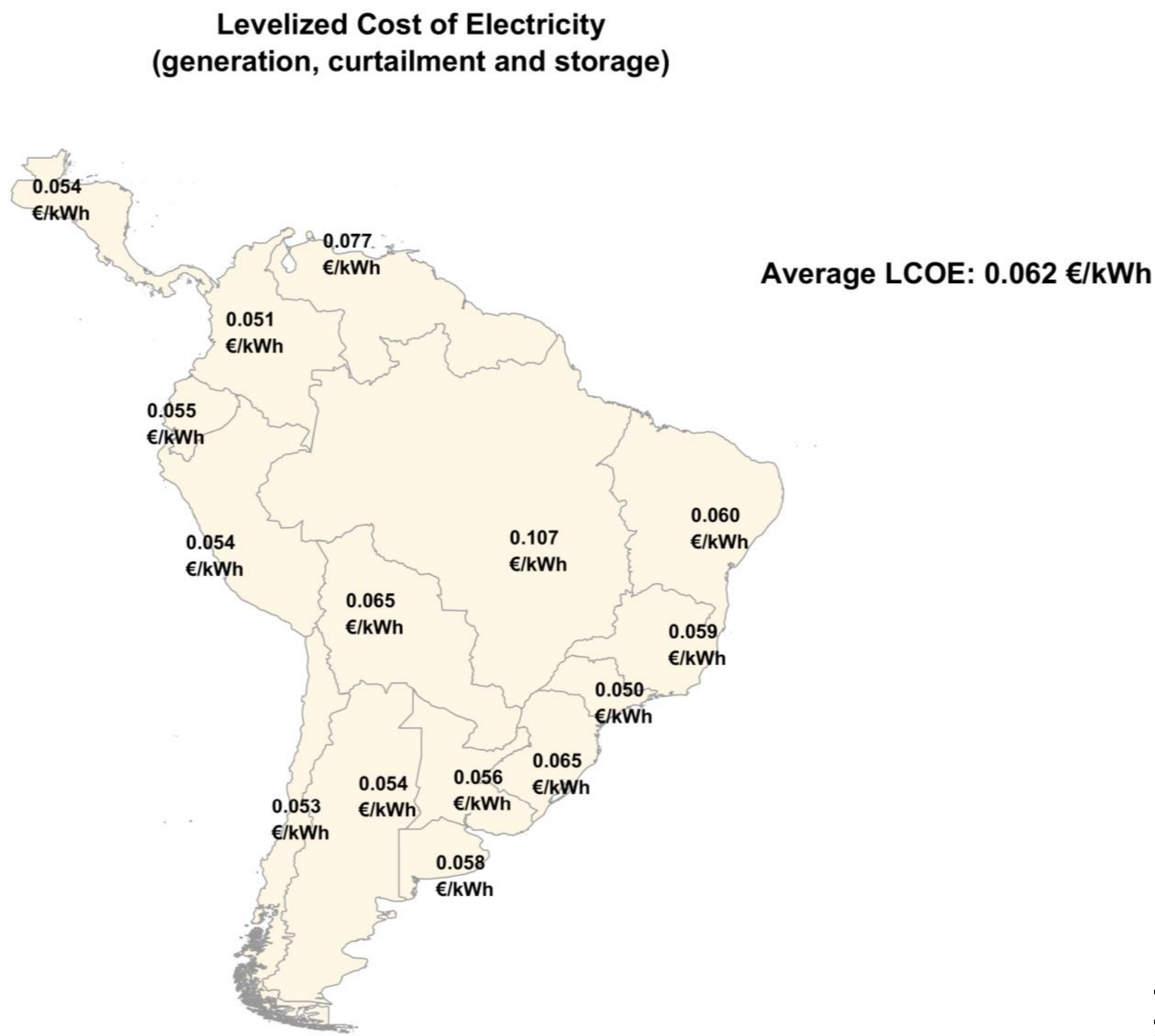
Results

Total LCOE (year 2030) – region-wide open trade



Results

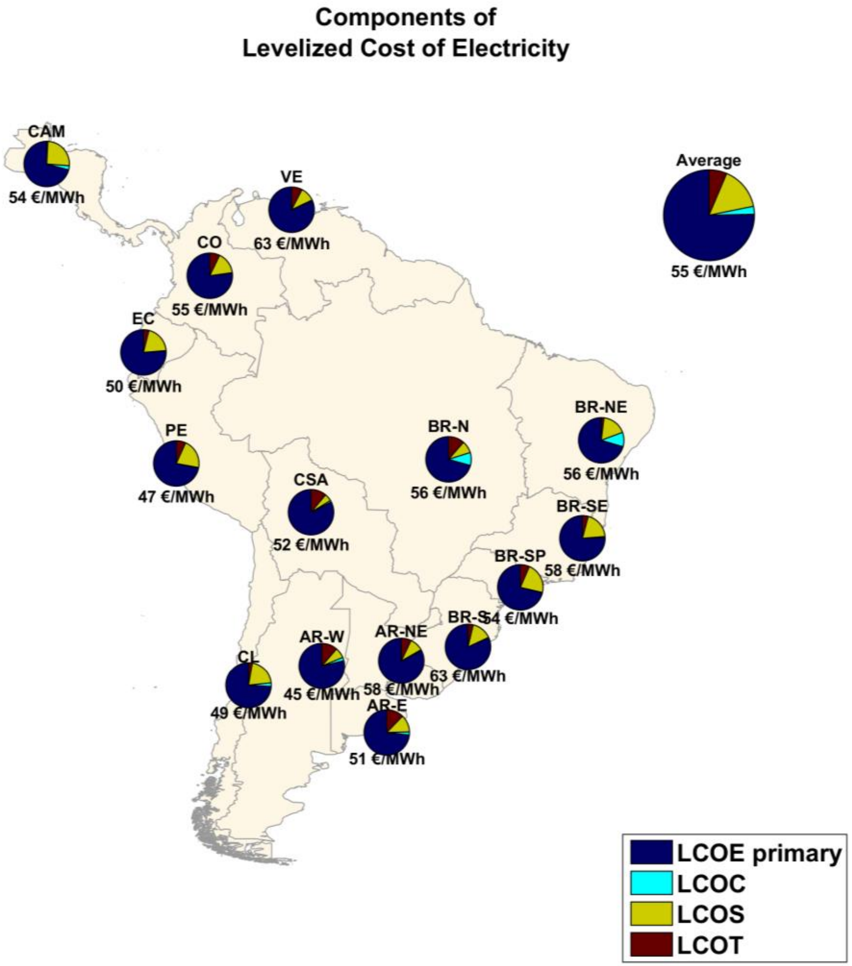
Total LCOE (year 2030) – region-wide open trade



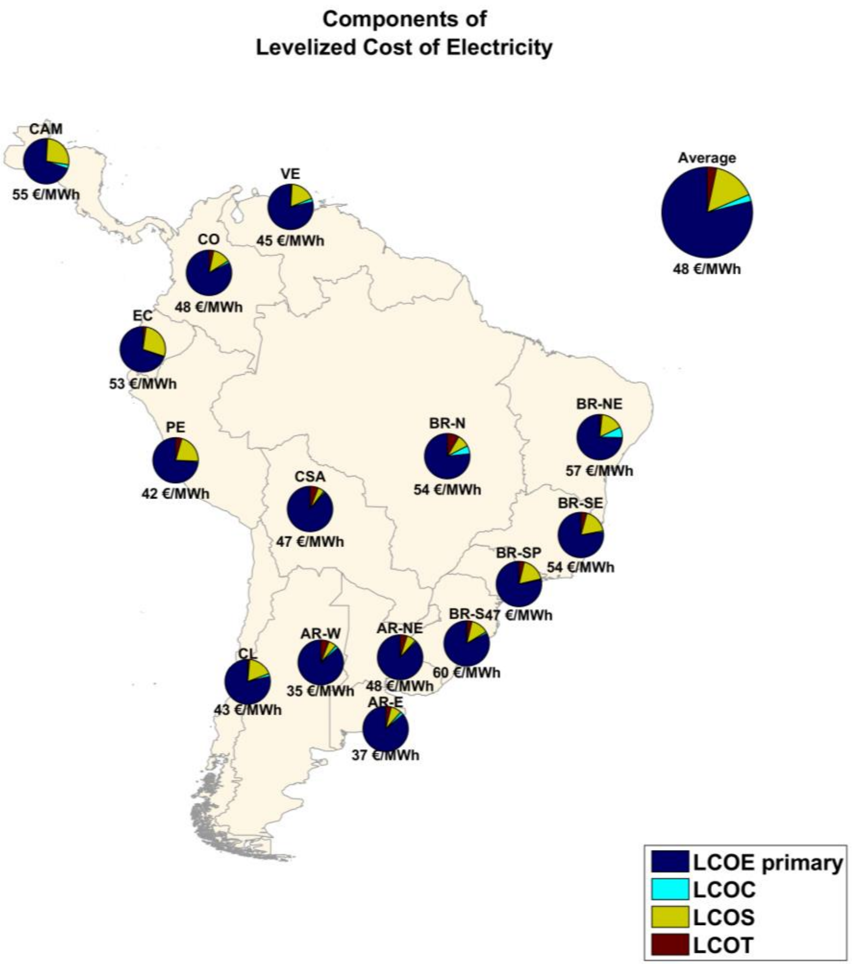
Results

Components of LCOE – area-wide open trade and area-wide desalination gas

Area-wide open trade



Area-wide open trade desalination gas



Results

Self-Consumption – South America super-region area-wide open trade

	2030 RES	2030 COM	2030 IND
Electricity price [€/kWh]	0.188	0.175	0.159
PV LCOE [€/kWh]	0.053	0.081	0.081
Self-consumption PV LCOE [€/kWh]	0.080	0.105	0.104
Self-consumption PV and Battery LCOE [€/kWh]	0.083	0.111	0.109
Self-consumption LCOE [€/kWh]	0.073	0.104	0.103
Benefit [€/kWh]	0.115	0.070	0.056
Installed capacities	**RES**	**COM**	**IND**
PV [GW]	105.5	54.4	107.9
Battery storage [GWh]	148.1	91.9	172.0
Generation	**RES**	**COM**	**IND**
PV [TWh]	167.5	86.6	174.3
Battery storage [TWh]	44.7	28.8	58.9
Excess [TWh]	56.3	20.3	38.8
Utilization	**RES**	**COM**	**IND**
Self-consumption of generated PV electricity [%]	66.4	76.6	77.7
Self-coverage market segment [%]	19.9	18.3	18.4
Self-coverage operators [%]	99.3	91.6	92.0

Source (electricity prices): Gerlach A., Werner Ch., Breyer Ch., 2014. Impact of Financing Cost on Global Grid-Parity Dynamics till 2030, 29th EU PVSEC, Amsterdam, September 22-26

Results

Self-Consumption – Sao Paulo region area-wide open trade

	2030		
	RES	COM	IND
Electricity price [€/kWh]	0.250	0.220	0.190
PV LCOE [€/kWh]	0.047	0.073	0.075
Self-consumption PV LCOE [€/kWh]	0.084	0.105	0.104
Self-consumption PV and Battery LCOE [€/kWh]	0.088	0.110	0.110
Self-consumption LCOE [€/kWh]	0.071	0.101	0.102
Benefit [€/kWh]	0.179	0.119	0.088
Installed capacities	RES	COM	IND
PV [GW]	18.3	9.9	19.5
Battery storage [GWh]	23.5	16.2	32.0
Generation	RES	COM	IND
PV [TWh]	28.2	15.3	30.1
Battery storage [TWh]	7.5	4.8	9.9
Excess [TWh]	12.5	4.6	8.6
Utilization	RES	COM	IND
Self-consumption [%]	55.7	70.1	71.5
Self-coverage [%]	20.0	20.0	19.7
Self-coverage operators [%]	100	100	98.5

Source (electricity prices): Gerlach A., Werner Ch., Breyer Ch., 2014. Impact of Financing Cost on Global Grid-Parity Dynamics till 2030, 29th EU PVSEC, Amsterdam, September 22-26

Results

Installed Capacities

2030 Scenario	Wind [GW]	PV [GW]	Hydro RoR [GW]	Hydro dams [GW]	Waste [GW]	Biogas [GW]	Biomass [GW]	Battery [GWh]	PHS [GWh]	PtG electrolyzers [GW_{el}]	CCGT [GW]	OCGT [GW]
Region-wide	56	446	24	151	0.92	21	38	654	1.22	8	28	5
Country-wide	44	421	24	144	0.92	20	36	643	1.10	6	16	4
Area-wide	39	365	23	148	0.92	16	35	469	1.10	0.3	17	3
Area-wide Des-Gas	98	764	23	155	0.92	12	35	596	1.10	120	6	3

2030 Scenario	PV fixed-tilted [GW]	PV 1-axis [GW]	PV prosumers [GW]	PV total [GW]	Battery system [GWh]	Battery prosumers [GWh]	Battery total [GWh]
Region-wide	1	177	268	446	242	412	654
Country-wide	1	151	268	421	231	412	643
Area-wide	1	96	268	365	57	412	469
Area-wide Des-Gas	1	495	268	764	184	412	596

Results

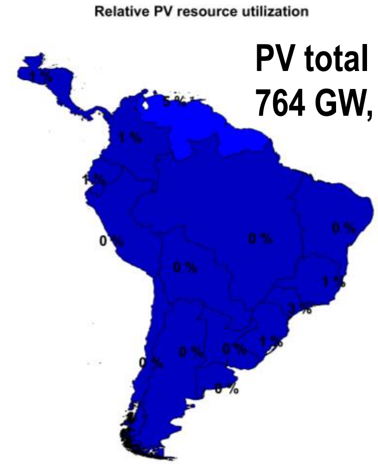
Resource utilization – area-wide open trade and area-wide desalination gas

Area-wide open trade

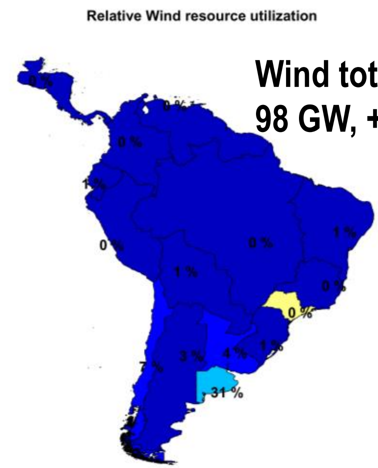
PV total capacity
365 GW

Wind total capacity
39 GW

Area-wide open trade desalination gas



PV total capacity
764 GW, +109%



Wind total capacity
98 GW, +151%

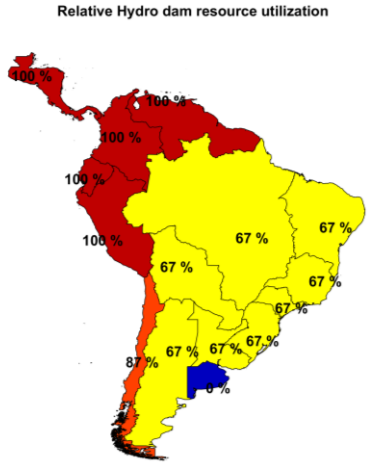
Key insights:

- PV and wind capacities are increased substantially in area-wide desalination-gas scenario
- total utilization very low

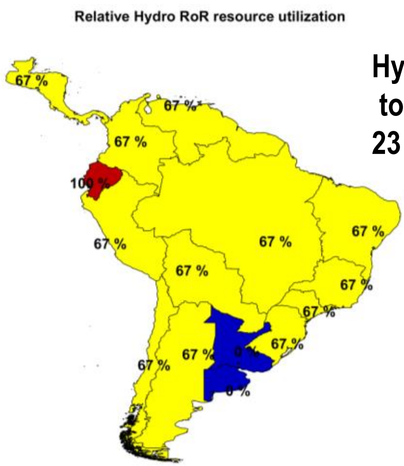
Results

Resource utilization – area-wide open trade and area-wide desalination gas

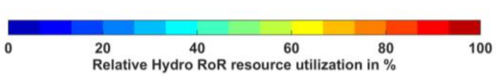
Area-wide open trade



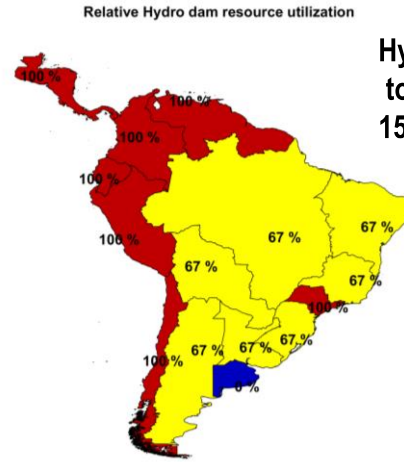
Hydro dam
total capacity
148 GW



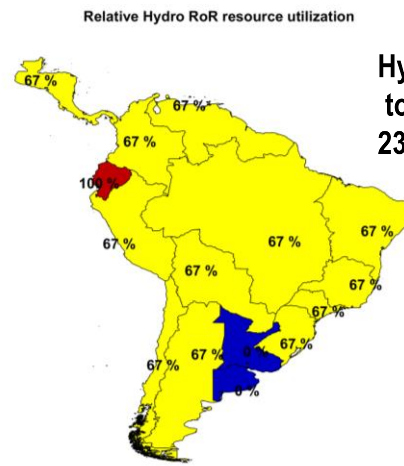
Hydro RoR
total capacity
23 GW



Area-wide open trade desalination gas



Hydro dam
total capacity
155 GW, +5%



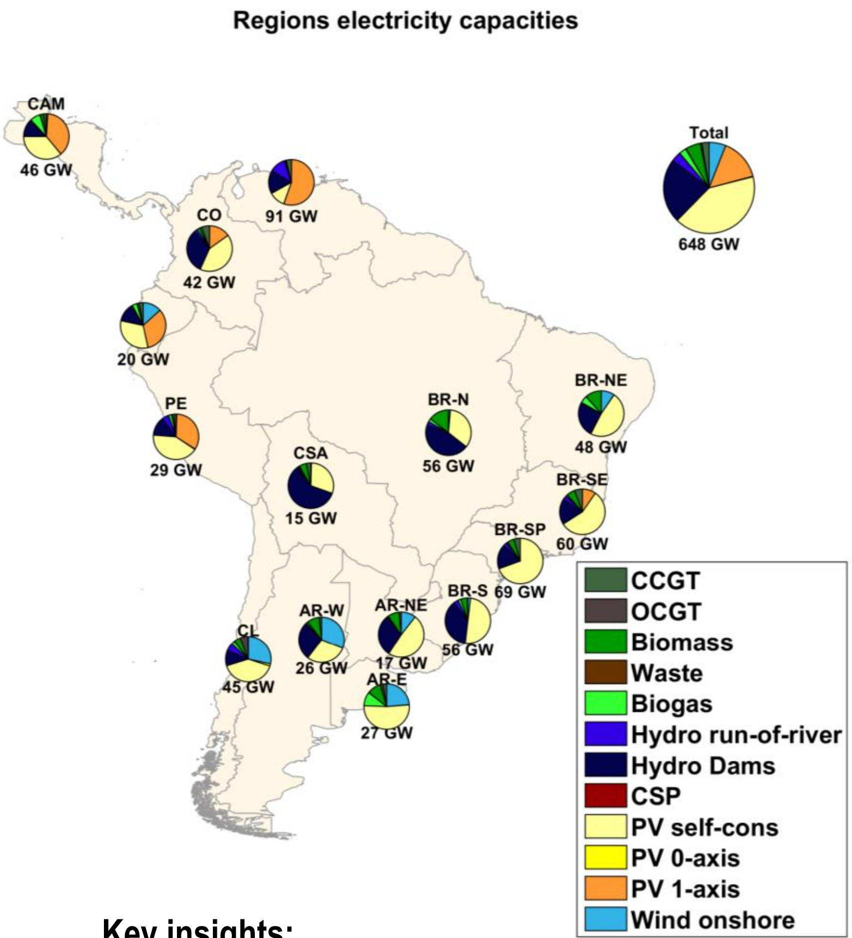
Hydro RoR
total capacity
23 GW

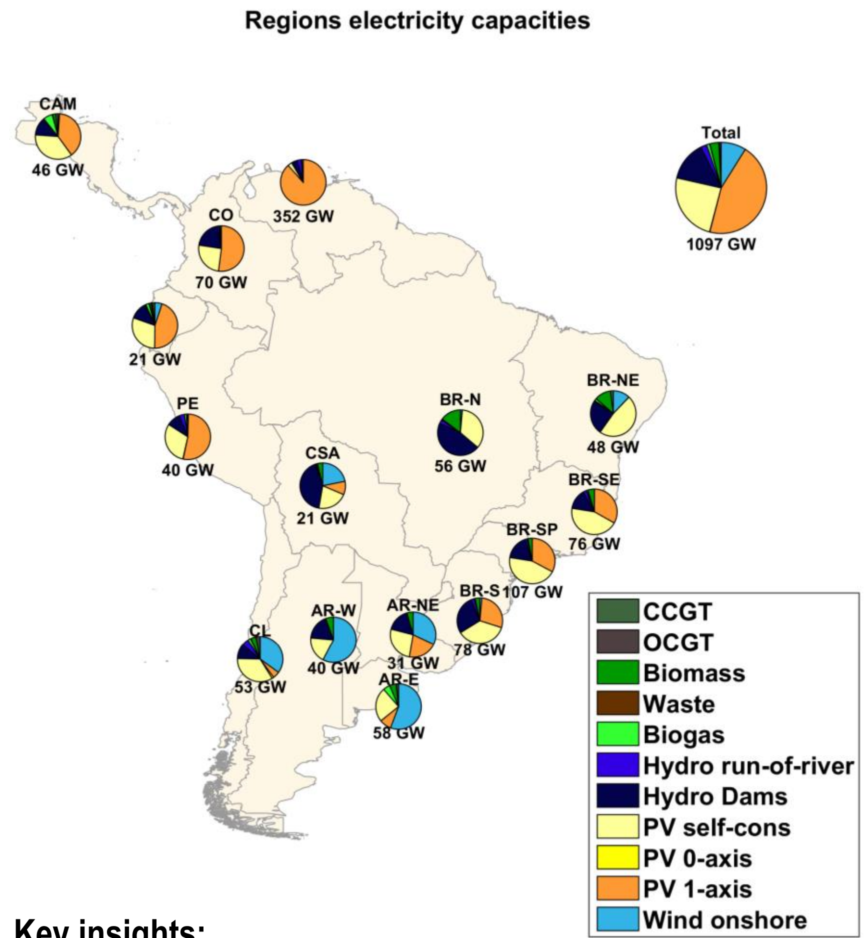
Key insights:

- Northern and western regions benefit from higher hydro dam capacities than today
- Only Sao Paulo and AR-W increased their hydro dam capacities for the area-wide open trade desalination-gas
- No increase in hydro RoR capacities for the area-wide open trade desalination-gas despite an upper limit 50% higher than the actual capacity
- PV and wind LCOE are more competitive than hydro, despite flexibility of dams

Results

Regions Electricity Capacities – area-wide open trade





Key insights:

- Area-wide scenario shows high PV capacities due to (prosumer) LCOE competitiveness all over the region
- Importing regions generate economic benefit from siginificant local PV self-consumption share

Key insights:

- Area-wide desalination gas scenario is dominated by PV
- Brazil-NE and the very south utilize its excellent wind resources
- PV 1-axis and wind are the main sources of electricity for water desalination and industrial gas production, especially for importing regions

Results

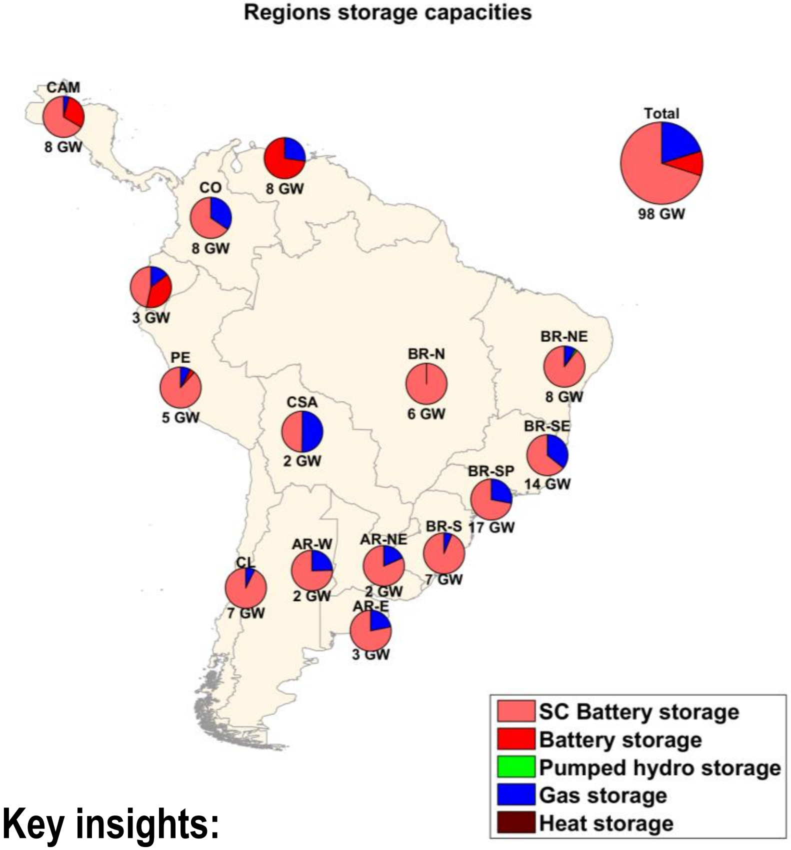
Storages

2030 Scenario	Storage capacities Battery [TWh$_{el}$]	Storage capacities PHS [TWh$_{el}$]	Storage capacities Gas [TWh$_{th}$]	Throughput of storages Battery [TWh$_{el}$]	Throughput of storages PHS [TWh$_{el}$]	Throughput of storages Gas [TWh$_{th}$]	Full cycles per year Battery [-]	Full cycles per year PHS [-]	Full cycles per year Gas [-]
Region-wide	0.6	0.1	61.1	211	0.140	133	322.4	114.0	2.2
Country-wide	0.6	0.1	43.5	207	0.129	79	322.2	117.4	1.8
Area-wide	0.5	0.1	37.9	150	0.140	94	319.1	127.3	2.5
Area-wide Des-Gas	0.6	0.1	41.1	187	0.114	18	314.7	103.3	0.4

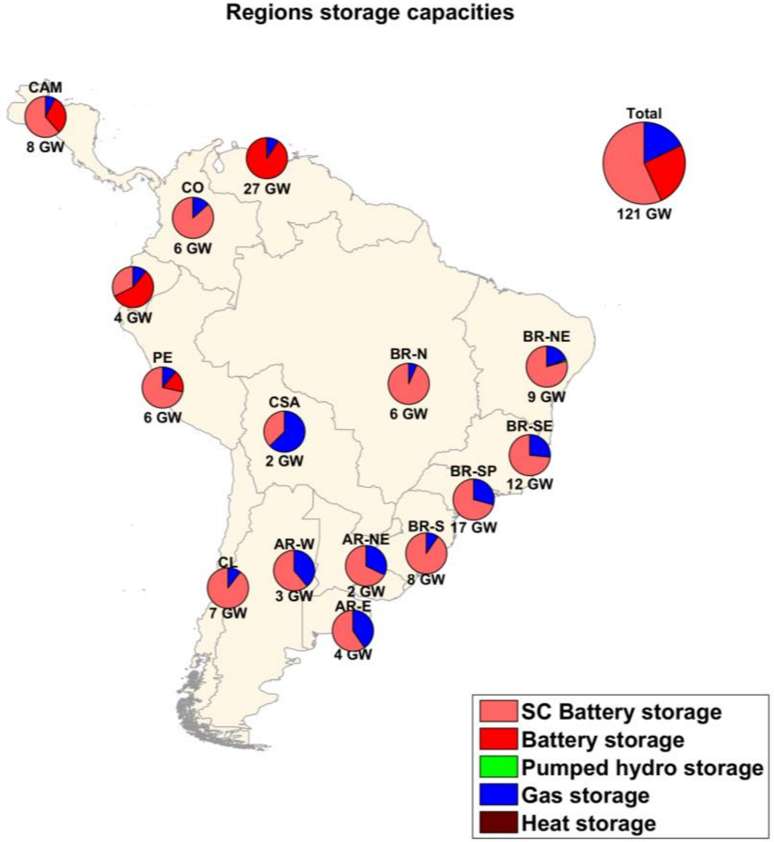
Results

Storages Capacities – area-wide and area-wide open trade desalination gas

Area-wide open trade



Area-wide open trade desalination gas



Key insights:

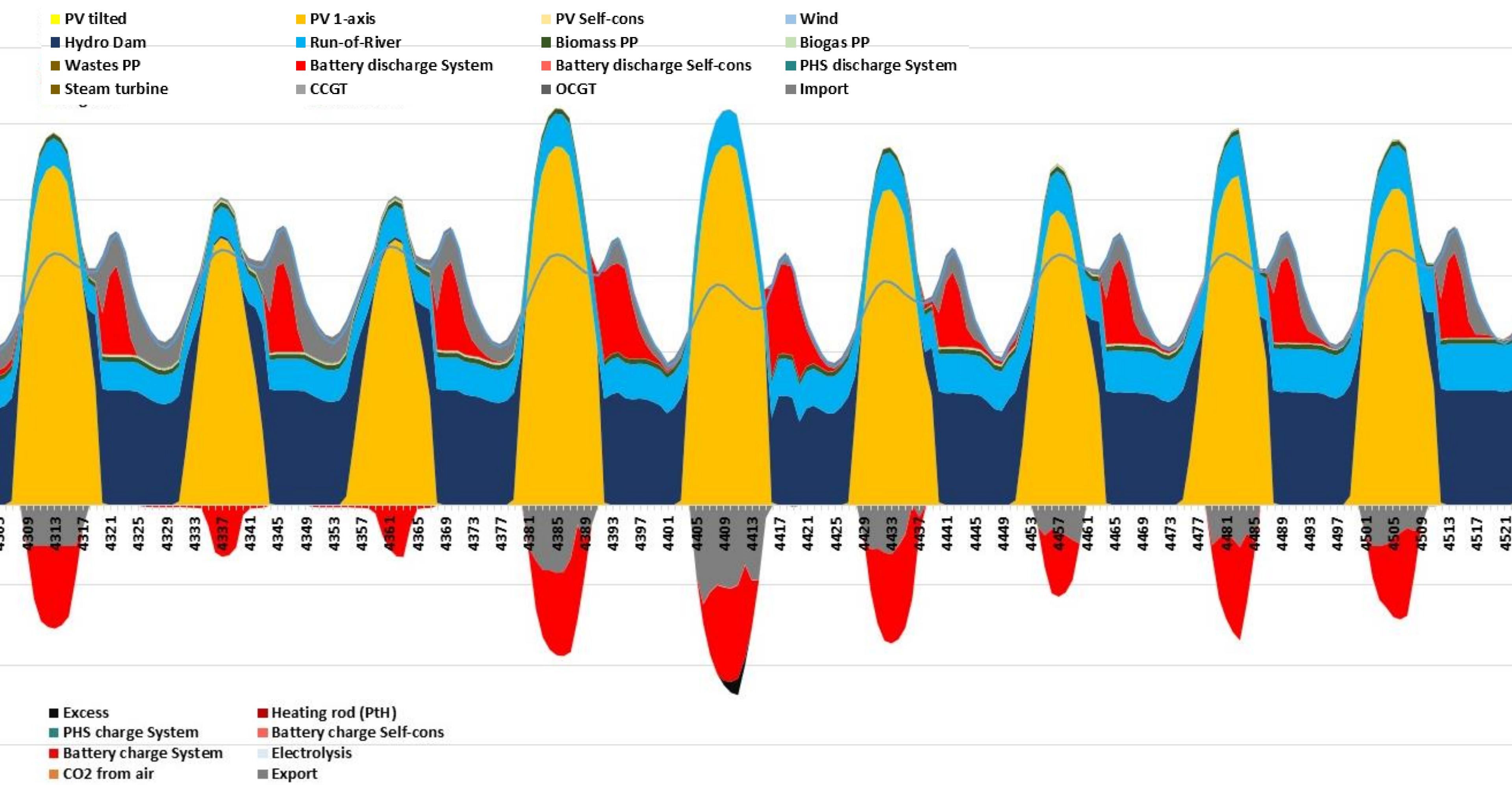
- Excess energy for area-wide open trade desalination gas: higher in absolute numbers, but lower in relative ones (from 3.6% to 2.9% of total generation), therefore generated electricity is used more efficient
- Hydro dams as virtual battery very important, batteries in a key role for prosumers but also on the grid level and gas storages for balancing periods of wind and solar shortages

Agenda

- Motivation
- Methodology and Data
- Results for the Energy System
- Results for Hourly Operation
- Alternatives
- Summary

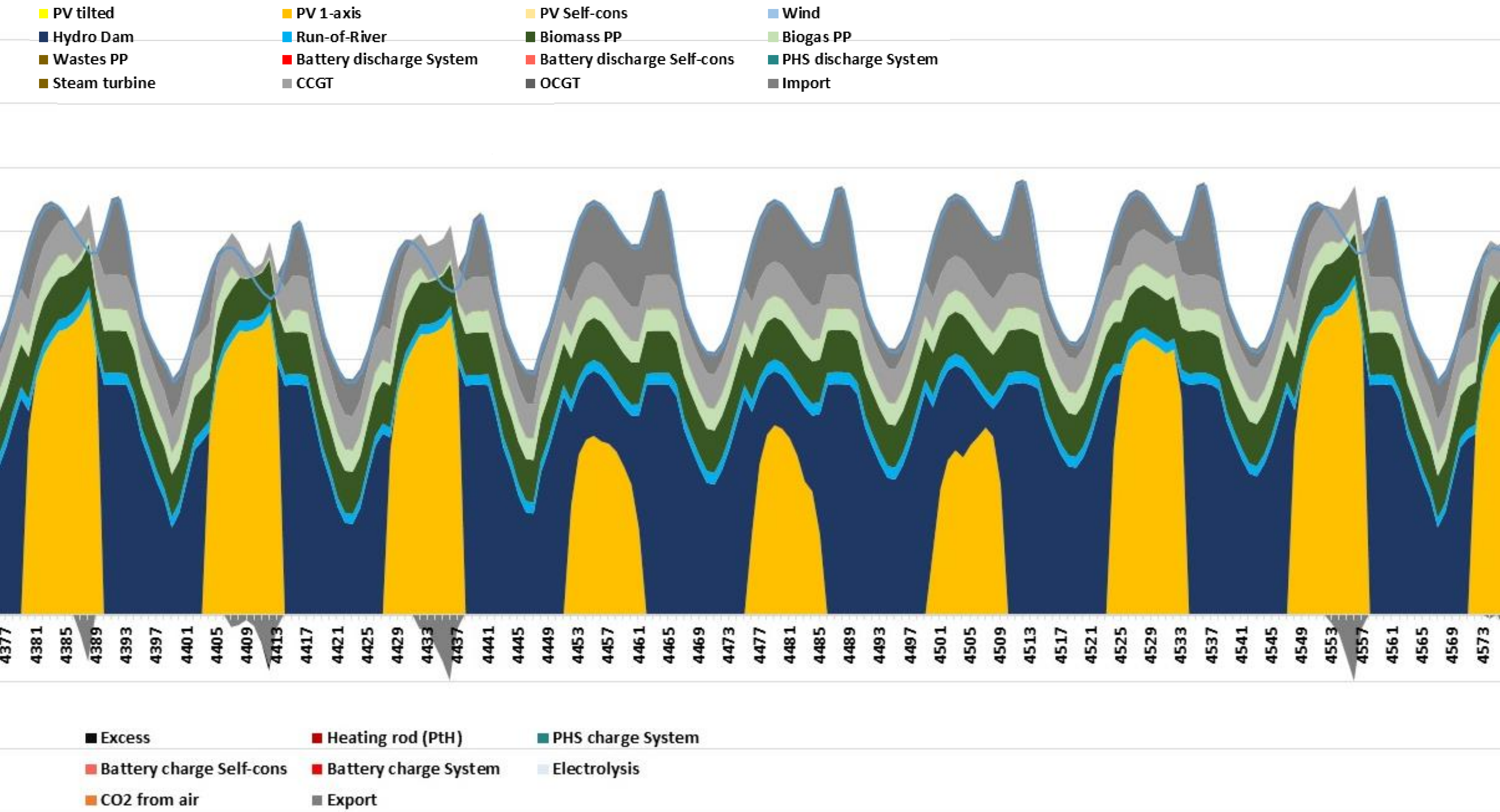
Results

Net importer region - Venezuela



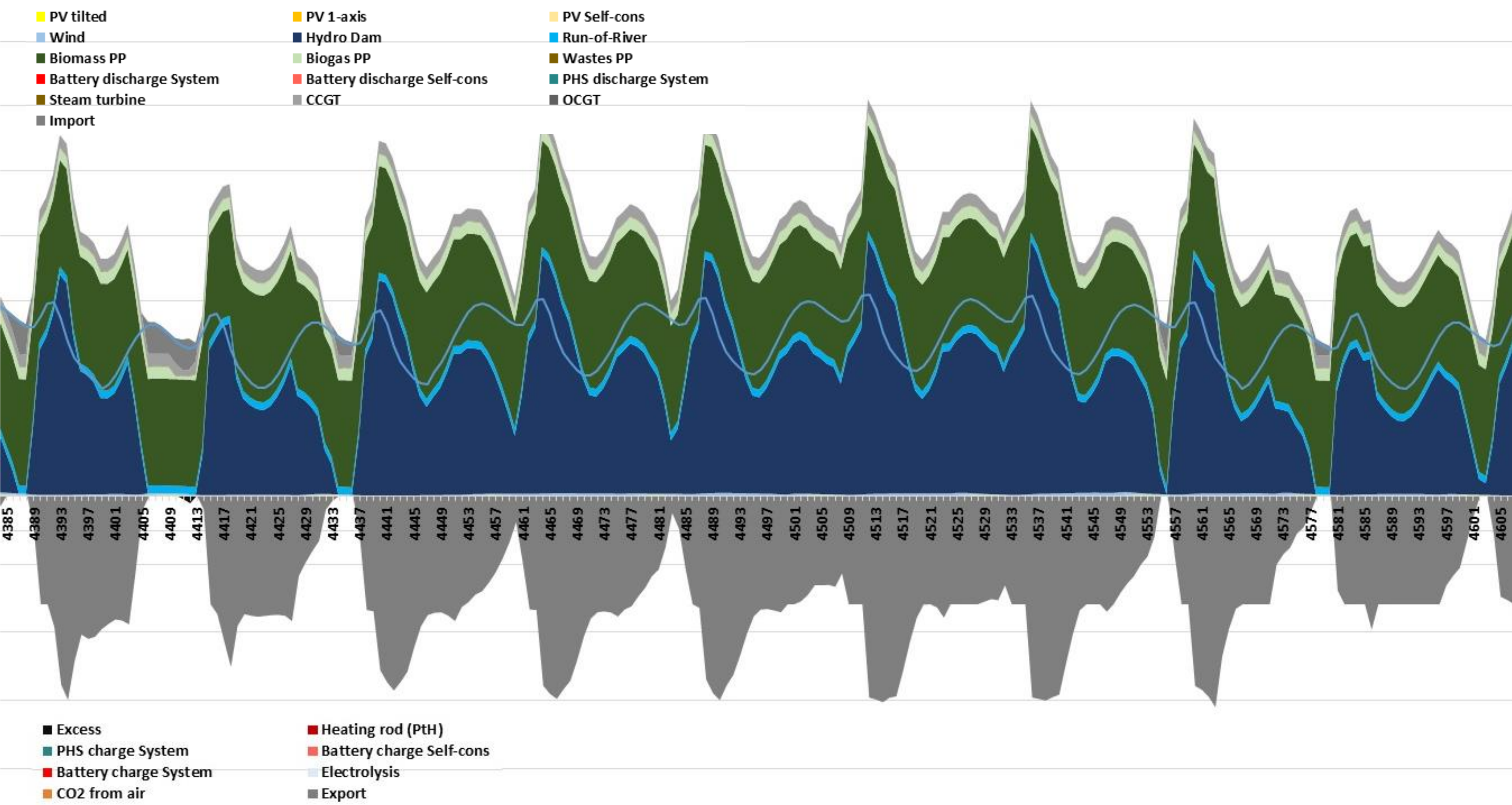
Results

Net importer region – Sao Paulo



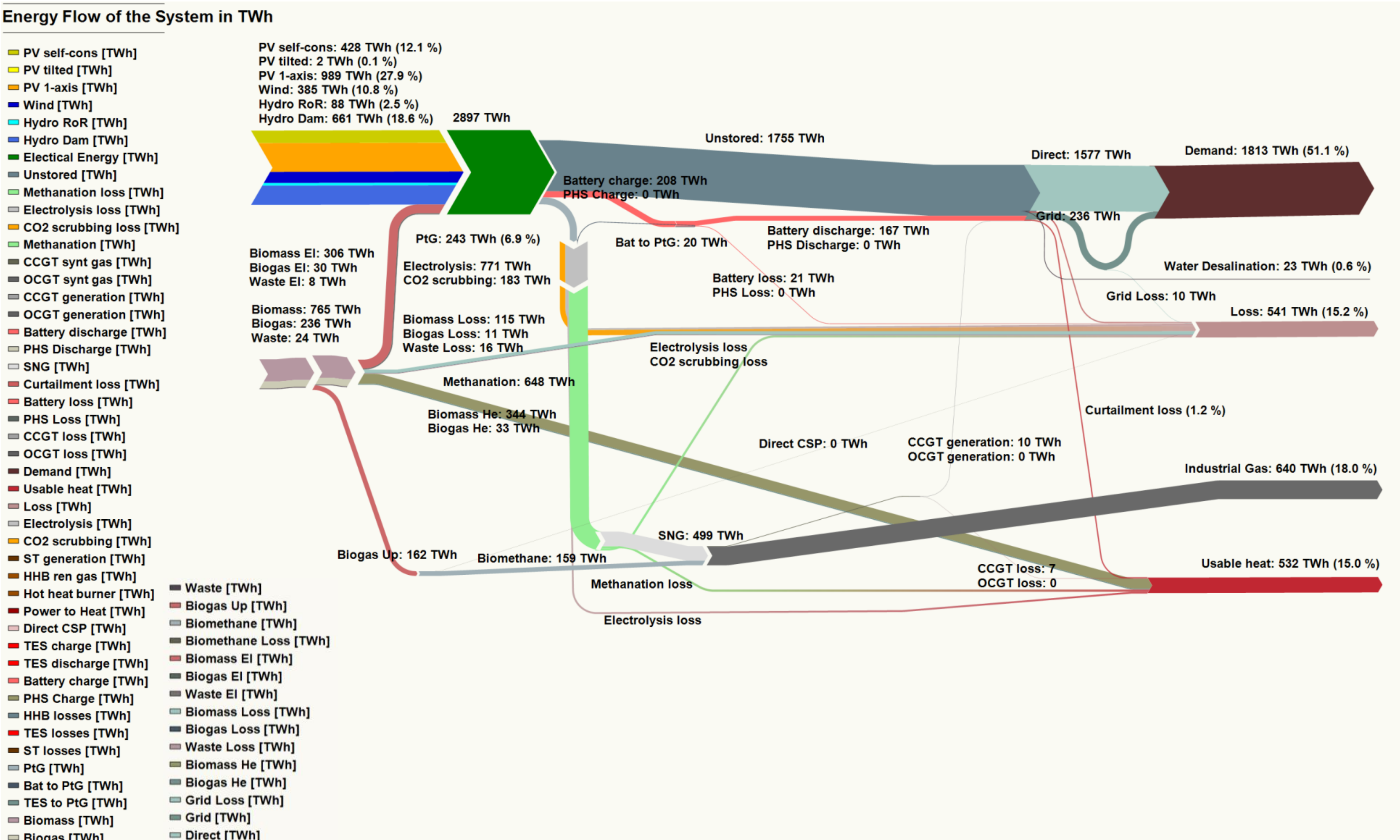
Results

Net exporter region – North Brazil



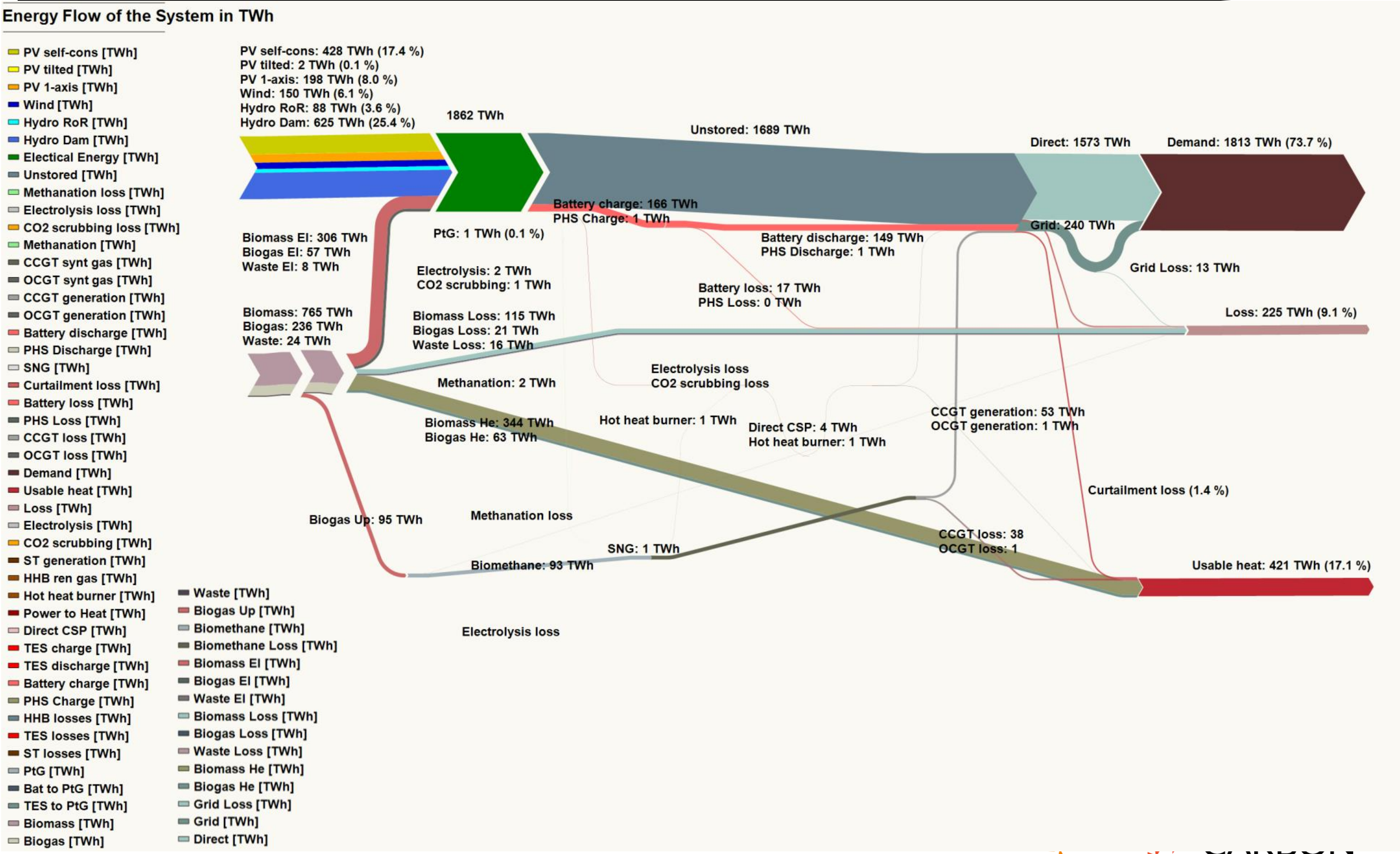
Results

Energy flow of the System of area-wide open trade desalination gas (2030)



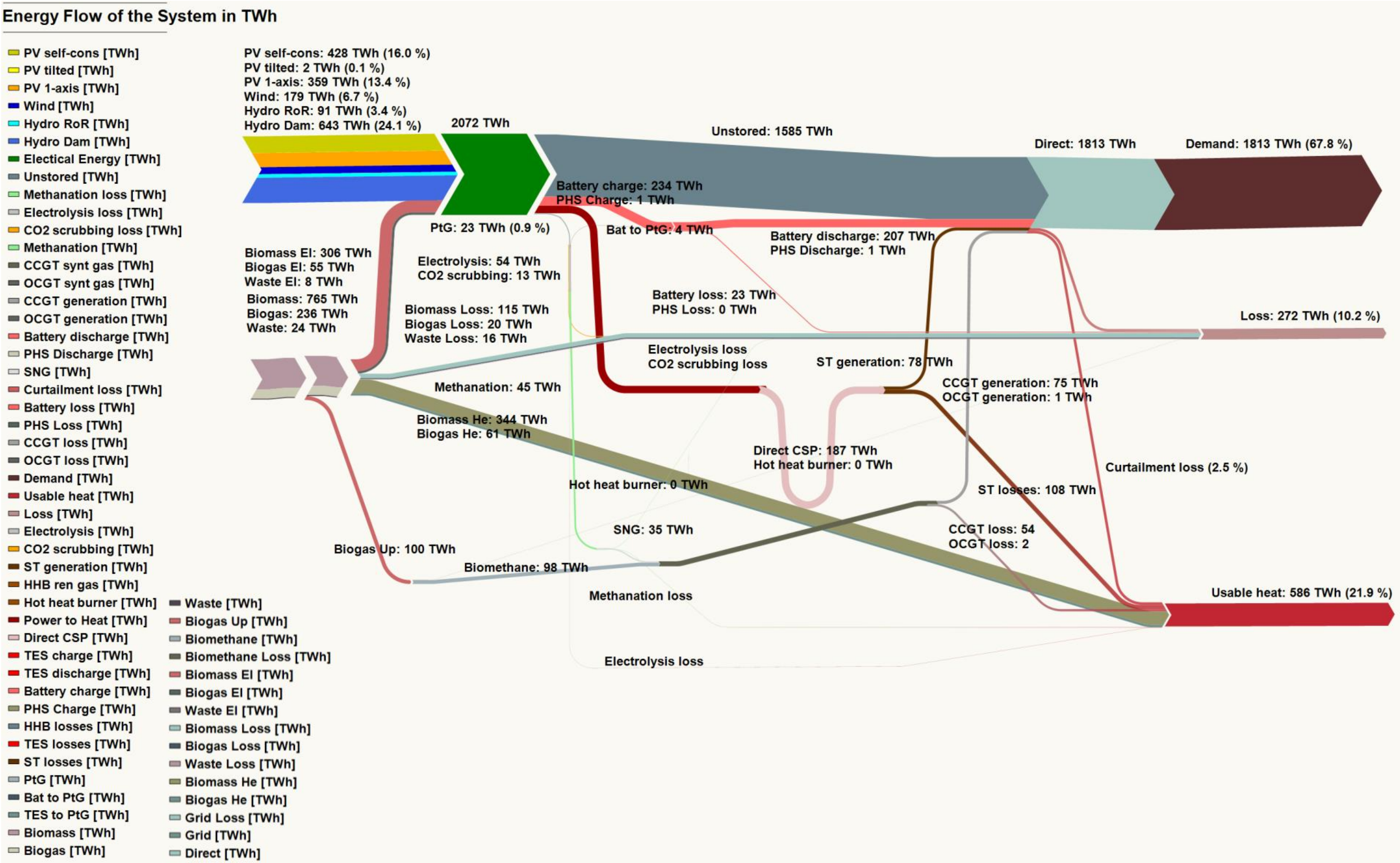
Results

Energy flow of the System of area-wide open trade (2030)



Results

Energy flow of the System of region-wide open trade scenario (2030)



Agenda

- Motivation
- Methodology and Data
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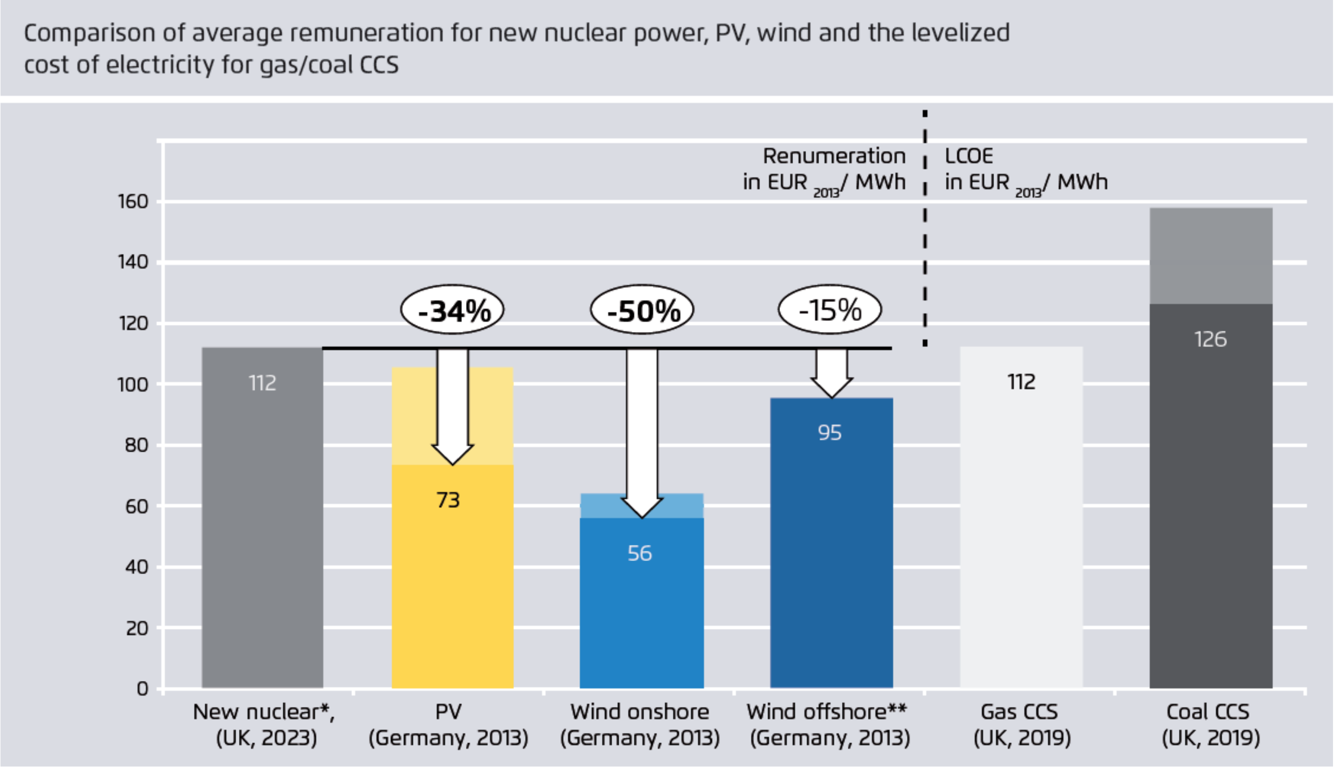
LCOE of alternatives are NO alternative



Key insights

- PV-Wind-Gas is the least cost option (in South America with existing hydro)
- nuclear and coal-CCS is too expensive
- nuclear and coal-CCS are high risk technologies
- high value added for PV-Wind due to higher capacities needed

Source: Agora Energiewende, 2014. Comparing the Cost of Low-Carbon Technologies: What is the Cheapest option, Berlin

Agenda

Summary

- 100% Renewable Energy system is reachable in South America!
- super grid interconnection decrease average cost of electricity to 0.054 €/kWh of the total area from 0.060 €/kWh (country-only) and 0.062 €/kWh (region-only)
- integration benefit of gas and desalination is about 7-8% (cost and generation) due more efficient usage of storage and flexibility options
- in 2030, for region, country and area-wide open trade scenarios hydro continues to dominate in the electricity sector in most regions of South America
- hydro dams can be used as a virtual battery for solar and wind electricity storage, diminishing the role of other storage technologies in the region: power-to-gas is not needed for seasonal storage
- the shift to power in the gas, desalination, heat and mobility sector will be driven by higher supply of least cost solar PV and wind sites
- despite an upper limit 50% higher than the ccurrent capacity for hydro dams and RoR, in all the considered scenarios PV and wind are more profitable technologies according to the availability of the regions' resources
- 100% RE system is more cost competitive than a nuclear-fossil option!

Thanks for your attention …
… and to my co-authors and the team!

NEO CARBON ENERGY

TRUST IN RENEWABLE.

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CNPq Conselho Nacional de Desenvolvimento Científico e Tecnológico

USP Universidade de São Paulo

VTT

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Lappeenranta University of Technology