Global Energy System based on 100% Renewable Energy – Power, Heat, Transport and Desalination Sectors
South America

Project funded by the
German Federal Environmental Foundation (DBU) and
Stiftung Mercator GmbH
Overview

- South America is structured into 15 sub-regions
  - Central America (Panama+Costa Rica+Nicaragua+Honduras+El Salvador+Guatemala+Belize)
  - Venezuela, Colombia, Ecuador, Peru and Chile
  - Central South America (Bolivia+Paraguay)
  - Brazil (North, Northeast, Southeast, São Paulo, South)
  - Argentina (West, East, Northeast+Uruguay)
Current Status: Power Sector

Key insights:
- Significant share of hydropower in the generation mix is observed
- After hydropower, biomass has the highest share among RE installed capacities by end of 2014
- Gas and oil are the major fossil fuel contributors with a share of 32% of the total power capacity across South America
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Key insights:
- Historically, a significant share of electric heat generation is observed, and is complemented by fossil and bio-based heating
- The transport sector is dominated by fossil liquid fuels with a share of around 88% in 2015
- The desalination sector is predominantly based on demand for reverse osmosis desalination plants, with some shares of MSF and MED in 2015
LUT Energy System Transition model
Fundamentals: Data Flow

Data preparation
(Technical and financial assumptions)

Model setup and simulation

Power prosumers and individual heat producers simulation

System simulation

Power sector
Heat sector
Transportation sector

Industrial sector:
Industrial fuels
Desalination
CO2 removal

Results collection and evaluation
(Installed capacities, annual generation, cost of system and components, cost of electricity, CO2 emissions, etc.)
- The technologies applied for the energy system optimisation include those for electricity generation, heat generation, energy storage and electricity transmission
- The model is applied at full hourly resolution for an entire year
- The LUT model has been applied across all energy sectors
**Key insights:**

- All forms of transportation categorised into Road, Rail, Marine and Aviation
- Majority of demand to be covered by electricity directly and indirectly by liquid hydrocarbon (including biofuels), methane and hydrogen
The LUT model applied to the desalination sector
The desalination demand is met with reverse osmosis and MED
Key insights:

- A regional cumulative average annual growth rate of about 1.9% in final energy demand drives the transition. This is aggregated by final energy demand growth for power and heat, desalinated water demand and transportation demand linked to powertrain assumptions. This leads to a comprehensive electrification, which massively increases overall energy efficiency, to an even higher growth rate in provided energy services.
- Resulting in an average annual growth rate of about 0.9% in total primary energy demand (TPED).
- The population is expected to grow from 464 to 572 million, while the average per capita PED decreases from around 10.5 MWh/person in 2015 to about 9 MWh/person by 2035 and increases nearly to 12 MWh/person by 2050.
- TPED slightly decreased from around 5000 TWh in 2015 to around 4900 TWh by 2035 and increases up to 6700 TWh by 2050 in this study (which assumes high electrification).
- In comparison, current practices (low electrification) would result in a TPED of nearly 11,500 TWh by 2050.
- The massive gain in energy efficiency is primarily due to a high level of electrification of more than 80% in 2050, saving nearly 4800 TWh compared to the continuation of current practices (low electrification).
Energy Resources (Solar, Wind)

Solar PV generation profile
Regional aggregated PV feed-in profile computed using the weighed average rule

Wind generation profile
Regional aggregated wind feed-in profile computed using the weighed average rule

Key insights:
- Solar PV can generate electricity throughout the year
- Perfect wind conditions in the middle of the year and good conditions otherwise
- Seasonal and hourly complementary of solar PV and wind energy

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more information ► office@energywatchgroup.org, manish.ram@lut.fi
Key insights:
- Wind: Very high potential in the southern regions and low potential in the Northern regions
- Solar PV: Excellent PV condition in almost all the countries/regions, especially in Peru, Chile, Central South America, Northwest Argentina and Northeast Brazil
Key insights:
- Electricity generation is comprised of demand for all energy sectors (power, heat, transport, desalination)
- Solar PV supply increases from 29% in 2030 to about 62% in 2050 becoming the main energy source
- Wind energy share increases to 23% of total electricity by 2030 and further declines to about 10% by 2050
- Heat pumps play a significant role in the heat sector with a share of nearly 34% of heat generation by 2050 coming from heat pumps on district and individual levels
- Gas-based heating decreases through the transition from above 32% in 2015 to around 9% by 2050, fossil-gas is eliminated and replaced by synthetic gas produced from renewables
**Key insights:**

- Electricity demand covered by storage increases through the transition period from about 220 TWh\(_{el}\) by 2035 and further significantly increases to over 800 TWh\(_{el}\) in 2050.
- The ratio of electricity demand covered by energy storage to electricity generation increases significantly from around 5% by 2025 to about 15% by 2050.
- Batteries emerge as the most relevant electricity storage technology contributing about 94% of the total electricity storage output by 2050 (more details on slide 19).
Key insights:

- Storage output covers over 500 TWh$_{th}$ of the total heat demand in 2050 and heat storage technologies play a vital role.
- The ratio of heat demand covered by energy storage to heat generation increases substantially to over 16% by 2050.
- Thermal energy storage emerges as the most relevant heat storage technology with about 67% of heat storage output by 2050 (more details on slide 19).
- Power-to-Gas contributes around 33% of the heat storage output in 2050.
**Energy System Cost**

**Key insights:**

- The total annual costs are in the range of 260-310 b€ through the transition period and well distributed across the 3 major sectors of Power, Heat and Transport.
- LCOE declines from around 68 €/MWh in 2015 to around 50 €/MWh and is increasingly dominated by capital costs as fuel costs continue to decline through the transition period, which could mean increased self-reliance for South America by 2050.
- Costs are well spread across a range of technologies with major investments for PV, wind, batteries, heat pumps and synthetic fuel conversion up to 2050.
- The cumulative investments are about 2,560 b€.
Sectoral Outlook
Power & Heat - Demand

Key insights:
- Electricity consumption per capita increases from 1.6 MWh/person in 2015 to over 2.5 MWh/person by 2050
- Total heat demand increases steadily from around 1700 TWh\textsubscript{th} in 2015 to 2800 TWh\textsubscript{th} by 2050, mainly driven by higher demand for industrial process heat, but also growing building space per person and domestic water heating
- Industrial heat contribute the major share of demand which is mainly low temperature (LT)
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more information ► office@energywatchgroup.org, manish.ram@lut.fi
Key insights:
- Batteries are the most important supporting technology for solar PV, particularly for PV prosumers
- Pumped hydro energy storage and compressed air energy storage contribute through the transition
- Thermal energy storage emerges as the most relevant heat storage technology with about 67% of heat storage output by 2050
- Gas storage contributes around 33% of the heat storage output in 2050 covering predominantly seasonal demand, which was covered by fossil gas before 2050
**Sectoral Outlook**

**Power – Costs and Investments**

Key insights:
- LCOE of the power sector decreases substantially from around 75 €/MWh in 2015 to around 39 €/MWh by 2050, including all generation, storage, curtailment and parts of the grid costs.
- Beyond 2030 the LCOE further declines up to 2050, signifying that larger capacities of RE addition result in reduction of energy costs.
- Investments are well spread across a range of technologies with major share in solar PV, wind, hydropower and batteries up to 2050.

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more information ► office@energywatchgroup.org, manish.ram@lut.fi
**Sectoral Outlook**

**Heat – Costs and Investments**

Key insights:

- LCOH of the heat sector declines from around 70 €/MWh in 2015 to about 52 €/MWh by 2050
- LCOH is predominantly comprised of capex as fuel costs decline through the transition
- Investments are mainly in heat pumps and some shares in biomass heating up to 2050 and a steep increase in heat pump investments in 2050, replacing the remaining fossil-based heating systems
Sectoral Outlook
Transport – Demand

Key insights:
- The final transport passenger demand increases from around 3.2 million p-km to around 8.8 million p-km
- The final transport freight demand also increases from around 6 million t-km to around 21 million t-km
- Whereas, the final energy demand for overall transport decreases from 2000 TWh/a in 2015 to 1700 TWh/a in 2035, and further increased to around 2000 TWh/a by 2050
- Marine freight is aligned to the scenario with a drastic decline in fuels transportation during the transition
Key insights:

- The final energy demand for road passengers decreases from around 930 TWh in 2015 to just around 500 TWh by 2050
- The final energy demand for road freight decreases from around 700 TWh in 2015 to around 490 TWh by 2050
- The significant decrease in final energy demand for overall road transport is primarily driven by the massive electrification
Sectoral Outlook
Transport – Rail, Marine and Aviation Demand

Key insights:
- The final energy demand for rail transport declines steadily from about 20 TWh in 2015 to around 14 TWh by 2050
- The final energy demand for marine transport increases steadily from around 250 TWh in 2015 to around 660 TWh by 2050
- The final energy demand for aviation transport increases significantly from nearly 130 TWh in 2015 to around 440 TWh by 2050
Sectoral Outlook
Transport – Defossilisation and Electrification

Key insights:
- Fossil fuel consumption in transport is observed to decline through the transition from about 88% in 2015 to zero by 2050
- Liquid fuels produced by renewable electricity contribute around 30% of the final energy demand in 2050
- Hydrogen constitutes more than 26% of final energy demand in 2050
- Electrification of the transport sector creates an electricity demand of around 2800 TWh$_{el}$ by 2050
- Massive demand for renewables-based liquid fuels kicks in from 2040 onwards up to 2050
Key insights:

- Solar PV with around 1360 GW and wind with around 75 GW constitute majority of the installed capacities by 2050
- Solar PV and wind generate all of the electricity in 2050 of nearly 3000 TWh
- Most of the capacity addition is 2035 onwards, with a rapid change in the transport sector toward increased electrification beyond 2030
Key insights:
- Utility-scale batteries and A-CAES installed storage capacities increase up to 2050, with very small share of PHES through the transition.
- Storage capacities increase beyond 2030 as electricity demand for transport increases.
- Utility-scale batteries contribute the major share of storage output in 2050 with over 300 TWh$_{el}$ along with some A-CAES.
- Conservative charging of vehicles is assumed, which excludes smart charging and vehicle-to-grid functionalities. Both would reduce storage demand. Some storage is needed for synthetic fuels production.
 Sectoral Outlook

Transport – Fuel Conversion, Storage Capacities and Heat Management

Key insights:
- Installed capacities of fuel conversion technologies increase significantly beyond 2040, with a major share of water electrolysis and some shares of Fischer-Tropsch and hydrogen up to 2050
- Installed capacity of gas storage comprised of hydrogen and methane reaches up to 3.8 TWh by 2050, with major share of hydrogen storage
- Installed CO₂ storage and CO₂ DAC increase significantly from 2040 onwards, with major share of CO₂ DAC
- Heat for fuel conversion process is managed with excess heat and utilisation of recovered heat

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more information ➤ office@energywatchgroup.org, manish.ram@lut.fi
Sectoral Outlook
Transport – Fuel Costs

Key insights:
- Fischer-Tropsch (FT) and Synthetic Natural Gas (SNG) fuel costs decline through the transition up to 2050
- FT fuels are in the range of costs of fossil liquid fuels with GHG emissions costs, on a level of about 81 €/MWh
- Electricity emerges as the most cost effective option with LCOE primary around 19 €/MWh and along with complementary costs of storage and other system components, total LCOE is around 26 €/MWh in 2050
- Hydrogen (H₂) fuel costs decline to be more cost competitive than fossil fuels, in the range of 47 €/MWh in 2050, while liquid H₂ is in the range of 56 €/MWh
- CO₂ from DAC is a critical component for synthetic fuels at around 30 €/tCO₂eq in 2050, using waste heat
Key insights:

- The total annual energy costs for transport are in the range of 110-130 b€ through the transition period with a decline from around 120 b€ in 2015 to about 105 b€ by 2050.
- Road transport form a major share of the costs in the initial years up to 2030, beyond which the aviation sector dominates the share of costs as cost in the road sector declines through the transition up to 2050.
- Rail and marine sector costs remain more steady through the transition.
- Annual system costs transit from being heavily dominated by fuel costs in 2015 to a very diverse share of costs across various technologies for electricity, synthetic fuels and sustainable biofuel production by 2050.
- FT units produce naphtha as by-product, which is included in overall system costs, but not in transport costs.
Sectoral Outlook

Transport – Capex and Opex

Key insights:

- Investments are predominantly in solar PV and wind up to 2030, beyond with significant investments are in fuel conversion technologies such as Fischer-Tropsch, water electrolysis and others
- A significant increase in annual fixed operational costs is observed beyond 2030, with more fuel conversion technologies up to 2050
- Whereas, the annual variable operational costs decrease beyond 2035 to very low amounts by 2050
**Key insights:**

- The total annual costs for transport are in the range of 110-130 b€ through the transition period with a decline from around 120 b€ in 2015 to about 118 b€ by 2050.
- Final transport passenger costs decline for road transport through the transition, whereas for marine and aviation there is a marginal decrease.
- Similarly, final transport freight costs decline in the case of road and increase slightly for aviation and remain stable for rail and marine.
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more information ► office@energywatchgroup.org, manish.ram@lut.fi

Key insights:
- The steady rise in water demand across South America leads to increased desalination capacities and some water storage by 2050
- Installed capacity of power generation for the desalination sector increases through the transition to around 15 GW by 2050, which is mainly renewables
- The LCOW for desalination remains stable around 0.9 €/m³ till 2030 and further increases to about 1.1 €/m³ by 2050
Key insights:

- GHG emissions can be reduced from about 900 MtCO$_2$eq in 2015 to zero by 2050 across all energy sectors.
- The remaining cumulative GHG emissions comprise around 13 GtCO$_2$eq from 2018 to 2050.
- The presented 100% RE scenario for the South America energy sector is compatible with the Paris Agreement.
- Deep defossilisation of the power and heat sectors is possible by 2030, while the transport sector is lagging and a massive decline of emissions is possible beyond 2030 up to 2050.
Job Prospects – Power Sector

Key insights:

- With the brisk build up in installations in South America, the total number of direct energy jobs rise from just under 1 million in 2015 to nearly 2.2 million by 2025 and a steady decline thereafter towards around 1.6 million by 2050.
- Jobs are predominantly created in the bioenergy sector with 827 thousand jobs by 2020 and hydropower sector with 357 thousand jobs by 2025 during the initial periods of the transition up to 2030.
- Solar PV emerges as the prime job creator in the region up to 2050 with about 930 thousand jobs.
- The share of operation and maintenance jobs grows through the transition period with 52% of total jobs by 2050, as fuel jobs decline rapidly.
Electricity generation and capacities

Key insights:
- Electricity generation is comprised of demand for the sectors power, heat, transport and desalination
- Solar PV capacities is widely distributed in the region, while most wind capacities is found in Chile and Argentina, hydropower installed capacities are predominant in Brazil
- Solar PV generation dominates electricity generation mix, and complemented by hydropower and wind energy
- Installed capacities are considered for all sectors of power, heat, transport and desalination
Storage capacities and throughput
Electricity

Key insights:
- Utility-scale batteries and A-CAES contributes a major share of the electricity storage capacities, with some prosumer batteries by 2050
- Storage capacities are much higher in Venezuela and Peru
- Batteries, both prosumers and utility-scale, deliver the largest shares of output by 2050
- Compressed air energy storage and pump hydro energy storage contributes through the transition
- Storage capacities and generation are considered for all sectors
Key insights:

- Gas storage contributes the most for heat storage capacities in 2050 covering predominantly seasonal demand, covered by fossil gas before 2050.
- Thermal energy storage output is much higher than gas storage in Ecuador, Chile and some regions in Brazil, whereas gas storage dominates the heat storage output in other regions.
- Thermal energy storage contributes to around 40% of heat storage output in 2050.
Major RE Supply Shares in 2050

Key insights:
- Solar PV dominates the total electricity generation shares in 2050
- Electricity generation shares in South America for all energy sectors are
  - Solar PV at about 75.9%
  - Wind energy at about 10.9%
  - Hydropower at about 12.1%
Major RE Capacities in 2050

Key insights:
- Solar PV dominates the total electricity generation capacity across South America in 2050
- Installed capacities in 2050 across South America for all energy sectors are
  - Solar PV: 2248 GW
  - Wind energy: 135 GW
  - Hydropower: 160 GW
Storage Supply Shares in 2050

Key insights:
- Battery storage mainly plays a role in providing diurnal storage with around 18% of the total supply
- In South America, a 100% RE system in the power and heat sector can run without seasonal storage based on PtG, due to sector coupling flexibility and high share of hydro dams (predominantly in Brazil), which can flexibly balance generation and demand
- Prosumers play a significant role and hence a large portion of batteries can be observed in 2050, also with low costs of solar PV and batteries
- Storage supply shares are considered just for the power and heat sectors
Losses (Curtailment, Storage, Grids) in 2050

Key insights:
- The total losses in a 100% RE based electricity system in 2050 are just around 20% of the total generation
- Curtailment has a share of 1.2%, storage contributes 9.7% and grid losses amount to 9.2%
- RE-based electricity system is significantly more efficient in comparison to the current system
- Losses are considered for the sectors of power and heat

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Total Cost and Share of Primary Generation

Key insights:

- Total LCOE by 2050 is around 53.6 €/MWh (including generation, storage, curtailment and some grid costs), the range for 75% of regional power demand is 30.7 – 53.3 €/MWh
- A 74% ratio of the primary generation cost to the total LCOE can be observed, in a range of 52% - 90% for 80% of regional power demand
- Cost of storage contributes substantially to the total energy system LCOE, with ratios ranging from 10% - 50% for 75% of regional power demand
- Costs are considered just for the power and heat sectors
Summary – Power & Heat

- Electricity consumption per capita increases from 1.6 MWh/person in 2015 to 2.5 MWh/person by 2050, while total heat demand increases steadily from around 1700 TWh\textsubscript{th} in 2015 to about 2800 TWh\textsubscript{th} by 2050

- Solar PV with 878 GW, hydropower with 160 GW and wind with 57 GW constitute a majority of the installed capacities by 2050, while heat pumps, electric heating and biomass-based heating constitute a majority of the installed capacities by 2050

- Utility-scale and prosumer batteries contribute a major share of the electricity storage output, while thermal energy storage emerges as the most relevant heat storage technology in the transition

- LCOE of the power sector decreases substantially from around 75 €/MWh in 2015 to around 39 €/MWh by 2050, while LCOH of the heat sector decreases from around 70 €/MWh in 2015 to around 52 €/MWh by 2050

- Deep defossilisation of the power and heat sectors is possible from around 375 MtCO\textsubscript{2}eq in 2015 to around 41 MtCO\textsubscript{2}eq in 2030 and further to zero by 2050
Summary – Transport

▪ The modes of transportation are: Road, Rail, Marine and Aviation
▪ The main forms of energy supply are direct and indirect electricity, the latter with liquid hydrocarbons, methane, hydrogen and some biofuels
▪ The final energy demand for road freight decreases from 700 TWh/a in 2015 to 490 TWh/a mainly driven by the massive electrification of road transport
▪ Fuel utilisation reduces drastically through the transition as fossil fuels are completely replaced by electricity and synthetic fuels along with some sustainable biofuels
▪ The final energy costs for transport remain around 110-130 b€ through the transition period, with massive reduction for road, while an increase for marine and aviation by 2050
▪ GHG emissions can be reduced from about 510 MtCO$_2$eq in 2015 to zero across the transport sector by 2050
Summary – Desalination

- The water desalination demand is mainly covered by reverse osmosis.
- The steady rise in water demand and water stress leads to increased desalination capacities and some water storage by 2050.
- Installed capacity of power generation for the desalination sector increases through the transition period to around 15 GW by 2050.
- Utility-scale solar PV and onshore wind dominates the total installed capacity by 2050.
- Installed storage capacities are dominated by gas storage, while storage output is mainly from utility-scale batteries.
- The LCOW for desalination remains quite stable 0.9 €/m³ till 2030 and further increases to about 1.1 €/m³ by 2050.
- GHG emissions can be reduced from about 4.5 MtCO₂eq in 2015 to zero across the desalination sector by 2050.
Summary – Energy Transition

- South America can reach 100% RE and zero GHG emissions by 2050, solar-wind-hydrowpower mix drives most of the system
- The LCOE obtained for a fully sustainable energy system for South America is 39 €/MWh by 2050
- The annual energy costs are in the range of 260-310 b€ through the transition, with cumulative investment costs of about 2560 b€ up to 2050
- Solar PV emerges as the most prominent electricity supply source with around 62% of the total electricity supply by 2050
- Heat pumps play a significant role in the heat sector with a share of nearly 34% of heat generation by 2050 coming from heat pumps on district and individual levels
- Batteries emerge as the key storage technology with 94% of total storage output
- GHG emissions can be reduced from about 900 MtCO₂eq in 2015 to zero by 2050, with remaining cumulative GHG emissions of around 13 GtCO₂eq from 2018 to 2050
- Around 1.6 million direct energy jobs are created annually in 2050 across the power sector
- A 100% RE system across South America is more efficient and cost competitive than a fossil based option and is compatible with the Paris Agreement
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<td>BECCS</td>
<td>Bioenergy Carbon Capture and Storage</td>
<td>HVAC</td>
<td>High Voltage Alternating Current</td>
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<td>CAES</td>
<td>Compressed Air Energy Storage</td>
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<td>CO$_2$ Direct Air Capture</td>
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<td>District Heating</td>
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<td>DME</td>
<td>Dimethyl Ether</td>
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more information ➤ office@energywatchgroup.org, manish.ram@lut.fi
Acronyms 2

PHEV  Plug-in Hybrid Electric Vehicle
PHES  Pumped Hydro Energy Storage
PP    power plant
PtG   Power-to-Gas
PtH   Power-to-Heat
PtL   Power-to-Liquids
PtX   Power-to-X
PV    Photovoltaics
RE    Renewable Energy
R/O   (Seawater) Reverse Osmosis
SNG   Synthetic Natural Gas
ST    Steam Turbine
TES   Thermal Energy Storage
TPED  Total Primary Energy Demand
TW    Terawatt
TTW   Tank to Wheel
Further Findings

Results for an overview on global aspects and all other major regions are available:

- Global results link
- Europe link
- Eurasia link
- MENA link
- Sub-Saharan Africa link
- SAARC link
- Northeast Asia link
- Southeast Asia/ Pacific link
- North America link
- South America link
- Supplementary Data link
- Report link

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Further information and all publications at:
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