Techno-economic assessment of deep defossilisation pathway for the entire energy sector for India

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Table of Contents

- Overview
- Current Status
- LUT Energy System Transition Model
- Long-term Energy Demand
- Resources
- Energy Mix
- Storage
- Costs & Investments
- Sectoral Outlook
- Summary
Overview

- 10 regions in India: Divided according to the regional grids which are further subdivided to gain deeper insights.

- Each region has one node (center of electricity consumption) and these nodes are interconnected via HVDC.

- It is assumed that the existing network of AC lines within each region will provide electricity to all consumers.
Current Status: Power Sector

Key insights:
- A significant share of coal in the generation mix to satisfy growing electricity demand
  - Plant Load Factor (PLF) decreasing year on year basis. Several plants in financial distress
  - Air pollution in major cities
  - Huge water requirements for coal power plants, in a water scarce country
- In recent times, significant growth in the share of installed capacity of renewables is observed
Current Status
Heat, Transport and Desalination Sectors

Key insights:
- The share of heat generation is dominated by coal, oil and natural gas fuel, followed by bio-based and electric heating.
- The transport sector is dominated by fossil liquid fuels with around 96% of the share in 2015.
- The desalination sector is predominantly based on demand for reverse osmosis desalination plants, with some shares of 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 from reverse osmosis and MED
Key insights:

- Cumulative average annual growth rate of about 3.6% 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 2.5% in total primary energy demand (TPED).
- TPED increases from around 8,000 TWh in 2015 to about 18,000 TWh by 2050 in this study (which assumes high electrification).
- Transport sector has a major share in the TPED in 2050, followed by the power sector.
- In comparison, current practices (low electrification) would result in a TPED of nearly 32,000 TWh by 2050.
- The massive gain in energy efficiency is primarily due to a high level of electrification of more than 45% 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
PV single-axis tracking profile (2050)

**Wind generation profile**
Regional aggregated wind feed-in profile
computed using the weighed average rule
Wind profile (2050)

**Key insights:**
- **Wind:** In the monsoon months, wind overcomes solar resource unavailability and complements perfectly in period of low solar radiation
- **Solar PV:** More evenly distributed all year around
Full Load Hours

Key insights:
- **Wind**: Distribution is uneven, mainly concentrated in the states of Gujarat, Maharashtra and Tamil Nadu
- **Solar PV**: More evenly distributed throughout India
Energy Supply

Electricity Generation

Key insights:
- Electricity generation includes demand for all sectors (power, heat, transport, desalination)
- Solar PV share increases from 47% in 2030 to about 91% in 2050 becoming the least cost energy source
- Wind energy increases to 19% by 2030 and decline steadily to about 6% by 2050
- Heat pumps play a significant role in the heat sector with a share of nearly 29% of heat generation by 2050 coming from heat pumps on district and individual levels
- The share of electricity district heating increases significantly from 2030 onwards to about 31% by 2050
- Coal-based heating decreases through the transition from about 63% in 2015 to zero by 2050

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Key insights:

- Electricity demand covered by storage increases through the transition period to about 750 TWh$_{el}$ by 2030 and further significantly increases to over 5000 TWh$_{el}$ in 2050.
- The ratio of electricity demand covered by energy storage to electricity generation increases significantly to around 32% by 2035 and to about 27% by 2050.
- Batteries emerge as the most relevant electricity storage technology contributing to a majority share in storage output by 2050.

* heat storage includes gas and thermal storage technologies
**Key insights:**

- The total annual cost for a fully renewable energy system is about 60800 bINR (800 b€) in 2050 and well distributed across the 3 major sectors of Power, Heat and Transport.
- LCOE increased from 2964 INR/MWh (39 €/MWh) to around 4408 INR/MWh (58 €/MWh) and further declines to about 3800 INR/MWh (50 €/MWh) and is increasingly dominated by capital costs as fuel costs continue to decline through the transition period, which could mean increased energy self reliance for India 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.
Key insights:

- Electricity consumption per capita increases from around 0.9 MWh/person in 2015 to over 3 MWh/person by 2050.
- Total heat demand increases steadily from around 3500 TWh\(_{th}\) in 2015 to 4600 TWh\(_{th}\) by 2050, mainly driven by higher demand for industrial process heat.
- Biomass demand for cooking decreases through the transition, while the share of space heating and domestic water heating slightly increases till 2050.
Key insights:

- **Solar PV** is the main source of electricity generation through the transition years, while wind energy and hydropower complements.

- 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.

- High share of renewables is already observed in the power sector in 2035, while in the heating sector gradually transforms towards embracing renewables.
Key insights:

- Utility-scale and prosumer batteries contribute a major share of the electricity storage output with nearly 99% by 2050
- Pumped hydro energy storage contribute through the transition
- About 14% of the electricity demand in 2030 is provided by storage technologies
- Thermal energy storage emerges as the most relevant heat storage technology providing about 18% of heat demand by 2050
Sectoral Outlook
Power and Heat – Costs and Investments

Key insights:
- LCOE of the power sector decreases from around 4864 INR/MWh (64 €/MWh) in 2015 to around 3420 INR/MWh (45 €/MWh) by 2050
- LCOE is predominantly comprised of capex for renewable technologies as fuel costs decline through the transition, indicating major share of investments solar PV, wind and batteries up to 2050
- LCOH of the heat sector increases from around 1216 INR/MWh (16 €/MWh) in 2015 to about 3420 INR/MWh (45 €/MWh) by 2050
- 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
Key insights:
- The final transport passenger demand increases from around 7000 billion p-km to over 30,000 billion p-km, with rapid growth expected across India
- The final transport freight demand also increases from around 9000 billion t-km to around 56,000 billion t-km by 2050
- Whereas, the final energy demand for overall transport increases from 2100 TWh/a in 2015 to 4900 TWh/a by 2050
**Sectoral Outlook**

**Transport – Passenger and Freight Costs**

Key insights:

- The total annual costs for transport increase from around 9880 bINR (130 b€) in 2015 to about 23,940 bINR (315 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 decrease slightly for rail and remains stable for aviation and marine.
GHG Emissions Reduction

Key insights:
- GHG emissions can be reduced from 2000 MtCO$_2$eq in 2015 to zero by 2050 across all energy sectors.
- The share of emissions from the power sector is highest of all the sectors in 2015.
- The decrease in the power and heat sector is rapid through the transition, while the emissions in the transport sector decrease slowly.
- The presented 100% RE scenario for the Indian 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 steady decline of emissions is possible beyond 2030 up to 2050.
Key insights:

- Electricity generation is comprised of demand for the sectors power, heat, transport and desalination.
- Solar PV capacities are predominantly in all the regions of India, while most wind capacities is found in Western and Southern parts.
- Overall, solar PV generate most of the electricity needed across India by 2050, due to excellent solar conditions and low seasonal variability.
Summary – Energy Transition

- India can reach 100% RE and zero GHG emissions by 2050, across the power, heat, transport and desalination sectors.
- The LCOE obtained for a fully sustainable energy system remains stable at about 50 €/MWh by 2050.
- Electricity consumption per capita increases from 0.9 MWh in 2015 to over 3.2 MWh by 2050, while heat demand increases steadily from around 4200 TWh\(_{th}\) in 2015 to 6393 TWh\(_{th}\) by 2050.
- Solar PV emerges as the most prominent electricity supply source with around 90% of the total electricity supply, while heat pumps, electric heating and biomass based heating constitute a majority of the installed heat capacities by 2050 by 2050.
- Batteries emerge as the key storage technology with 99% of total storage output.
- In Transport sector, 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 the transport sector remain around 150-340 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 2000 MtCO\(_2\)eq in 2015 to zero by 2050.
- A 100% RE system is more efficient and cost competitive than a fossil-based option and is compatible with the Paris Agreement, in addition to an array of benefits for India.
## Acronyms 1

<table>
<thead>
<tr>
<th>BECCS</th>
<th>Bioenergy Carbon Capture and Storage</th>
<th>HVAC</th>
<th>High Voltage Alternating Current</th>
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<tbody>
<tr>
<td>BEV</td>
<td>Battery Electric Vehicle</td>
<td>HVDC</td>
<td>High Voltage Direct Current</td>
</tr>
<tr>
<td>CAES</td>
<td>Compressed Air Energy Storage</td>
<td>ICE</td>
<td>Internal Combustion Engine</td>
</tr>
<tr>
<td>CAPEX</td>
<td>Capital Expenditures</td>
<td>IEA</td>
<td>International Energy Agency</td>
</tr>
<tr>
<td>CCS</td>
<td>Carbon Capture and Storage</td>
<td>IH</td>
<td>Individual Heating</td>
</tr>
<tr>
<td>CCGT</td>
<td>Combined Cycle Gas Turbine</td>
<td>LCOC</td>
<td>Levelised Cost of Curtailment</td>
</tr>
<tr>
<td>CHP</td>
<td>Combined Heat and Power</td>
<td>LCOE</td>
<td>Levelised Cost of Electricity</td>
</tr>
<tr>
<td>CSP</td>
<td>Concentrated Solar Thermal Power</td>
<td>LCOH</td>
<td>Levelised Cost of Heat</td>
</tr>
<tr>
<td>DAC</td>
<td>CO₂ Direct Air Capture</td>
<td>LCOS</td>
<td>Levelised Cost of Storage</td>
</tr>
<tr>
<td>DACCS</td>
<td>Direct Air Carbon Capture and Storage</td>
<td>LCOT</td>
<td>Levelised Cost of Transmission</td>
</tr>
<tr>
<td>DH</td>
<td>District Heating</td>
<td>LCOW</td>
<td>Levelised Cost of Water</td>
</tr>
<tr>
<td>DME</td>
<td>Dimethyl Ether</td>
<td>LDV</td>
<td>Light Duty Vehicle</td>
</tr>
<tr>
<td>FCEV</td>
<td>Fuel Cell Electric Vehicle</td>
<td>LNG</td>
<td>Liquefied Natural Gas</td>
</tr>
<tr>
<td>FLH</td>
<td>Full Load Hours</td>
<td>LT</td>
<td>Low Temperature</td>
</tr>
<tr>
<td>FT</td>
<td>Fischer-Tropsch</td>
<td>MDV</td>
<td>Medium Duty Vehicle</td>
</tr>
<tr>
<td>GHG</td>
<td>Greenhouse Gases</td>
<td>MED</td>
<td>Multiple-Effect Distillation</td>
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<tr>
<td>GT</td>
<td>Gas Turbine</td>
<td>MSF</td>
<td>Multi-Stage Flash</td>
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<tr>
<td>GW</td>
<td>Gigawatt</td>
<td>MT</td>
<td>Medium Temperature</td>
</tr>
<tr>
<td>HDV</td>
<td>Heavy Duty Vehicle</td>
<td>MW</td>
<td>Megawatt</td>
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<tr>
<td>HHB</td>
<td>Hot Heat Burner</td>
<td>OCGT</td>
<td>Open Cycle Gas Turbine</td>
</tr>
<tr>
<td>HT</td>
<td>High Temperature</td>
<td>OPEX</td>
<td>Operational Expenditures</td>
</tr>
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## Acronyms 2

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>PHEV</td>
<td>Plug-in Hybrid Electric Vehicle</td>
</tr>
<tr>
<td>PHES</td>
<td>Pumped Hydro Energy Storage</td>
</tr>
<tr>
<td>PP</td>
<td>power plant</td>
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<tr>
<td>PtG</td>
<td>Power-to-Gas</td>
</tr>
<tr>
<td>PtH</td>
<td>Power-to-Heat</td>
</tr>
<tr>
<td>PtL</td>
<td>Power-to-Liquids</td>
</tr>
<tr>
<td>PtX</td>
<td>Power-to-X</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaics</td>
</tr>
<tr>
<td>RE</td>
<td>Renewable Energy</td>
</tr>
<tr>
<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>
</tr>
<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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Thank you

Further information and all publications at:
https://www.researchgate.net/profile/Ashish_Gulagi
Supplementary Slides
Key insights:

- Storage output covers about 2000 TWh\textsubscript{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 almost 33% by 2050.
- Thermal energy storage emerges as the most relevant heat storage technology with around 56% of heat storage output by 2050.
- Power-to-Gas contributes around 42% of the heat storage output in 2050.
Key insights:

- The final energy demand for road passengers increases from around 800 TWh in 2015 to around 1160 TWh by 2050.
- The final energy demand for road freight increases from around 760 TWh in 2015 to around 1000 TWh by 2050 in the transport sector across India.
Sectoral Outlook
Transport – Rail, Marine and Aviation Demand

Key insights:
- The final energy demand for rail transport increases from around 164-305 TWh through the transition
- The final energy demand for marine transport increases steadily from around 265 TWh in 2015 to over 1541 TWh by 2050
- The final energy demand for aviation transport increases significantly from nearly 135 TWh in 2015 to over 922 TWh by 2050
Key insights:

- Fossil fuel consumption in transport is observed to decline through the transition from about 96% 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 24% of final energy demand in 2050
- Electrification of the transport sector creates an electricity demand of around 7600 TWh\textsubscript{el} by 2050
- Massive demand for renewables-based liquid fuels kicks-in from 2040 onwards up to 2050
### Sectoral Outlook

**Transport – Power Capacities and Generation**

**Key insights:**

- **Solar PV with around 4275 GW and wind with around 14 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:**

- Utility-scale batteries and A-CAES installed storage capacities increase up to 2050, with some share of PHES through the transition.
- Storage capacities increase beyond 2025 as electricity demand for transport increases.
- Utility-scale batteries contribute the major share of storage output in 2050 to around 1000 TWh\(_{el}\) along with some A-CAES.
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 27 TWh by 2050, with major share of methane storage.
- Installed CO$_2$ storage and CO$_2$ DAC increase significantly from 2040 onwards, with major share of CO$_2$ DAC.
- Heat for fuel conversion process is managed with excess heat and utilisation of recovered 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 with GHG emissions costs, on a level of about 6460 INR/MWh (85 €/MWh).
- Electricity emerges as the most cost effective option with LCOE primary around 1368 INR/MWh (18 €/MWh) and along with complementary costs of storage and other system components, total LCOE is around 1900 INR/MWh (25 €/MWh) in 2050.
- Hydrogen (H₂) fuel costs decline to be more cost competitive that fossil fuels, in the range of 3959 INR/MWh (52 €/MWh) in 2050, while liquid H₂ is in the range of 4484 INR/MWh (59 €/MWh).
- CO₂ from DAC is a critical component for synthetic fuels at around 2356 INR/MWh (31 €/tCO₂eq) in 2050, using waste heat.
Key insights:

- The total annual energy costs for transport are in the transition period are around 9880 bINR (130 b€) in 2015 to about 23,940 bINR (315 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
**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 400 GW by 2050, which is mainly renewables.
- The LCOW for desalination decreases through the transition and declines from about 98.8 INR/m³ (1.3 €/m³) in 2015 to 53.2 INR/m³ (0.7 €/m³) by 2050.
Major RE Supply Shares in 2050

Key insights:
- Solar PV dominates the total electricity generation supply shares in 2050
- Electricity generation shares in India for all energy sectors are
  - Solar PV at about 94.5%
  - Wind energy at about 3.9%
  - Hydropower at about 1.1%
Major RE Capacities in 2050

Key insights:
- Solar PV dominates the total electricity generation capacity across India in 2050
- Installed capacities in 2050 across Indian regions for all energy sectors are
  - Solar PV: 9367 GW
  - Wind energy: 306 GW
  - Hydropower: 55 GW
Key insights:
- Battery storage mainly plays a role in providing diurnal storage with around 30.2% 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.
Key insights:

- The total losses in a 100% RE-based electricity system in 2050 are just around 13.3% of the total generation.
- Curtailment has a share of 3.0%, storage contributes 5.3% and grid losses amount to 5.0%.
- 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.
Key insights:
- Total LCOE by 2050 is around 3443 INR/MWh (45.3 €/MWh) (including generation, storage, curtailment and some grid costs), the range for different regions is 37.0 – 47.5 €/MWh
- A 60% ratio of the primary generation cost to the total LCOE can be observed, in a range of 41% - 64% for 75% of regional power demand
- Cost of storage contributes substantially to the total energy system LCOE, with ratios ranging from 35% - 50% for 75% of regional power demand
- Costs are considered just for the power and heat sectors