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

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- Summary
Overview

- North America is structured into 20 sub-regions
  - Canada is divided into 2 sub-regions (East and West)
  - United States of America consists of 14 sub-regions
  - Mexico consists of 4 sub-regions (Northwest, North, Center, South)
Current Status: Power Sector

Key insights:
- In recent times, RE has seen significant growth in the share of installed capacity
- Strong increase in RE capacities in 2010-2014 (50%)
- Historically, a significant share of fossil powered plants in the generation mix is observed (70% by end of 2014)
Key insights:

- Historically, a significant share of fossil powered heat generation is present with some shares of bio-based heating.
- The transport sector is dominated by fossil liquid fuels with a share of around 95% 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.
LUT Energy System Transition model

Transport

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
Long-term Energy Demand

Key insights:

- A regional cumulative average annual growth rate of about 0.9% 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 -0.7% in total primary energy demand (TPED).
- The population is expected to grow from 477 to 608 million, while the average per capita PED decreases from around 60 MWh/person in 2015 to 31 MWh/person by 2035 and then increases up to 35 MWh/person by 2050.
- TPED decreases from around 28,000 TWh in 2015 to around 17,000 TWh by 2035 and increases up to 22,000 TWh by 2050 in this study (which assumes high electrification).
- In comparison, current practices (low electrification) would result in a TPED of nearly 42,000 TWh by 2050.
- The massive gain in energy efficiency is primarily due to a high level of electrification of more than 88% in 2050, saving nearly 20,000 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:
- Wind: Considerable generation at the beginning and end of the year
- Solar PV: excellent potential during the middle of the year
- Seasonal and hourly complementary of PV and wind
Full Load Hours

Key insights:
- Wind: High FLH in central US, western Alaska, North and Northeast Canada
- Solar PV: excellent resources in most of the regions in the US and all around Mexico, but lower potential in Canada and Alaska
Energy Supply

Key insights:

- It is the least-cost option to supply 90% of all electricity in North America from solar PV and wind by 2050.
- Solar PV supply increases from 26% in 2030 to about 62% in 2050 becoming the main energy source.
- Wind energy share increases to 55% of total electricity generation by 2030 and declines to about 28% by 2050.
- Heat pumps play a significant role in the heat sector with a share of nearly 50% of heat generation by 2050 coming from heat pumps on district and individual levels.
- Gas-based heating decreases through the transition from above 84% in 2015 to around 8% by 2050, fossil-gas is eliminated and replaced by synthetic gas produced from renewables.

Global Energy System based on 100% RE – Power, Heat, Transport and Desalination Sectors: North America

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**Key insights:**

- **Electricity demand covered by storage increases through the transition period** from about 1300 TWh\(_{el}\) by 2030 and further significantly increases to about 3500 TWh\(_{el}\) in 2050.
- **The ratio of electricity demand covered by energy storage to electricity generation increases significantly** from around 8.2% by 2035 to about 18% by 2050.
- **Batteries emerge as the most relevant electricity storage technology** contributing about 93% of the total storage output by 2050 (more details on slide 19).

*heat storage includes gas and thermal storage technologies*
Energy Storage

Heat

Key insights:

- Storage output covers more than 1500 TWh\textsubscript{th} of total heat demand in 2050 and heat storage technologies play a vital role with minor shares of electricity storage.
- The ratio of heat demand covered by energy storage to heat generation increases substantially to about 16.2% by 2050.
- Thermal energy storage emerges as the most relevant heat storage technology with around 58% of heat storage output by 2050 (more details on slide 19).
- Power-to-Gas contributes around 42% of the heat storage output in 2050.
Energy System Cost

Key insights:

- The total annual costs are in the range of 1000-1200 b€ through the transition period and well distributed across the 3 major sectors of Power, Heat and Transport.
- LCOE remains around 54-67 €/MWh and is increasingly dominated by capital costs as fuel costs continue to decline through the transition period, which could mean increased self-reliance 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 10,200 b€.

Global Energy System based on 100% RE – Power, Heat, Transport and Desalination Sectors: North America

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Key insights:
- Electricity consumption per capita increases from 10.6 MWh/person in 2015 to 11 MWh/person by 2050
- Total heat demand increases steadily from around 5400 TWh\(_{th}\) in 2015 to 7000 TWh\(_{th}\) by 2050, mainly driven by higher demand for industrial process heat, but also growing building space per person reducing the gains from building efficiency standards
- Space heating and Industrial heat contribute the major share of demand which is mainly low temperature (LT)
Sectoral Outlook

Power & Heat – Installed Capacities and Generation

Key insights:

- Solar PV and wind energy dominate the electricity generation mix during the transition.
- Solar PV with around 3900 GW and wind with 800 GW constitute a majority of the installed capacities by 2050.
- Heat pumps, electric heating and biomass-based heating constitute a majority of the installed heat generation capacities during the transition, with a significant increase in 2050 due to the absence of fossil fuels in the system in this period.
Key insights:
- Utility-scale and prosumer batteries contribute a major share of the electricity storage output with nearly 93% by 2050
- 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 58% of heat storage output by 2050
- Gas storage contributes around 42% of the heat storage output in 2050 covering predominantly seasonal demand, which was covered by fossil gas before 2050
Key insights:

- **LCOE of the power sector decreases substantially from around 81 €/MWh in 2015 to around 55 €/MWh by 2050**
- **LCOE** is predominantly comprised of capex as fuel costs decline through the transition
- Investments are well spread across a range of technologies with major share in solar PV, wind and batteries up to 2050
Key insights:

- LCOH of the heat sector increases marginally from around 53 €/MWh in 2015 to around 55 €/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, eliminating fossil fuels based heating.
Sectoral Outlook
Transport – Demand

Key insights:
- The final transport passenger demand increases from around 11 million p-km to around 23 million p-km
- The final transport freight demand also increases from around 22 million t-km to around 38 million t-km
- Whereas, the final energy demand for overall transport decreases from 8100 TWh/a in 2015 to 5200 TWh/a by 2050, enabled by high efficiency of electric vehicles
- Marine freight is aligned to the scenario with a drastic decline in fuels transportation during the transition
Sectoral Outlook
Transport – Road Demand

Key insights:
- The final energy demand for road passengers decreases significantly from around 4400 TWh in 2015 to just around 1300 TWh by 2050.
- The final energy demand for road freight decreases substantially from around 2300 TWh in 2015 to around 1100 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 from about 180 TWh in 2015 to nearly 140 TWh by 2050
- The final energy demand for marine transport increases steadily from around 810 TWh in 2015 to around 1900 TWh by 2050
- The final energy demand for aviation transport increases significantly from nearly 710 TWh in 2015 to around 1000 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 97% in 2015 to zero by 2050.
- Liquid fuels produced by renewable electricity contribute around 37% of the final energy demand in 2050.
- Hydrogen constitutes more than 28% of final energy demand in 2050.
- Electrification of the transport sector creates an electricity demand of around 8000 TWh_{el} by 2050.
- Massive demand for renewables based liquid fuels kicks in from 2040 onwards up to 2050.

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Sectoral Outlook
Transport – Power Capacities and Generation

Key insights:
- Solar PV with around 2800 GW and wind with around 900 GW constitute majority of the installed capacities by 2050
- Solar PV and wind generate all of the electricity in 2050 of nearly 8200 TWh
- Most of the capacity addition is 2035 onwards, with a rapid change in the transport sector toward increased electrification beyond 2030
Sectoral Outlook
Transport – Storage Capacities and Output

Key insights:
- A-CAES and utility-scale batteries installed storage capacities increase up to 2050
- 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 250 TWh$_{el}$
- 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 19.8 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
**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 80 €/MWh.
- Electricity emerges as the most cost effective option with LCOE primary around 16 €/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 46 €/MWh in 2050, while liquid H₂ is in the range of 52 €/MWh.
- CO₂ from DAC is a critical component for synthetic fuels at around 31 €/tCO₂eq in 2050, using waste heat.
Key insights:

- The total annual energy costs for transport are in the range of 280-550 b€ through the transition period with a decline from around 510 b€ in 2015 to about 280 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 increase till 2030 and decrease beyond 2035 to very low amounts by 2045

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Sectoral Outlook
Transport – Passenger and Freight Costs

Key insights:
- The total annual costs for transport are in the range of 280-550 b€ through the transition period with a decline from around 510 b€ in 2015 to about 280 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 remains stable for rail, aviation and marine
Sectoral Outlook
Desalination

Key insights:
- The steady rise in water demand across North America leads to increased desalination capacities (reverse osmosis) and some water storage by 2050
- Installed capacity of power generation for the desalination sector increases through the transition to around 520 GW by 2050, which is mainly renewables
- The LCOW for desalination decreases through the transition and declines from 1.1 €/m³ in 2015 to 1.0 €/m³ by 2050
Key insights:

- GHG emissions can be reduced from over 6000 MtCO$_2$eq in 2015 to zero by 2050 across all energy sectors.
- The remaining cumulative GHG emissions comprise around 68 GtCO$_2$eq from 2018 to 2050.
- The presented 100% RE scenario for the North American 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:

- Total direct energy jobs are set to increase from around 1.8 million in 2015 to nearly 3.8 million, with the rapid ramp up in installations up to 2025 and then a steady decline towards nearly 2.7 million by 2050.
- Solar PV emerges as the prime job creator in the region up to 2050 with about 1.67 million jobs.
- With great potential for wind power, jobs from 2020 to 2030 are observed to be associated with wind power development creating around 762 thousand jobs in 2025.
- Operation and maintenance jobs continue to grow through the transition period and become the major job creating segment by 2050 with 64% of total jobs across North America.
Electricity generation and capacities

Key insights:
- Electricity generation is comprised of demand for the sectors power, heat, transport and desalination.
- Solar PV capacities are predominantly in the southern and northern regions of USA and Mexico, while most wind capacities is found in the Central and Mid-West of the USA, as well in Alaska and Canada.
- Overall, solar PV and wind generate most of the electricity needed across North America by 2050.
- Installed capacities and electricity generation are considered for all sectors of power, heat, transport and desalination.
Key insights:

- Utility-scale and prosumer batteries contribute a major share of the electricity storage capacities, with some shares of compressed air energy storage by 2050
- Storage capacities are much higher in the USA and Mexico
- Batteries, both prosumers and utility-scale, deliver the largest shares of output by 2050
- Compressed air energy storage contributes through the transition
- Storage capacities and generation are considered for all sectors
Storage capacities and throughput
Heat

Key insights:
- Gas storage contributes the most for heat storage capacities in 2050 covering predominantly seasonal demand, covered by fossil gas before 2050
- Gas storage output is much higher than other storage options in most regions in the USA and Mexico
- Thermal energy storage emerges as the most relevant heat storage technology in terms 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 North America for all energy sectors are
  - Solar PV at about 61.5%
  - Wind energy at about 33.3%
  - Hydropower at about 4.1%
Major RE Capacities in 2050

Key insights:
- Solar PV dominates the total electricity generation capacity across North America in 2050
- Installed capacities in 2050 for all energy sectors are
  - Solar PV: 7022 GW
  - Wind energy: 1765 GW
  - Hydropower: 208 GW
Key insights:
- Battery storage mainly plays a role in providing diurnal storage with around 31% of the total supply.
- SNG via PtG plays a role in providing seasonal storage with just 0.1% of the total supply for the power sector. The other sectors are not considered for this diagram, however sector coupling of power and heat leads indirectly to a lower SNG demand for the power sector due to more flexibility.
- 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 23.3% of the total generation
- Curtailment has a share of 3.3%, storage contributes 10.2% and grid losses amount to 9.8%
- RE-based electricity system is significantly more efficient in comparison to the current system based predominantly on fossil fuels and nuclear
- Losses are considered just for the power and heat sectors
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 global power demand is 41.2 – 59.1 €/MWh
- A 62% ratio of the primary generation cost to the total LCOE can be observed, in a range of 30% - 72% for 75% of regional power demand
- Cost of storage contributes substantially to the total energy system LCOE, with ratios ranging from 15% - 40% 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 over 10.6 MWh/person in 2015 to 11 MWh/person by 2050, while total heat demand increases steadily from around 5400 TWh\(_{th}\) in 2015 to 7000 TWh\(_{th}\) by 2050

- Solar PV with around 3900 GW and wind with 800 GW constitute a majority of the installed power generation capacities by 2050, while heat pumps, electric heating and biomass-based heating constitute a majority of the installed heat generation 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 81 €/MWh in 2015 to around 55 €/MWh by 2050, while LCOH of the heat sector increases marginally from around 53 €/MWh in 2015 to around 55 €/MWh by 2050

- Deep defossilisation of the power and heat sectors is possible from around 3827 MtCO\(_{2eq}\) in 2015 to around 438 MtCO\(_{2eq}\) 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 transport decreases from 8,100 TWh/a in 2015 to 5,200 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 280-550 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 2219 MtCO$_{2eq}$ 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 520 GW by 2050.
- Utility-scale solar PV and onshore wind comprise around 90% of the 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 through the transition and declines from 1.1 €/m$^3$ in 2015 to 1.0 €/m$^3$ by 2050.
- GHG emissions can be reduced from about 0.4 MtCO$_{2eq}$ in 2015 to zero across the desalination sector by 2050.
North America can reach 100% RE and zero GHG emissions by 2050, solar and wind energy supply bulk of the electricity demand

The LCOE obtained for a fully sustainable energy system for North America is about 53 €/MWh by 2050

The annual energy costs are in the range of 1000-1200 b€ through the transition, with cumulative investment costs of about 10,200 b€ up to 2050

Heat pumps play a significant role in the heat sector with a share of nearly 50% of heat generation by 2050 coming from heat pumps on district and individual levels

Batteries emerge as the key storage technology with 93% of total storage output

GHG emissions can be reduced from over 6000 MtCO$_2$eq in 2015 to zero by 2050, with remaining cumulative GHG emissions of around 68 GtCO$_2$eq from 2018 to 2050.

Around 2.7 million direct energy jobs are created annually in 2050 across the power sector

A 100% RE system across North America is more efficient and cost competitive than a fossil based option and is compatible with the Paris Agreement
### Acronyms 1

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tr>
<td>BECCS</td>
<td>Bioenergy Carbon Capture and Storage</td>
<td>HVAC</td>
<td>High Voltage Alternating Current</td>
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<td>BEV</td>
<td>Battery Electric Vehicle</td>
<td>HVDC</td>
<td>High Voltage Direct Current</td>
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<td>CAES</td>
<td>Compressed Air Energy Storage</td>
<td>ICE</td>
<td>Internal Combustion Engine</td>
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<td>CAPEX</td>
<td>Capital Expenditures</td>
<td>IEA</td>
<td>International Energy Agency</td>
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<tr>
<td>CCS</td>
<td>Carbon Capture and Storage</td>
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<td>Individual Heating</td>
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<td>CCGT</td>
<td>Combined Cycle Gas Turbine</td>
<td>LCOC</td>
<td>Levelised Cost of Curtailment</td>
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<td>CHP</td>
<td>Combined Heat and Power</td>
<td>LCOE</td>
<td>Levelised Cost of Electricity</td>
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<td>CSP</td>
<td>Concentrated Solar Thermal Power</td>
<td>LCOH</td>
<td>Levelised Cost of Heat</td>
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<td>DAC</td>
<td>CO$_2$ Direct Air Capture</td>
<td>LCOS</td>
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<td>DACCS</td>
<td>Direct Air Carbon Capture and Storage</td>
<td>LCOT</td>
<td>Levelised Cost of Transmission</td>
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<td>DH</td>
<td>District Heating</td>
<td>LCOW</td>
<td>Levelised Cost of Water</td>
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<td>DME</td>
<td>Dimethyl Ether</td>
<td>LDV</td>
<td>Light Duty Vehicle</td>
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<td>FCEV</td>
<td>Fuel Cell Electric Vehicle</td>
<td>LNG</td>
<td>Liquefied Natural Gas</td>
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<td>FLH</td>
<td>Full Load Hours</td>
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<td>Low Temperature</td>
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<td>GW</td>
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<td>Hot Heat Burner</td>
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<td>HT</td>
<td>High Temperature</td>
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<td>Operational Expenditures</td>
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## Acronyms 2

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

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

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

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Further information and all publications at:
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