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

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Overview

Europe is structured into 20 sub-regions:

- Iceland, Norway, Denmark, Sweden, Finland, BALTIC (Estonia+Latvia+Lithuania),
- Germany, Poland, CRS (Czech Republic+Slovakia), AUH (Austria+Hungary), CH (Switzerland+Liechtenstein)
- IBERIA (Portugal+Spain+Gibraltar), France (France+Monaco+Andorra), Italy (Italy+San Marino+Vatican+Malta)
- BRI (Ireland+United Kingdom), BNL (Belgium+Netherlands+Luxembourg)
- BKN-W (Slovenia+Croatia+Bosnia and Herzegovina+Kosovo+Serbia+Montenegro+Macedonia+Albania), BKN-E (Romania+Bulgaria+Greece), UA (Ukraine+Moldova), TR (Turkey+Cyprus)
Current Status
Power Sector

Key insights:
- Historically, a significant share of fossil powered plants in the generation mix is observed.
- In recent times, RE has seen significant growth in the share of installed capacity.
Current Status
Heat, Transport and Desalination Sectors

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 97% 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 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.)

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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 categorized 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 from reverse osmosis and MED
Long-term Energy Demand

Key insights:
- A cumulative average annual growth rate of about 0.9% in the energy transition period is assumed, compared to 0.3% - 0.6% assumed by IEA; growth assumed to be higher in some countries than in others
- The European population is expected to remain stable between 664 to 666 million people, while the average per capita energy demand decreases from around 33 MWh/person in 2015 to 24 MWh/person by 2035 and increases up to around 30 MWh/person by 2050
- The primary energy demand decreases from almost 21,000 TWh in 2015 to around 16,000 TWh by 2035 and increases up to 20,000 TWh by 2050 in this study (which assumes high electrification)
- In comparison, current practices (low electrification) would have resulted in a primary energy demand of nearly 35,000 TWh by 2050
- The massive gain in energy efficiency is primarily due to a high level of electrification of more than 85% in 2050, saving nearly 15,000 TWh compared to the continuation of current practices (low electrification)
Energy Resources (Solar, Wind)

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

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

Key insights:
- Wind: Seasonal variation and overall distribution is uneven
- PV: Seasonal and diurnal variation of the resource in Europe
- Wind and PV: balancing effect throughout the year, resulting in less overall variability
Full Load Hours

PV (single-axis tracking) full load hours

Wind onshore (E101 at 150m) full load hours

Key insights:
- Wind: More consistent winds in north, Atlantic and Baltic Sea regions
- PV: The Mediterranean and Balkan regions are rich in solar irradiation
- Wind+PV: A balancing effect has been observed, resulting in less overall European variability

Global Energy System based on 100% RE – Power, Heat, Transport and Desalination Sectors: Europe
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**Key insights:**

- **Electricity generation** is comprised of demand for all sectors (power, heat, transport, desalination)
- Solar PV supply increases from 29% in 2030 to about 62% in 2050 becoming the least cost energy source
- Wind energy increases to 32% by 2030 and remains steady onwards up to 2050
- Heat pumps play a significant role in the heat sector with a share of over 50% of heat generation by 2050 coming from heat pumps on district and individual levels with some shares of biomass based heating
- Gas based heating decreases through the transition from above 75% in 2015 to around 30% by 2050
Energy Storage
Electricity

Key insights:
- Storage output covers around 17% of the total electricity generation in 2050, which is nearly 3000 TWh$_{el}$
- The ratio of electricity demand covered by energy storage to electricity generation increases significantly to around 13% by 2035 and remains around 11-13%, plus around 4% covered by heat to electricity by 2050
- Batteries emerge as the most relevant electricity storage technology contributing about 83% of the total electricity storage output by 2050
- A significant share of gas storage is installed to provide seasonal storage
Energy Storage

Heat

Key insights:

- Storage output covers more than 2000 TWh\(_{th}\) 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 over 20% by 2050 with a major share of heat storage technologies.
- Thermal energy storage emerges as the most relevant heat storage technology with around 40-50% of heat storage output from 2030 until 2050.
- Power-to-Gas contributes around 50% of the heat storage output in 2050.
Energy System Cost

Key insights:

- The total annual costs are in the range of 950-1100 b€ through the transition period and well distributed across the 3 major sectors of Power, Heat and Transport.
- LCOE remains around 50-60 €/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 Europe 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 investment costs are about 9,910 b€.
**Sectoral Outlook**

**Power & Heat - Demand**

**Key insights:**
- Electricity consumption per capita increases from over 5 MWh/person in 2015 to over 8 MWh/person by 2050.
- Heat demand increases steadily from around 6500 TWh\(_{th}\) in 2015 to 8500 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 with 4400 GW and wind with 960 GW constitute a majority of the installed capacities by 2050
- Heat pumps, electric heating and biomass based heating constitute a majority of the installed capacities during the transition, with a significant increase in 2050 due to the absence of fossil fuels in the system in this period
- From a fossil fuel and nuclear dominated power & heat sector in 2015 to a solar PV and wind dominated sector by 2050, with some hydropower and bioenergy
Key insights:

- Large-scale and prosumer batteries contribute a major share of the electricity storage output with nearly 83% 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 around 40-60% of heat storage output from 2030 until 2050.
- Gas storage contributes more than 50% of the heat storage output in 2050 covering predominantly seasonal demand, which is covered by fossil gas before 2050.

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

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**Key insights:**

- **LCOE of the power sector decreases substantially from around 80 €/MWh in 2015 to around 56 €/MWh by 2050**
- **LCOE** is predominantly comprised of capex as fuel costs decline through the transition
- **Investments** are well spread across a range of electricity generation technologies with major shares in solar PV and wind energy up to 2050

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**Sectoral Outlook**

**Power – Costs and Investments**

**Key insights:**

- **LCOE of the power sector decreases substantially from around 80 €/MWh in 2015 to around 56 €/MWh by 2050**
- **LCOE** is predominantly comprised of capex as fuel costs decline through the transition
- **Investments** are well spread across a range of electricity generation technologies with major shares in solar PV and wind energy up to 2050
**Key insights:**

- **LCOH of the heat sector increases marginally from over 41 €/MWh in 2015 to around 47 €/MWh by 2025 and further declines to about 42 €/MWh by 2050.**
- **LCOH** is predominantly comprised of capex by 2050 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.
Key insights:

- The final transport passenger demand increases from around 9 million p-km to around 19 million p-km.
- The final transport freight demand also increases from around 1.9 million t-km to around 3.3 million t-km.
- Whereas, the final energy demand for overall transport decreases from 7000 TWh/a in 2015 to 5000 TWh/a by 2050, enabled by high efficiency of electric vehicles.
Sectoral Outlook
Transport – Road Demand

Key insights:
- The final energy demand for road passengers decreases significantly from around 2800 TWh in 2015 to just around 850 TWh by 2050
- The final energy demand for road freight decreases substantially from around 2600 TWh in 2015 to around 1300 TWh by 2050
- The significant decrease in final energy demand for overall road transport is primarily driven by the massive electrification
Key insights:

- The final energy demand for rail transport remains steady, ranging around 70-80 TWh through the transition.
- The final energy demand for marine transport increases steadily from around 680 TWh in 2015 to around 880 TWh by 2050.
- The final energy demand for aviation transport increases significantly from nearly 800 TWh in 2015 to around 1800 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 35% of the final energy demand in 2050.
- Hydrogen constitutes more than 25% of final energy demand in 2050, with some shares of sustainable biofuels.
- Electrification of the transport sector creates an electricity demand of around 7500 TWh\textsubscript{el} by 2050.
- Massive demand for liquid fuels kicks-in from 2040 onwards up to 2050.
Sectoral Outlook
Transport – Power Capacities and Generation

Key insights:
- Solar PV with around 4300 GW and wind with around 800 GW constitute majority of the installed capacities by 2050
- Solar PV and wind generate all of the electricity in 2050 of nearly 8000 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:
- Large-scale batteries and A-CAES installed storage capacities increase up to 2050, with some share of PHES, through the transition to over 3.2 TWh by 2050
- Storage capacities increase beyond 2030 as electricity demand for transport increases
- Large-scale batteries contribute the major share of storage output in 2050 with over 500 TWh_{el}
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 comprising of hydrogen and methane reaches up to 13 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 recovered use of heat.
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 including GHG emissions costs, in the range of 90-100 €/MWh in 2050, SNG is more cost effective than LNG in 2050.
- Electricity emerges as the most cost effective option with LCOE primary around 25 €/MWh and along with complementary costs of storage and other system components, total LCOE is around 32 €/MWh in 2050.
- Hydrogen (H₂) fuel costs decline to be more cost competitive that fossil fuels, in the range of 55 €/MWh in 2050, while liquid H₂ is in the range of 60 €/MWh.
- CO₂ from DAC is a critical component for synthetic fuels at around 33 €/MWh in 2050, using waste heat.
Sectoral Outlook
Transport – Annual Energy Costs

Key insights:
- The total annual energy costs for transport are in the range of 300-450 b€ through the transition period with a decline from around 430 b€ in 2015 to about 330 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 decline 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, that is included in overall system costs but not in transport cost.
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

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Sectoral Outlook
Transport – Passenger and Freight Costs

Key insights:
- The total annual costs for transport are in the range of 300-450 b€ through the transition period with a decline from around 430 b€ in 2015 to about 330 b€ by 2050
- Final transport passenger costs decline for road transport through the transition, whereas for marine and aviation there is a marginal increase
- Similarly, final transport freight costs decline in the case of road and increase slightly for aviation and remains stable for rail and marine
Key insights:

- The steady rise in water demand 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 250 GW by 2050, which is mainly renewables with PV and wind.
- The LCOW for desalination decreases through the transition and declines from 1.2 €/m³ in 2015 to 0.6 €/m³ by 2050.
Integrated Outlook
Value of co-operation and interconnections

Key insights:

- This research assumes a regional self-supply of all energy demand.
- Other research indicate that European co-operation can reduce power system costs by about 10%, leading to cross-border trade between the regions of about 15% of electricity demand. Such an energy system is called ‘SuperSmart Energy System’ since it combines elements of a strong distributed structure, but also centralised components to achieve and overall optimization.
- Cost reduction is based on better utilisation of system components, in particular storage capacity, but also reduced curtailment, more supply from least cost regions and improved seasonal balance.
- Fuels used in the transport sector and also partly the heat sector can be traded globally, in particular liquid hydrocarbons and LNG, so that international co-operation would be a means of further cost reduction and a more balanced use of partly limited area.
Key insights:

- GHG emissions can be reduced from over 4200 MtCO$_2$eq in 2015 to zero by 2050 across all energy sectors.
- The cumulative GHG emissions reduction comprises of around 85 GtCO$_2$eq.
- The presented 100% RE scenario for the European energy sector is compatible with the Paris Agreement.
- A 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.
Key insights:

- A 100% RE based electricity system in Europe creates 3 to 3.5 million jobs through the transition, substantially more than the existing 2 million jobs.
- Solar PV emerges as the major job creating sector with 1.73 million jobs by 2050, while bioenergy (675 thousand jobs by 2050) and hydropower (212 thousand jobs by 2050) create stable jobs up to 2050.
- Storage technologies led by batteries are observed to start creating jobs from 2025 onwards, with a stable share until 2050 with 277 thousand jobs in the battery sector.
- Operation and maintenance jobs continue to grow through the transition period and become the major job segment by 2050 with 61% of total jobs.
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 regions of Europe, while wind energy capacities are mainly in the northern regions of Europe.
- Solar PV generation is higher in the southern region, while wind energy generation is higher in the northern regions with better wind conditions.
- Overall, solar PV and wind generate most of the electricity needed across Europe by 2050.
Storage capacities and throughput

Electricity

Regional electricity storage capacities

Regional electricity storage annual generation

Key insights:
- Large-scale and prosumer batteries contribute a major share of the electricity storage capacities, with some shares of pumped hydro energy storage and compressed air energy storage by 2050
- Storage capacities are much higher in the southern parts of Europe compared to the northern regions
- Batteries, both prosumers and large-scale, deliver the largest shares of output by 2050
- Pumped hydro energy storage and compressed air energy storage contribute through the transition
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 in the northern parts of Europe as compared to the southern regions
- 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 supply shares in 2050
  - Solar PV at about 62%, as the least cost source
  - Wind energy at about 32%
  - Hydropower at about 4%
  - Others at about 2% (bioenergy, geothermal)
Major RE Capacities in 2050

Key insights:
- Solar PV dominates the total electricity generation capacity
- Installed capacities in 2050 across Europe
  - Solar PV: 8909 GW
  - Wind energy: 1783 GW
  - Hydropower: 226 GW
Storage Supply Shares in 2050

Key insights:
- Total supply includes energy demand for all sectors of power, heat, transport and desalination.
- Battery storage mainly plays a role in providing diurnal storage with around 15.5% of the total supply.
- Gas storage mainly plays a role in providing seasonal storage with just 0.3% of total supply, complemented by 0.2% dispatchable biomethane.
- 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.
Losses (Curtailment, Storage, Grids) in 2050

Key insights:
- The total losses in a 100% RE based electricity system in 2050 are just around 15% of the total generation.
- Curtailment has a share of 4.6%, storage contributes 2.4% and grid losses amount to 8%.
- Renewable energy based electricity system is significantly more efficient in comparison to the current system based predominantly on fossil fuels and nuclear.
- Losses are considered for the sectors power and heat.

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Total Cost and Share of Primary Generation

Key insights:
- Average LCOE in 2050 is around 54.5 €/MWh (including generation, storage, curtailment and some grid costs), the range for 75% of regional power demand is 47.6 – 63.7 €/MWh
- A 77% ratio of the primary generation cost to the total LCOE can be observed, in a range of 70% - 90% for 80% of regional power demand
- Cost of storage contributes substantially to the total energy system LCOE, with a range of 5% to 29% and an average of 19% across the region
- Considered are the sectors of power and heat
Summary – Power & Heat

- Electricity consumption per capita increases from over 5 MWh/person in 2015 to over 8 MWh/person by 2050, while heat demand increases steadily from around 6500 TWh\textsubscript{th} in 2015 to 8500 TWh\textsubscript{th} by 2050.

- Solar PV with 4400 GW and wind with 960 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.

- Large-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 along with gas storage in the transition.

- LCOE of the power sector decreases substantially from around 80 €/MWh in 2015 to around 56 €/MWh by 2050, while LCOH of the heat sector increases marginally from around 41 €/MWh in 2015 to around 47 €/MWh by 2025 and further declines to around 43 €/MWh by 2050.

- Deep defossilisation of the power and heat sectors is possible from around 2300 MtCO\textsubscript{2eq} in 2015 to around 700 MtCO\textsubscript{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 sustainable biofuels
- The final energy demand for transport decreases from 7000 TWh/a in 2015 to 5000 TWh/a mainly driven by the massive electrification of road transport
- Electricity demand for sustainable transport increases substantially up to 7500 TWh\textsubscript{el} by 2050 with high levels of direct and indirect electrification in 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 300-450 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 1900 MtCO\textsubscript{2eq} in 2015 to zero across the transport sector by 2050, which could be further accelerated with ambitious policies and targets
Summary – Desalination

- The desalination demand is mainly from reverse osmosis and MED
- 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 250 GW by 2050
- Large-scale solar PV and onshore wind comprise around 85% of the installed power capacity for desalination by 2050
- Installed storage capacities are dominated by gas storage, while storage output is mainly from large-scale batteries
- The LCOW for desalination declines through the transition from 1.2 €/m³ in 2015 to 0.6 €/m³ by 2050
- GHG emissions from the desalination sector increase from about 4.5 MtCO₂eq in 2015 to around 13 MtCO₂eq in 2035 and further reduce to zero by 2050
Europe can reach 100% RE and zero GHG emissions by 2050, which could be further accelerated by ambitious policies and targets to achieve zero GHG emissions well before 2050.

LCOE obtained for a fully sustainable energy system remains stable at around 50-60 €/MWh by 2050.

The annual energy costs are in the range of 950-1100 b€ through the transition, with cumulative investment costs of about 9,910 b€ up to 2050.

Solar PV emerges as the most prominent electricity supply source with around 62% of the total electricity supply by 2050, complemented by wind energy, hydropower and bioenergy.

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, with biomass based heating.

Batteries emerge as the key storage technology with 83% of total storage output.

Massive electrification, complemented by renewable based synthetic fuels, hydrogen and sustainably produced biofuels provide energy for the transport sector by 2050.

GHG emissions can be reduced from about 4200 MtCO$_2$eq in 2015 to zero by 2050, with cumulative GHG emissions reduction of around 85 GtCO$_2$eq.

Around 3.5 million direct energy jobs are permanently created across the power sector, about 1.5 million jobs more compared to the early phase of the energy transition.

A 100% RE system is more efficient and cost competitive than a fossil based option and is compatible with the Paris Agreement.
The authors gratefully acknowledge the financing of Stiftung Mercator GmbH and Deutsche Bundesstiftung Umwelt.

Further information and all publications at:
www.energywatchgroup.org
www.researchgate.net/profile/Christian_Breyer
### Acronyms 1

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<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>
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<td>Internal Combustion Engine</td>
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<td>CAPEX</td>
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<td>CCS</td>
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<td>CCGT</td>
<td>Combined Cycle Gas Turbine</td>
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<td>Concentrated Solar Thermal Power</td>
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<td>Dimethyl Ether</td>
<td>LDV</td>
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### Acronyms 2

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<td>PHEV</td>
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<td>R/O</td>
<td>(Seawater) Reverse Osmosis</td>
</tr>
<tr>
<td>SNG</td>
<td>Synthetic Natural Gas</td>
</tr>
<tr>
<td>ST</td>
<td>Steam Turbine</td>
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<tr>
<td>TES</td>
<td>Thermal Energy Storage</td>
</tr>
<tr>
<td>TPED</td>
<td>Total Primary Energy Demand</td>
</tr>
<tr>
<td>TW</td>
<td>Terawatt</td>
</tr>
<tr>
<td>TTW</td>
<td>Tank to Wheel</td>
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