Energy and Technology need assessment for India under 2070 – Net Zero Pathway

Table of contents

List of tables

List of figures

List of Abbreviations

AI	Artificial Intelligence
BAU	Business As Usual
BESS	Battery Energy Storage System
BEV	Battery Electric Vehicles
BF-BOF	Blast furnace-basic oxygen furnace
BPKM	Billion Passenger-Kilometres
BS	Bharat Stage
BU	Billion Units of electricity
CAGR	Compounded Annual Growth Rate
CAN	Calcium Ammonium Nitrate
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilisation and Storage
CDR	Carbon Di-oxide Removal
CEA	Central Electricity Authority
CNG	Compressed Natural Gas
COP	Conference of the Parties
CUF	Capacity Utilization Factor
DAP	Diammonium Phosphate
DG	Diesel Generator
DRI	Direct Reduced Iron
DRI-EAF	Direct reduction of iron-electric arc furnace
DRI-IF	Direct reduction of iron-induction furnace
EAF	Electric Arc Furnaces
EU	European Union
EV	Electric Vehicles
FCEV	Fuel Cell Electric Vehicles
FY	Financial Year
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GJ	Giga Joules
GVA	Gross Value Added
GW	Giga Watts
H2 ICE	Hydrogen Combustion Engine
HCV	Heavy Commercial Vehicle
IF	Induction Furnace
INR	Indian National Rupee

IRP	Integrated Resource Planning
LCV	Light Commercial Vehicle
LDES	Long-duration Energy Storage
LP	Linear Programming
LPG	Liquified Petroleum Gas
ML	Machine Learning
MNRE	Ministry of New and Renewable Energy
MOP	Muriate of Potash
MOPNG	Ministry of Petroleum and Natural Gas
MSME	Micro, Small and Medium Enterprises
MT	Metric tonnes
MTPA	Million Tonnes per annum
NITI	National Institution for Transforming India
NZS	Net-Zero Scenario
PAHAL	Pratyaksh Hanstantrit Labh
PLF	Plant Load Factor
PM KUSUM	Pradhan Mantri Kisan Urja Suraksha Evam Utthaan Mahaabhiyan
PMUY	Pradham Mantri Ujjawala Yojana
PNG	Piped Natural Gas
PPP	Public-Private Partnership
PSP	Pumped Storage Plant
PV	Photovoltaic
RE	Renewable Energy
SEC	Specific Energy Consumption
SMR	Small Modular Reactor
TWH	Tera Watt Hours
UNFCCC	UN Climate Change Conference
USD	United States Dollar
VC	Variable Cost

Executive Summary

India ranks third globally in energy consumption, despite its per capita energy usage being only one-third of the global average. India's contribution to annual global emissions is less than 7%, even though it accounts for around 17% of the world's population. With a growing population of over 1.4 billion and strong economic growth, India is expected to remain one of the largest energy consumers in absolute terms for the foreseeable future. This presents a significant dual challenge for the country: meeting its rising energy demands while addressing environmental concerns to sustain economic growth.

India's energy mix is heavily dependent on fossil fuels—coal, oil, and gas. India's energy-related carbon emissions have risen from approximately 1,800 million tonnes in 2013 to 2,500 million tonnes in 2022, with a temporary decline during 2020-21 due to the pandemic. The electricity sector is the largest emitter, accounting for 45-50% of total emissions, followed by the industrial, transport, and captive power generation sectors. Despite this, India's per capita emissions remain low at around 2 tonnes, less than half the global average of 4.6 tonnes.

At the 26th session of the United Nations Framework Convention on Climate Change (COP 26) in 2021, India set an ambitious target to achieve net-zero emissions by 2070, aligning with commitments from other nations. This was a significant pledge for a developing country with a rapidly growing economy. In conjunction with this target, India updated its Nationally Determined Contributions (NDCs) under the 'Panchamrit' strategy, which includes achieving 50% of its cumulative installed electric power capacity from non-fossil fuel sources by 2030 and reducing the emissions intensity of its GDP by 45% from 2005 levels by 2030.

Given its reliance on fossil fuels, India should consider implementing robust decarbonization measures to achieve its net-zero target by 2070. This will necessitate a rapid transition to a low-carbon power system, reduced fossil fuel dependence in industries, a decarbonized transport sector, and a societal shift towards sustainable living practices. Achieving these objectives will require the adoption of new technologies, supportive policies, effective support mechanisms, and consistent access to low-cost financing. India's decarbonization path should align with the "Life for Environment (LiFE)" initiative, which encourages eco-friendly practices in daily life, such as using public transportation, minimizing waste, and adopting mindful consumption habits.

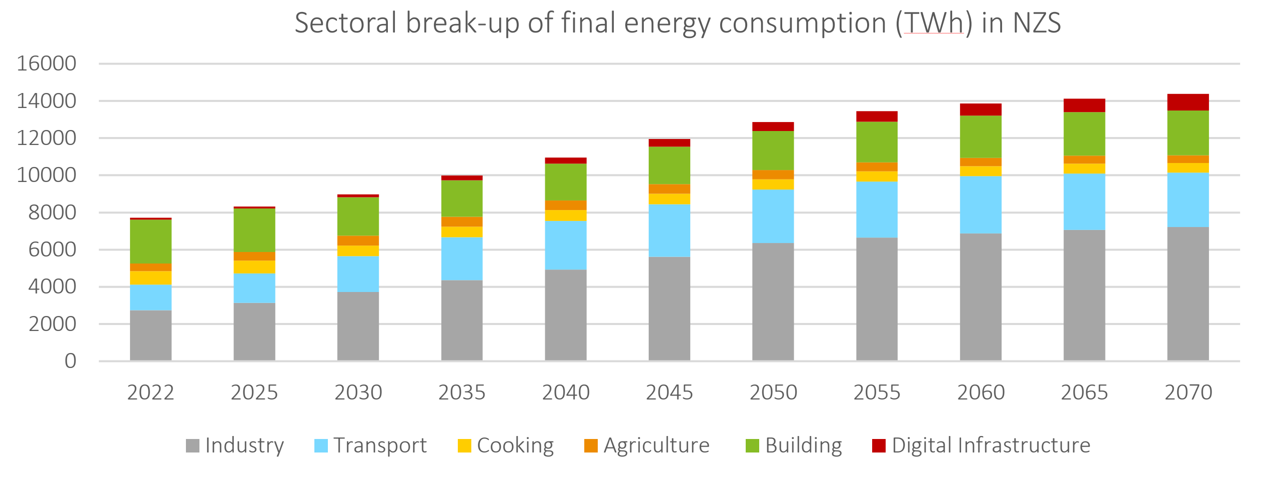
This study aims to explore potential energy transition pathway by modelling energy demand, supply, and emissions up to 2070, considering growth drivers, technological advancements, and behavioural shifts. It examines two scenarios: the Net Zero Scenario (NZS) and the Business-As-Usual (BAU) Scenario.

Outlook of final energy consumption

In the Net Zero Scenario (NZS), India's final energy consumption[1] is projected to increase by 80-90% by 2070, reaching between 14,000 and 14,500 TWh (1,200–1,250 Mtoe). The NZS would be shaped by adoption of energy efficiency, technological advancement, and a behavioural shift in consumption pattern. Therefore, the growth of final energy is expected to be lower than business-as-usual scenario due to aggressive energy efficiency measures. The industrial sector will be the primary driver, accounting for 50-55% of the final energy demand, followed by the transport sector at 18-22% and the building sector at 16-18% by 2070.

- Industry sector is the largest end user of energy and is expected to adopt new technologies and focus aggressively on reduction of energy intensity through direct electrification and incremental energy efficiency measures.
- While passenger and freight transport demand are expected to grow 3-5 times by 2070, the overall energy demand growth in the transport sector will remain moderate due to the widespread adoption of Electric Vehicles (EVs) and some Fuel Cell Electric Vehicles (FCEVs) with higher energy conversion efficiency.
- Building and cooking sector are expected to reduce energy intensity through higher electrification and substitution of inefficient traditional biomass use.
- Data Centres and telecom infrastructure are expected to grow rapidly from present levels to contribute 5-6% of final energy consumption by 2070.

[1] Final energy is the energy delivered to the consumers, which is net of primary energy and the efficiency loss



In the BAU scenario, energy demand is projected to be 15-20% higher than in the NZS, reaching 16,500-17,500 TWh (1,400-1,500 Mtoe) by 2070. This increase is attributed to lower levels of energy efficiency and electrification in the BAU scenario compared to the NZS.

It is worth noting that India is the first country to incorporate the "Lifestyle for Environment" (LiFE) mission in its Nationally Determined Contributions (NDCs) to combat climate change. At the UN Climate Change Conference (UNFCCC COP26), India's Hon'ble Prime Minister introduced the LiFE mission to encourage individuals to engage in climate action through mindful and intentional resource use. This initiative aims to drive behavioral changes to reduce energy consumption.

The following 'LiFE measures' are expected to impact overall energy demand and emissions:

- A shift from personal vehicles to public transport could reduce the growth in private vehicle numbers, leading to lower emissions.
- In the cooking sector, transitioning from traditional biomass to LPG, then PNG, and eventually to electric cookstoves represents a significant behavioral change with the potential to lower emissions from cooking.
- In the residential sector, adopting energy-efficient appliances and transitioning from biomass-based heating to electric heating can improve energy conversion efficiency.
- In the commercial sector, energy-efficient or green buildings hold potential for reducing emission footprints.

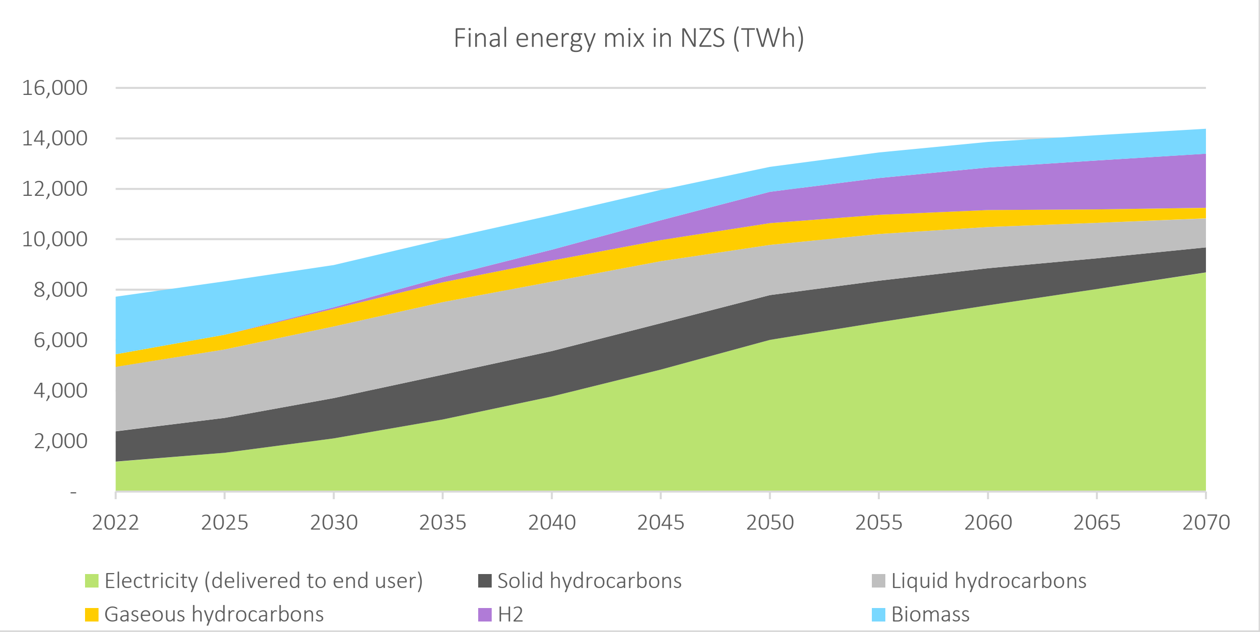
The sectoral attributes in NZS and BAU are illustrated below[2]:

Sector	NZS measures	BAU measures
Steel	Entire steel sector shall be decarbonized through H2-DRI and scrap recycling.	BF-BOF and Coal based DRI will steel continue to operate. H2-DRI penetration will be delayed – penetration of H2-DRI may be limited to 30 - 40% H2-DRI production by 2070 with 20% production through scrap recycling.
Cement	Higher electrification; Specific Energy Consumption (SEC) improvement from 0.67 TWh/Mn Ton to 0.59 TWh/Mn Ton driven by clinker substitution, energy efficiency and fuel switch.	SEC improvement will be in the same range; Indian cement players are in the top quartile amongst the global players.
Aluminium	SEC improvement by ~10%, based on global benchmarks.	SEC improvement by ~10%, based on global benchmarks.
Refinery	100% substitution of grey hydrogen with green hydrogen	Up to 40% substitution by green hydrogen
Fertilizer	Entire non-urea fertilizer will replace grey hydrogen with green. Urea production and consumption may gradually come down	Substitution in non-urea segment will be limited to 40-50%; Urea will continue to be dominant category in India's fertilizer mix.

[2] Sectoral assumptions are based on inputs from industry experts, Government targets, global mega trends and future technology innovation pathways.

Sector	NZS measures	BAU measures
Other industries	Rapid electrification; (up to 50% electrified) Aggressive energy efficiency adoption	Slower electrification (up to 30% electrified) Moderate adoption of energy efficiency
Building	Rapid electrification – Biomass-based heating (winter season – 3 months) will gradually reduce; adoption of energy efficient appliances, energy efficient building will increase rapidly	Same as NZS; Building sector is expected to transit rapidly towards electrification and energy efficiency even in BAU scenario.
Cooking	Transition to electric cookstoves, with some PNG.	Same as NZS; the sector will gradually move to electrification.
Passenger transport	Complete transition to low-carbon powertrain; Large adoption of EV with some penetration of FCEV	Lower adoption of electrification. ~60% adoption of electric vehicle in the private car segment; bus will be 100% electrified. FCEV will only be a niche segment.
Freight transport	50 – 60% low carbon powertrain – FCEVs and EVs	20 – 30% low carbon powertrain – FCEVs and EVs
Modal shift	Aggressive shift from private transport to public transport through efficient urban planning, infrastructure development	Moderate shift from private to public transport

As a result, in the NZS (or in a low carbon scenario), India's final energy mix will be highly electrified. In this scenario, direct electricity and green hydrogen are expected to be the dominant energy sources by 2070, contributing 65-75% of total demand. Green hydrogen will eventually increase demand of renewable electricity. Coal and oil will have limited applications in the industry and transport sectors.



The growth rate of electricity is projected to outpace overall final energy growth—around 7% from 2022 to 2030, approximately 5% from 2030 to 2050, and then slowing to about 1.5% from 2050 to 2070. Share of electrification in the final energy mix is expected to increase from 16% (2022) to 50 – 55% by 2070. This surge in electricity demand is expected to be driven by direct electrification in various sectors: industry (electrification of process heat and furnaces), transport (transition from internal combustion engine vehicles to battery electric vehicles), buildings (electrification of heating), cooking (adoption of electric cookstoves) and emergence of large-scale data centres.

Green Hydrogen (GH2) is expected to find applications in fertiliser, refineries, steel production, and transport. In the NZS, Green Hydrogen demand is expected to reach ~30 million tons by 2050 and 50 - 60 million tons by 2070, which is nearly ~10% of projected global demand. Adoption is likely to pick up post 2030 once the commercial parity is achieved, industries are ready with required process changes and ecosystem is developed.

- **Steel sector** is expected to emerge as the largest consumer of green hydrogen. By 2070, H2-DRI based steel production is expected to contribute 75 – 80% of total steel production, with an assumption of 100% green steel by 2070.
- **Refinery and Fertilizer** may transit to green hydrogen completely by 2050; increased production of complex (NPK) and phosphate-based fertilizer (Diammonium Phosphate) will drive hydrogen adoption in fertilizer sector[3].
- **In transport**, freight vehicle is expected to see higher adoption of FCEV due to higher energy density and higher payload capacity. However, passenger vehicle is expected to see limited adoption (15-20%) through a mix of FCEV and H2 engine (H2-ICE). H2-ICE is expected to play the role of transitional technology.
- **Cement and 'Other' sector** may see penetration of green H2 up to 5% of total energy consumption, mainly as an alternative fuel co-fired with coal and gas.
- **Power sector in India** is not expected to create a sizeable demand of hydrogen due to commercial disadvantages of green ammonia over renewable. Some demonstration projects may be implemented to partially decarbonize coal-based plants. In addition, hydrogen based gas turbines are expected to see commercial maturity around 2035-40; however, their uses are likely to be limited as "seasonal storage".

Coal is expected to be used in specific industries like cement, petrochemicals, and certain MSMEs. Oil is expected to have limited applications in heavy-duty transport, shipping, and aviation. Biomass usage as a final energy source is expected to decline due to the aggressive electrification of the cooking and building sectors.

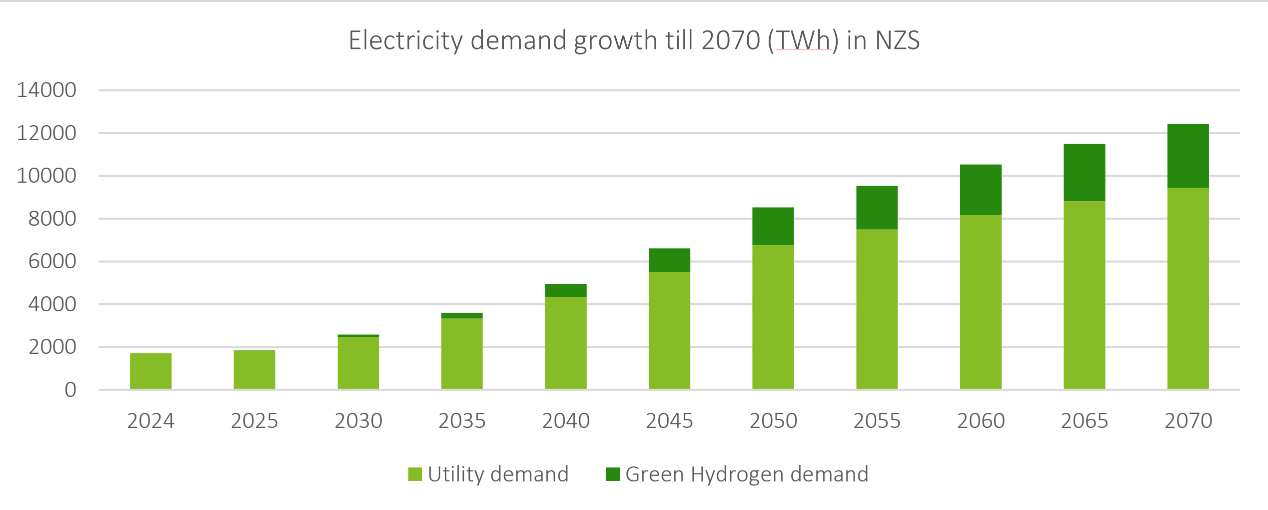
In the BAU scenario, the adoption of direct electricity and green hydrogen will be lower than the adoption in the NZS, accounting for only 45-50% of total final energy demand. Direct electrification and investments in energy-efficient technologies across sectors are expected to be lower than investment in the NZS. Green hydrogen-based decarbonization in hard-to-abate sectors like industry and transport will be lower than NZS. Coal is expected to be used in significant quantities in industries such as steel, cement, petrochemicals, and MSMEs, while oil will be more prominent in freight vehicles, shipping, and aviation. Biomass usage as a final energy source will still decline due to the electrification of cooking and building sectors, even in the BAU scenario.

In the NZS, the demand for green hydrogen is expected to reach approximately 30 million tons by 2050 and around 55 million tons by 2070, with adoption likely to gain momentum after 2030. Electrolyser demand could reach 200-250 GW by 2050 and 450-500 GW by 2070[4]. In the BAU scenario, green hydrogen demand is expected to be lower, reaching about 12-15 million tons by 2050 and 23-25 million tons by 2070.

Outlook of electricity supply side

The supply side model has focused on electricity system modelling to meet the projected electricity demand with certain assumptions and constraints (e.g., no transmission constraint, capacity addition limitation, etc.). It also assessed the supply requirement of other direct form of energy, such as coal, gas, oil, and biomass to meet the final energy demand.

In the NZS, utility electricity demand is expected to grow to 9000 – 9500 BU by 2070 and RE demand for green hydrogen is likely to grow to 2700 – 3000 BU during the same period.



[3] Currently, Urea is the dominant fertilizer in India. Urea can't be decarbonized completely through green hydrogen due to process related challenges while complex (NPK) fertilizer and DAP can substitute 100% grey hydrogen with green. Going forward, share of DAP and NPK fertilizer is expected to increase gradually.

[4] This figure is excluding the electrolyser demand for generating hydrogen as "seasonal storage"

During the same period, Peak demand is expected to increase at a CAGR of 3 – 3.5%, with 850 – 900 GW by 2050 and 1100 – 1200 GW by 2070. The peak demand growth projection has been considered similar with the overall electricity demand growth in the near term; however, in the long term, a lower growth rate has been considered.

The electricity sector is the largest contributor to greenhouse gas (GHG) emissions in India; therefore, decarbonizing this sector is crucial to achieving the country's net-zero goals. **This will require a significant increase in the use of non-fossil energy sources such as solar, wind, nuclear, hydro, and others. The integration of variable renewable energy will be supported by a strong transmission system and the deployment of long-duration energy storage solutions, including seasonal storage.**

Considering country's energy security and rapid increase in electricity demand in the near to medium term, new coal-based power plants are expected to be constructed until 2035 to meet overall electricity and peak demand needs. However, as the renewable capacity addition picks up, no new coal-based capacity additions are anticipated after 2035. Additionally, green hydrogen is expected to be utilized in sectors such as fertilizers, refineries, steel production, cement kilns, gas distribution networks, and transport.

The supply side model (Linear Programming based model) has projected the installed capacity mix based on the least cost dispatch methodology as per the constraints provided as model inputs.

Table: Capacity expansion projection till 2070 (GW), NZS

		2024	2030	2035	2040	2045	2050	2055	2060	2065	2070
Utility (GW)	Coal	219	264	287	267	254	234	163	101	66	0
	Gas	24	24	24	20	16	16	16	13	13	13
	Solar (Utility)	74	216	280	471	761	1095	1534	2014	2344	2599
	Solar (Rooftop)	13	25	90	150	210	270	350	390	450	540
	Wind	45	82	206	366	564	751	967	1186	1247	1360
	Wind Offshore	0	5	30	60	90	120	120	130	140	150
	Hydro	56	70	80	90	110	130	140	140	140	140
	Nuclear	7	18	34	45	60	80	100	120	140	150
	Biomass	11	14	16	18	20	22	24	26	28	28
	PSP	5	12	16	24	31	41	51	71	88	88
	BESS (4 hour)	0	27	56	159	282	553	800	1000	1200	1500
	BESS (8 hour)	0	0	20	70	150	200	250	300	350	400
	Seasonal storage (H2 based)	0	0	0	0	3	16	36	68	110	132
Capacity for GH2 (GW)	Solar	0	17	32	87	139	205	266	386	606	978
	Onshore	0	3	3	14	43	105	164	164	153	125
	Storage for GH2 (4 hours)	-	9	36	38	32	116	500	700	900	1500

Note: The outputs presented above are directional and based on mathematical modelling. However, actual capacity expansion may vary due to factors such as supply chain constraints, execution challenges, grid-off grid interconnection and other real-world limitations.

Key takeaways from the net zero supply side modelling are:

- **Coal based installed capacity is expected to peak in 2035 at 287 GW**. Apart from under-construction capacity of ~26 GW as on March 2024, 35-40 GW new capacity is likely to be finalized and commissioned between 2024 – 2035. After 2035, no coal based capacity addition is envisaged.
- Rapid decommissioning of coal based plant (mainly driven by completion of economic life) may be required after 2050 to green the grid. The gap in base load arising out of coal based capacity decommissioning should be bridged through renewables integrated with storage system, nuclear and hydro capacity.
- **Plants with variable cost (VC) > Rs. 4.0/kWh[5] are likely to hit the ramping limits the most (1%/min)**. In 2024, these plants hit the ramping limits almost 6-8% of the time. This behavior is expected as the plants in the variable cost of more than Rs. 4/kWh tend to be the marginal generators within the system. As the RE mix increases, the marginal generators also change, and lower VC plants also may breach ramping limit. Therefore, all plants with higher VC (can be started with VC> INR 4.0 per kWh) should be retrofitted for at least 1%/min ramp limit.
- **Solar, Wind, Hydro are likely to hit the maximum potential of 3600 GW, 1500 GW (onshore), 150 GW (Offshore) and 140 GW respectively**. Nearly 45–50 GW of annual RE capacity addition is required for grid

[5] VC as of 2024. VC is assumed to be escalated at 3.5% y-o-y due to escalation in coal price

decarbonization till 2050, which is likely to grow to 150 – 180 GW per year from 2050 -70, similar to what China has achieved during 2023 - 24.

- **To achieve net-zero by 2070, Energy Storage System (ESS) deployment is expected to grow multifold with new long-duration energy storage technology gaining maturity**. Short-duration energy storage systems would be sufficient in the ongoing decade. Later years would require a significant amount of Long-duration Energy Storage (LDES) systems, such as eight hours of battery storage, and H2 storage (to be fired in the gas turbine). Therefore, energy storage systems for stationary grid applications must evolve beyond lithium-ion technologies, such as sodium ion technology, GH2-based storage solutions for seasonal storages, etc. Cumulative energy storage requirement may grow to 3500 – 4000 GWh by 2050 and 12000 – 15000 GWh by 2070.
- **Hydro and nuclear power will also play a crucial role in grid decarbonisation**. In the absence of coal based capacity, Nuclear is expected to provide baseload support. India may need to exploit the full technically feasible hydro potential (~140 GW) and increase nuclear capacity. **In addition, it may need to import hydro power from Nepal and Bhutan** to achieve India's net-zero ambitions. A regional electricity market and resource sharing would be critical to achieve their net-zero targets.
- **Renewable energy requirement for green hydrogen production is expected to reach 1600 – 1700 BU by 2050 and 2700-3000 BU by 2070**. Green hydrogen will be powered through off-grid or captive renewable projects as well as grid as the emission intensity of grid declines gradually.
- **No gas-based capacity addition has been considered due to shortage of domestic gas.** Some of the existing gas stations are expected to be retrofitted for Hydrogen blending. New Hydrogen turbines are likely to be installed as seasonal storage. Seasonal storage (H2 turbine based) deployment is expected to kick-in in 2035, which is anticipated to increase gradually to 130 – 150 GW by 2070.

In terms of generation, Solar is expected to contribute 60-65% of electricity demand by 2070, followed by Wind (26 – 28% Onshore), Nuclear (~8%), Offshore wind (~5%) and Hydro (~4%). Rooftop deployment would be critical to decarbonize the residential and commercial segments. In addition to domestic capacity addition, hydro import from Nepal and Bhutan would be critical; import of 150 - 180 BU is expected by 2070. As the grid becomes decarbonized, green hydrogen plants can purchase more electricity from the grid to meet demand in non-solar hours.

However, if capacity addition of coal and renewable is delayed in the short to medium term, gas based plants will be utilized to meet the peak demand. Throughout the year, there will be periods with substantial unmet demand, during which gas-based plants will likely be deployed to bridge the gap.

Developing a robust domestic manufacturing ecosystem is essential to mitigate risks associated with supply chain disruptions and geopolitical factors. At present, the manufacturing ecosystem is in its early stages and needs substantial enhancement to support India's ambition of achieving net-zero emissions.

Table: Inda's manufacturing demand for clean technologies

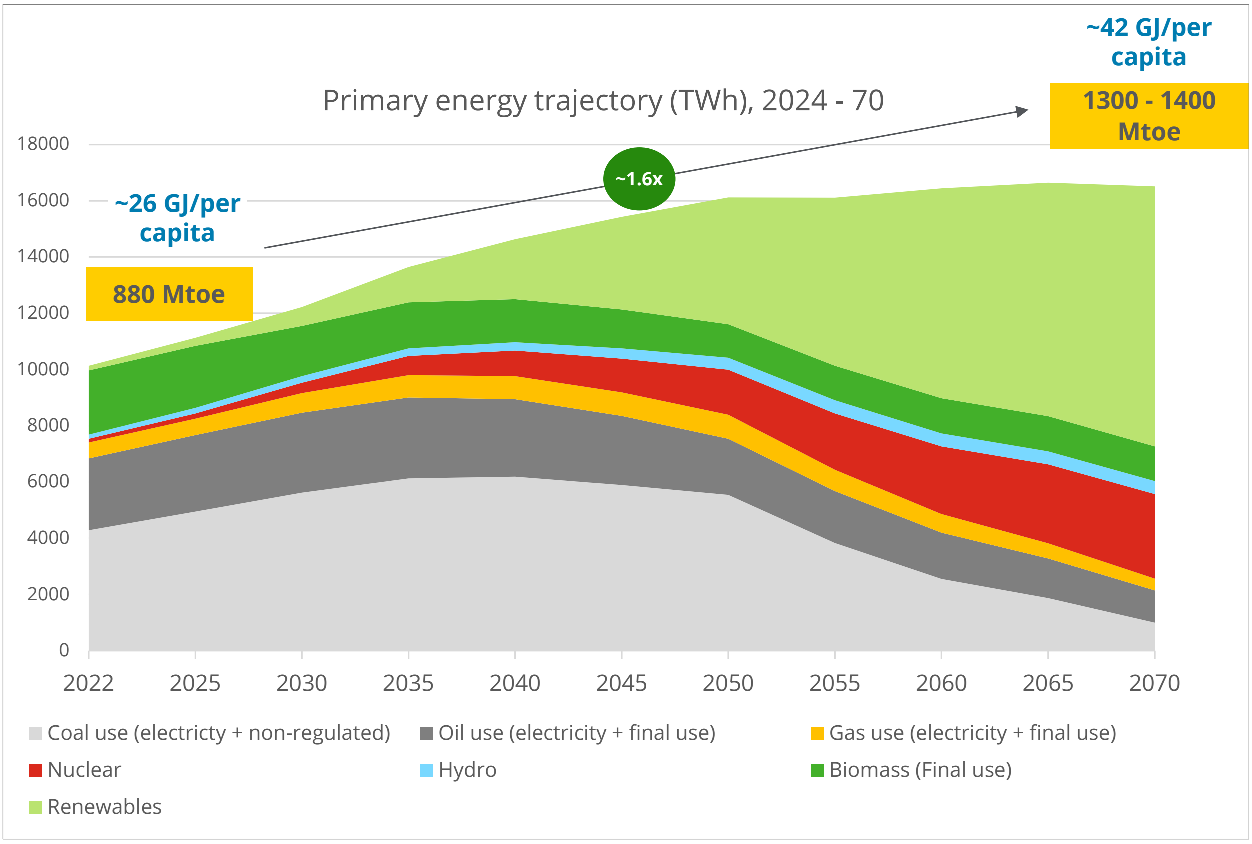
Category	Unit	Annual demand			Comments
		2024 - 30	2030 - 50	2050 - 70	
Solar upstream manufacturing	GW	30 - 40	50 - 60	100 - 120	Integrated manufacturing from polysilicon to module is the critical to achieve supply chain sustainability and cost leadership
Wind turbine	GW	5 – 8	25 - 35	35 - 45	Focus should be on high capacity WTG for onshore as well as offshore projects
BESS (Stationary storage)	GWh	5 - 8	100 - 150	250 - 350	Manufacturing capability should be developed at both cell and pack level
BESS (mobility)	GWh	10 – 20	100 - 200	150 - 250	
Electrolyser	GW	1- 2	8 - 10	10 - 20	Demand is expected to increase multifold post 2030 driven by industrial decarbonization and emergence of H2-turbine as seasonal storage

In a Net Zero scenario, Primary Energy requirement will grow by 50 – 60% by 2070 from 2022 level

In the NZS, India's primary energy in 2070 is expected to increase by 50 – 60% from the 2022 level. The gap between final energy and primary energy (energy transformation loss) is expected to reduce gradually due to higher level of electrification, aggressive adoption of energy efficiency and fuel switch.

In order to meet the emission reduction targets, there will be substantial uptake of cleaner sources of energy, especially solar and wind in a net zero scenario. In 2070, 55-60% of energy demand is expected to be met through renewable electricity, where efficiency is more than 90%. Hydrogen is expected to contribute another 13-15%, where efficiency is expected to be around 70 – 75% by 2070. In addition, improvement in energy efficiency in the rest of the technologies would lead to bridge the gap between primary and final energy. One of the major improvements from business-as-usual is expected from transition to BEV (>80% efficiency) from ICE vehicles (~25% efficiency). Other improvement areas include:

- Substitution of fossil-based energy (efficiency 40 – 60%) to RE (>90% energy)
- Substitution of traditional biomass with electricity
- Reduction of T&D loss
- Improvement in specific energy consumption across sectors



Key takeaways include:

- Renewable energy (Solar and Wind) is expected to meet 55 – 60% of primary energy by 2070.
- Coal is expected to contribute 6 – 8% of primary energy by 2070, driven by use in the industry sectors, such as Cement and MSME sectors[6].
- The share of oil in the energy mix is projected to be around 6–8% by 2070, primarily due to freight transport. Oil's contribution to the primary energy mix is expected to peak around 2035–2040, driven by demand from the transportation sector. This share is anticipated to decline as the transition in transport sector gains momentum, including the adoption of Zero Emission Vehicles (ZEVs), aviation decarbonization, and a shift towards public transport.

[6] Coal based power plants are assumed to be decommissioned completely

- Gas is expected to be utilized in industries as a cleaner fuel and in cooking (PNG), contributing around 3–4% to the overall primary energy mix. The limited availability of domestic gas and the high cost of imported LNG are significant barriers to its wider use.
- While increasing the penetration rate of renewables is a clear part of the solution to reaching carbon neutrality, Nuclear and Hydroelectric energy will remain as critical element for India's Net Zero ambition, contributing 15-18% of primary energy.

Energy related emission must peak around 2035 – 40 to achieve net zero by 2070

CO_2 emissions under the NZS is expected peak around 2035 - 40 and gradually come down to 700 - 800 million tonnes (Mt) CO2 by 2070[7]. These residual emissions must be abated through mix of deployment of Carbon Capture and Storage (CCS) and through carbon sequestration through afforestation.

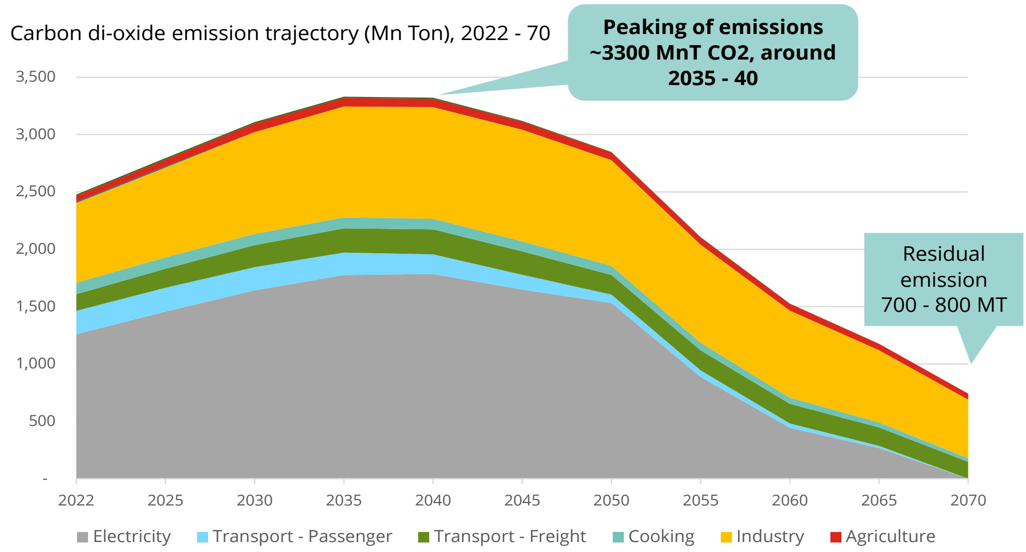


Figure: Emission trajectory till 2070, NZS

The residual emissions are most likely to be contributed by hard to abate sectors like Cement, Petrochemical and few MSME industries. The cement sector is considered the most viable sector for the adoption of CCS. In this sector, CO_2 is emitted as a result of the clinker production process – ~50 percent of total emissions from cement production are process emissions, and they can only be eliminated by adoption of suitable "Carbon Removal Methodologies", such as Carbon Capture and Storage (CCS) and afforestation & reforestation.

Both carbon use and storage will be critical to achieve scale for CCUS. Policy support, market creation through a cluster-based approach, and incentives for demonstration projects in the initial years are a crucial enabler for the uptake of CCUS technology.

In a BAU scenario, the emission is expected to peak around 2045 – 50 and the residual energy related emission is expected to be in the range of 3000 – 3200 Mt CO2 due to significant use of fossil fuel in power generation, industry and transport.

India would require a massive USD 13 – 14 trillion investments between 2024 – 70 to realize the net zero aspirations.

India's energy transition will be expensive. Total cost towards energy transition to achieve net zero by 2070 is expected to be USD 13 – 14 trillion between 2024 – 70. This is a meaningful cost to the economy – at 1-2% of annual GDP over 50 years. However, there could be reasonable front-loading of these investments, with the 2030-2050 decades seeing substantially higher investment intensity.

[7] If the country decides to operate some coal-based power plants to meet the base load requirement, the residual emission would increase accordingly

Investments will be undertaken in the areas of renewable project development, transmission infrastructure, energy storage, ZEVs and transportation infrastructure, green hydrogen and associated infrastructure, green steel infrastructure, industrial energy efficiency, building energy efficiency, CCUS and just transition.

Investment areas	Investment amount (USD Billion)	Investment share (%)	Assumptions and Rationale
Coal based capacity addition	80 – 100	0 -1%	40 – 50 GW new Coal based capacity (in addition to under-construction) is expected to be commissioned by 2035 to meet the increasing energy demand.
Renewable energy	3800 - 4200	28 – 30%	Capital expenditure towards Solar, Wind, Hydro, Nuclear
Energy storage	1500 - 1700	10 - 12%	Capital expenditure towards Pump Storage, Battery Storage and H2 turbine based seasonal storage
Transmission & Distribution	900 - 1200	8 – 9%	Capital expenditure towards augmentation and modernization of T&D infrastructure for integration of RE
Transport – ZEV and Infrastructure	4500 - 5000	28 – 32%	Capital expenditure towards EV battery, FCEV, Charging infrastructure and Hydrogen refuelling system
GH2 infra and associated RE	1500 - 1700	11 – 13%	Capital expenditure towards deployment of electrolyser, associated RE and energy storage, hydrogen storage.
Green Steel Infrastructure	500 - 600	4 – 5%	Additional expenditure towards green steel infrastructure
CCUS	150 - 180	1 – 1.5%	Cost of CCUS deployment in cement industry for 400 - 500 Million Tons. This includes capex towards carbon capture, pipeline and storage infrastructure.
RE equipment manufacturing and recycling facilities	40 – 50	0.5%	Capital expenditure towards indigenization of renewable equipment and systems manufacturing, such as Solar upstream value chain, battery storage manufacturing, electrolyser manufacturing etc.
Just transition	70 - 100	0.4 – 0.6%	Cost towards decommissioning of power plant, social cost towards job loss in power plant and coal mines
Others – Energy efficiency, Buildings, Cooking etc.	500 - 1000	5 – 7%	Cost towards industrial energy efficiency, energy efficient building, appliances, PNG pipeline etc.
Total	**13500 - 15000**		

Note: Investment includes additional cost towards replacement of capacity after end of economic life.

In an alternate scenario, if coal plants are not decommissioned after 2060, overall investment may reduce by USD 300 – 400 billion due to lower requirement of BESS and installed RE. However, the impact will not be significant as coal-based power generation is likely to be very costly due escalation of coal price and logistics cost (coal price escalation is assumed as 3.5% y-o-y). The coal capacity is expected to operate as peaking power stations, reducing the overall BESS requirement by 1500 – 2000 GWh.

Policy and regulatory enablers are critical to drive investments into energy transition

The Government and public sector play critical roles by providing a conducive and predictable enabling environment (through policy framework) to drive long-term private sector investment decisions. Conducive policies and regulations will incentivise and facilitate private sector investors and developers' decisions in developing, financing and building the volume of projects needed for the energy transition. Major focus areas for policy development include:

- Strengthening the supply chain and development of a domestic manufacturing ecosystem for clean technologies, such as solar upstream, wind turbine, battery storage, electrolyser etc.
- Preparing coal-based fleet for flexible operation and higher ramping capabilities
- Prioritization of hydro and nuclear capacity addition
- Strengthening transmission grid and regional grid interconnections

- Transport decarbonization with focus on deployment of ZEVs and associated infrastructure and efficient urban planning
- Scaling up of industrial decarbonization technologies, such as green steel, circularity, CCUS etc.
- Introduction of carbon pricing
- Demand response

Key policy and regulatory recommendations are elaborated in Chapter 9.

Additionally, channelizing public and private finance to fund the transition capex becomes imperative for the country. Securing the necessary funds and ensuring their efficient allocation while maintaining the country's fiscal discipline remain critical hurdles on India's path to energy transition.

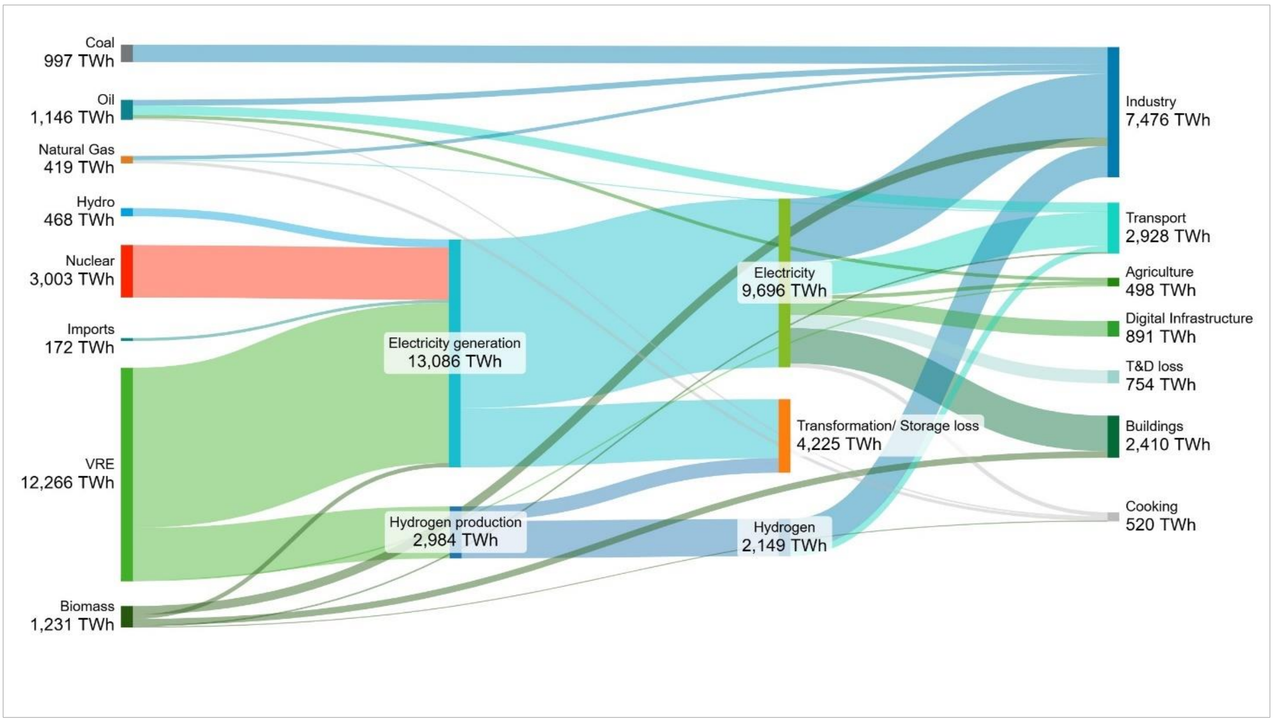
The government, the private sector, and Multilateral Development Banks (MDBs) will play a critical role in financing the transition. Development Banks are instrumental in providing concessional finance in the initial years. In addition to concessional financing, credit enhancement schemes, such as Credit Risk Guarantee Funds, First Loss, and project aggregation, can help de-risk projects and attract capital to novel and risky projects.

India needs to work backward to achieve net-zero and develop decisive plans and implementation roadmaps for energy transition. Along with developing an enabling environment and formulation plans, ensuring timely implementation is critical. Long, intermediate, and short-term plans need to be developed, along with diligent follow-ups, to ensure implementation with zero tolerance for slippage.

Implementation of energy transition initiatives would require collaboration with central government, state governments, industry players and academic institutes. The energy transition targets need to be translated into actions for the respective state governments and sector-specific industry players. Sector-specific targets will give policy direction and timelines for emission reduction by corporates.

Indian states are important implementation actors in India's energy transition journey. States should be proactive in realizing national targets, developing a conducive energy policy, participating in demand aggregation to drive economies of scale, and developing appropriate regulatory frameworks. For example, states can identify potential industrial clusters for aggregation of GH2 or CCUS that can help in market creation and cost reduction.

The energy balance diagram for 2070 in the Net Zero Scenario is illustrated below:



1 Introduction

India ranks third in the world for energy consumption, despite having only one-third of the global average per capita energy consumption. Historically, India's contribution to global emissions has been less than 7%, even though it represents around 17% of the world's population[8]. With a growing population of over 1.4 billion and strong economic growth, India is expected to remain one of the largest energy consumers in absolute terms for the foreseeable future. Therefore, the country faces a significant dual challenge: meeting its increasing energy demands while addressing environmental concerns to sustain economic growth.

Traditionally, India has relied heavily on fossil fuels to meet a substantial portion of its energy requirements. However, it has recently been diversifying its energy mix, with a focus on renewable sources such as solar, wind, and hydroelectric power. Government initiatives, driven by ambitious renewable energy capacity expansion targets, underscore India's commitment to sustainability and energy security. Over the past decade, the government has made notable efforts to ensure energy security and reduce carbon emissions.

In FY22, India's final energy consumption was approximately 650 Mtoe, growing at a CAGR of about 3.2% over the last decade (FY13–22). In FY 2022, oil and biomass[9] each accounted for 32% of final energy consumption, while electricity contributed about 14%. The demand for oil is primarily driven by the transport sector, while biomass is largely used for residential cooking and heating in rural and semi-urban areas. Coal consumption growth (excluding power generation) has been driven by energy-intensive industries such as steel and cement, as well as the MSME sub-sectors. During the same period (FY13–22), primary energy consumption increased from around 640 Mtoe in FY13 to 870 Mtoe in FY22, at an annual growth rate of approximately 3.5%. Coal has remained the dominant energy source in the overall mix, holding a 42% share in FY22, largely due to its domestic abundance.

India's energy-related emissions have steadily risen from around 1,700 million tonnes in 2013 to 2,500 million tonnes in 2022, with a temporary dip in 2020-21 due to the pandemic[10]. The electricity sector is the largest contributor to CO2 emissions, accounting for over 40%, primarily due to its heavy dependence on coal—more than 70% of the electricity generated in 2022 came from coal.[11] Besides ensuring the country's energy security, fossil-fuel-based power plants provide essential grid stability to balance the intermittent generation from wind and solar sources.

The industrial sector is the second-largest contributor to India's CO2 emissions, making up over 30% of the total. The steel industry is the largest emitter within the industrial sector. Indian steel production largely depends on coal-fired blast furnaces, which are more emission-intensive compared to gas-based direct reduction or electric arc furnaces that use recycled scrap. This reliance makes India's steel production more carbon-intensive compared to other countries. The cement industry follows as the second-largest emitter in the industrial sector, primarily using coal and oil as fuels. Other significant industries contributing to emissions include aluminium, fertilizer, and petrochemical. Looking ahead, India's macroeconomic growth and increasing focus on domestic manufacturing are expected to drive up industrial output.

About 13% of India's CO2 emissions come from the transport sector. Since 2000, oil demand for road freight transport in India has tripled, the highest increase after China, with trucks accounting for over 45% of transport emissions. In terms of passenger vehicles, India has a much larger share of two- and three-wheelers compared to developed countries. The rapid expansion of mobility in India has been supported by the growing road network and overall infrastructure improvements.

At the 26th session of the United Nations Framework Convention on Climate Change (COP 26) in 2021, India announced its ambitious target of achieving Net-Zero emissions by 2070, aligning itself with other developed nations. This was a significant commitment for a developing nation with a rapidly growing economy. Alongside this pledge, India updated its Nationally Determined Contributions (NDCs) under the 'Panchamrit' strategy. Key goals include achieving 50% of its cumulative electric power installed capacity from non-fossil fuel sources by 2030 and reducing the emissions intensity of its GDP by 45% from 2005 levels by 2030 [12].

Given that India's economy is predominantly dependent on fossil fuels, it is crucial for the country to announce and implement robust decarbonization measures to reach its Net-Zero target by 2070. This will require a rapid shift to a low-carbon power system, reduced reliance on fossil fuels in industries, a decarbonized transport system, and a

[8] India's energy related emission is ~2.5 billion ton CO2eq vis-à-vis global emission of ~38 billion ton CO2eq (IEA)
[9] Source: Biomass consumption is as per India Energy Outlook by IEA
[10] Estimated based on primary energy mix
[11] Source: Central Electricity Authority (CEA)
[12] UNFCC, India's Updated Nationally Determined Contributions, 2022 (access here)

societal move towards sustainable living. Achieving these goals will demand the adoption of new technologies, supportive policies, effective support mechanisms, and a steady supply of low-cost financing. India's decarbonization pathway aligns with the “Life for Environment (LiFE)” concept, which promotes eco-friendly practices in daily life, such as using public transportation, minimizing waste, and adopting mindful consumption patterns.

India’s final energy demand is projected to rise substantially by 2070, driven by increasing incomes and a higher standard of living, fueled by economic growth, rapid urbanization, and industrialization. However, under the Net-Zero scenario, aggressive energy efficiency measures could moderate this growth, leading to more efficient and sustainable energy use.

The industrial sector is expected to remain the largest consumer of energy, with demand driven by the expansion of the steel, cement, and aluminum industries. In the transport sector, while passenger and freight transport demand will grow significantly, energy demand will be moderated by a shift to more efficient modes of transport and alternative fuels. The increasing electrification of vehicles is expected to enhance energy efficiency, with battery electric vehicles achieving efficiencies of 70-80% compared to 25-30% for combustion engine vehicles. Similar efficiency improvements will be seen in the building and cooking sectors. Urbanization, the replacement of older buildings with new, more energy-efficient construction, and greater ownership of appliances like air conditioners will drive up energy demand in the building sector. This demand will be counterbalanced by the adoption of energy-efficient appliances and thermally efficient buildings. In the cooking sector, traditional biomass stoves in rural areas are likely to be replaced with LPG/PNG and electric stoves, further improving efficiency.

On the supply side, to meet the rising primary energy demand, a substantial increase in cleaner energy sources, especially solar and wind, will be essential. Other significant non-fossil energy sources will include hydro and nuclear power. The demand for electricity is expected to grow faster than overall energy demand due to the electrification of transport and industry. Most of this electricity will come from non-fossil fuel-based sources, and the integration of renewable energy will be supported by the deployment of long-duration and seasonal energy storage solutions.

In a net-zero scenario, it is crucial to limit energy demand to a reasonable level without hindering economic growth. This can be achieved by adopting energy efficiency measures, implementing new technologies, and meeting energy needs through cleaner sources. This study provides a comprehensive analysis of India’s energy landscape to model different energy demand-supply scenarios. It involves forecasting energy demand across various sectors until 2070, modelling sustainable supply-side options to meet this demand, and projecting emissions. The study explores two scenarios: the Net Zero Scenario and the Business-As-Usual (BAU) Scenario.

2 Approach and Methodology

This study aims to explore energy transition pathways by modeling energy demand, supply, and emissions up to 2070, taking into account various growth drivers, technological changes, and behavioral shifts. The modeling covers two scenarios: Net Zero and Business-As-Usual (BAU).

Additionally, the study projects key macroeconomic parameters that remain constant across both the scenarios. These parameters include GDP, population, household size, and the degree of urbanization, based on projections from credible organizations such as the World Bank, the United Nations, and NITI Aayog in India.

2.1 Energy demand modelling

The study conducts demand-side modelling to project energy demand across all major energy-consuming sectors of the economy up to 2070. Energy is used in these sectors both in its raw form for direct use and in intermediate forms, such as electricity or green hydrogen. For instance, vehicles may use fossil fuels like petrol and diesel, as well as electricity for charging batteries in electric vehicles. Similarly, industries rely on fossil fuels both as feedstock and for process heat, as well as electricity for various manufacturing and transformation processes.

For each sector, the study identifies relevant sub-sectors and develops forecasts for growth in final energy demand by examining baseline energy usage and the specific growth drivers for each sector. For example, industrial energy demand is driven by economic growth; energy demand for agricultural pumps depends on the number of tractors and the area under irrigation; and cooking demand is influenced by population size and household dynamics. In addition to growth projections for each sector, the demand modelling also considers shifts in the energy mix, changes in Specific Energy Consumption (SEC), and potential energy reductions through "LiFE" interventions. Key considerations for estimating energy demand are outlined below:

<u>Analysis of growth prospect</u>

As the initial step in estimating energy demand across various sectors, the study analyzed the long-term growth prospects for each sector from 2024 to 2070. The following approaches were considered:

- **National/Sectoral targets**: Various interim sectoral targets have been taken into account. Additionally, it is assumed that India will attain the status of a developed nation with a per capita GDP of USD 14,000 (in constant dollars).
- **Country comparison:** The study compared the historical economic growth of at least eight countries and found that China's growth trajectory from 1998 to 2020 could be comparable to India's projected growth from 2024 to 2050.

<u>Future mix of final energy sources for each sector</u>

The report identified the mix of intermediate energy sources for each sector from 2024 to 2070, considering technological advancements. The energy demand model projects the potential energy mix for each sector up to 2070, incorporating electrification, the adoption of green hydrogen, natural gas, biofuels, and other alternatives.

<u>Energy efficiency and LiFE interventions</u>

The energy model has also accounted for the effects of improved energy efficiency across each sector. Sectors such as industry, building, and cooking are anticipated to experience significant reductions in specific energy consumption due to technological advancements and changes in the fuel mix. Additionally, LiFE interventions are expected to influence energy consumption patterns in most sectors. In a net-zero scenario, the impacts of enhanced energy efficiency and LiFE interventions are projected to be more pronounced than in other scenarios.

Based on the above three considerations, growth in final energy demand for each sector has been finalized for each scenario. **Key outcomes of the demand model are:**

- Final energy demand for each sector through 2024-70
- Demand of all sources of final energy through 2024-70 – for example, electricity, hydrogen, direct fuels, such as coal, gas, oil, biomass etc.

An illustration of the approach and methodology for demand estimation is illustrated below:

Key steps for demand estimation

- Identify the relevant sectoral **growth drivers**
  - Target: ~$25 trillion economy by 2047)
  - Country comparison (studied 8-10 countries; *China's growth from 1998-2020 could be analogous to India's 2024 – 2050 growth story*)
  - China has become developed nation in 2020
- Identify the **mix of intermediate energy sources based on technology changes**
  - Electrification (industry, transport)
  - Green Hydrogen
  - Any other (Bioenergy, biomass)
- **Energy efficiency and LiFE interventions**
  - Improvement potential in energy efficiency,
  - LiFE interventions (modal shift, Cooking electrification etc.)
- Develop forecasts for **growth in final energy demand**

Inputs for demand model

Major industry sectors	Sub-sectors (Illustrative)	Factors considered for demand estimation
Industry	Cement, Iron & steel, aluminium, textiles, pulp & paper,fertilisers, chlor-alkali, refineries, other industries	Growth rate, technology changes/ fuel switch, energy efficiency
Transportation (Passenger)	Road (2W, 3W, 4W, buses, taxis), Rail (Diesel/ Electric), Air transport and Shipping	Growth rate, Technology changes, LiFE interventions (modal shift)
Transportation (Commercial)	Road (HCVs/ LCVs), Rail (Diesel/ Electric), Air transport and Shipping	Economic output, Growth rate, technology changes
Buildings (Residential)	-	Population, urbanization, appliance occupancy, energy efficiency etc.
Buildings (Commercial)	School, hospital, university, commercial space etc.	Increase in economic output, Energy efficiency, green building adoption
Agriculture	Tractor, irrigation pump	Agricultural growth and efficiency, growth in tractor demand
Cooking	n/a	Increase in households Conversion from biomass to LPG and electric cookstoves
Data Centers	n/a	GenAI and Industry 4.0 will be data driven
Electrolysers	n/a	Increased uptake of Green Hydrogen

Energy demand estimation

Broken down in sectors:

- Industry, Residential, Commercial, Cooking, Agriculture, Transport, Telecom

Source of final energy:

Coal, Oil, Gas, Hydrogen, Biofuel/Biomass etc.

Outputs from demand model

Electricity demand

Hydrogen demand

Demand of direct fuels
- Coal, Oil, Gas
- Biofuel/Biomass
- Any other

Figure 1: Methodology for demand modelling

Above methodology has been adopted for each of the sector:

- **Industry Sector**: Demand projections have been made for each major industry, including steel, cement, aluminum, fertilizers, textiles, chlor-alkali, refineries, data centers, etc. All other sub-sectors are grouped under a category labeled "Others." The final energy sources for each sub-sector have been evaluated based on the future technological landscape and the potential for fuel switching.
- **Transportation Sector**: Projections consider both freight and passenger transportation, analyzing the energy mix and the adoption of various vehicle technologies, along with their modal share, up to 2070.
- **Cooking Sector**: The study estimates total energy requirements by examining the penetration of different fuel-based cooking technologies in rural and urban areas, with a focus on per capita cooking energy needs up to 2070.
- **Agricultural Sector**: The focus is on the growth in the number of tractors and the solarization of irrigation pumps up to 2070, calculating the energy mix based on operational hours, the number of tractors in use, and diesel consumption per hour.
- **Building Sector**: Energy consumption is segmented into residential and commercial categories, emphasizing the growth in electrical appliances and floor area to project energy use up to 2070.

This study employs a sector-wise, bottom-up approach for demand modeling. Growth projections and potential technology adoption for each sector have been analyzed to determine the final energy demand. The electricity demand, in the form of final energy, from each sector, along with the expected trajectory of transmission and distribution losses, is then integrated into the energy supply model.

2.2 Energy supply modelling

The projected energy demand in all these sectors is fed as an input to an optimization module, which determines generation capacity expansion/retirement along with optimal dispatch to meet the electricity demand. Based on the overall energy demand estimated, the supply side is simulated to meet the energy demand using a **Linear Programming (LP) optimization model**. Energy sources will comprise of primary sources like fossil fuels, renewable energy, biofuels, hydrogen and nuclear. Secondary energy sources will further comprise of electricity produced from fossil fuels and renewable energy and hydrogen produced from renewable energy which are the form in which these resources are consumed in the end use sectors. The model maps the transformation of primary energy to secondary energy and its ultimate consumption by the various end use sectors.

Once the electricity demand is ascertained, **the generation mix is determined based on least cost optimization using an Integrated Resource Planning model.** The energy model also takes into consideration the policy targets and allocations made by the Government for various end use sectors and the fuel/ technology adoption within those.

Integrated Resource Planning (Supply) module[13]

The electricity demand from each sector and the expected trajectory of transmission & distribution losses are passed on to the electricity supply module. Based on the overall energy demand estimated, the supply side is simulated to meet the energy demand using an optimization module. Energy sources will comprise of primary sources like fossil fuels, renewable energy, biofuels, hydrogen and nuclear. Secondary energy sources will further comprise of electricity produced from fossil fuels and renewable energy which is the form in which these resources are consumed in the end use sectors. The module maps the transformation of primary energy to secondary energy and its ultimate consumption by the various end use sectors.

The model optimizes the energy system so that it can satisfy specified energy demands at the optimal costs. The model used Deloitte's proprietary least-cost Integrated Resource Planning (IRP) model, which runs on a 15 min resolution for each modelled year. The IRP works on a framework based on a **Linear Programming (LP)** formulation and is an internationally recognized model used for supply side optimization.

The future demand obtained is projected on a 15 min resolution based on historic load patterns and policy changes. Supply side data, assumptions, technical parameters, and constraints are provided to the model as various variables. **The LP model is written in python to minimize the overall system cost, including capital costs, operations and maintenance costs, fuel costs, transmission cost, etc. and is solved using commercial optimization algorithms**.

Based on supply side modelling, fuel mix for each type of energy source has been evaluated ("the source"). Emission intensity of various type fuels have been modelled and sector wise emission for each year through 2070 have been estimated. Emission intensity factors have been obtained from literature and emission databases in the Indian context.

An illustration of the methodology for supply side model is provided below:

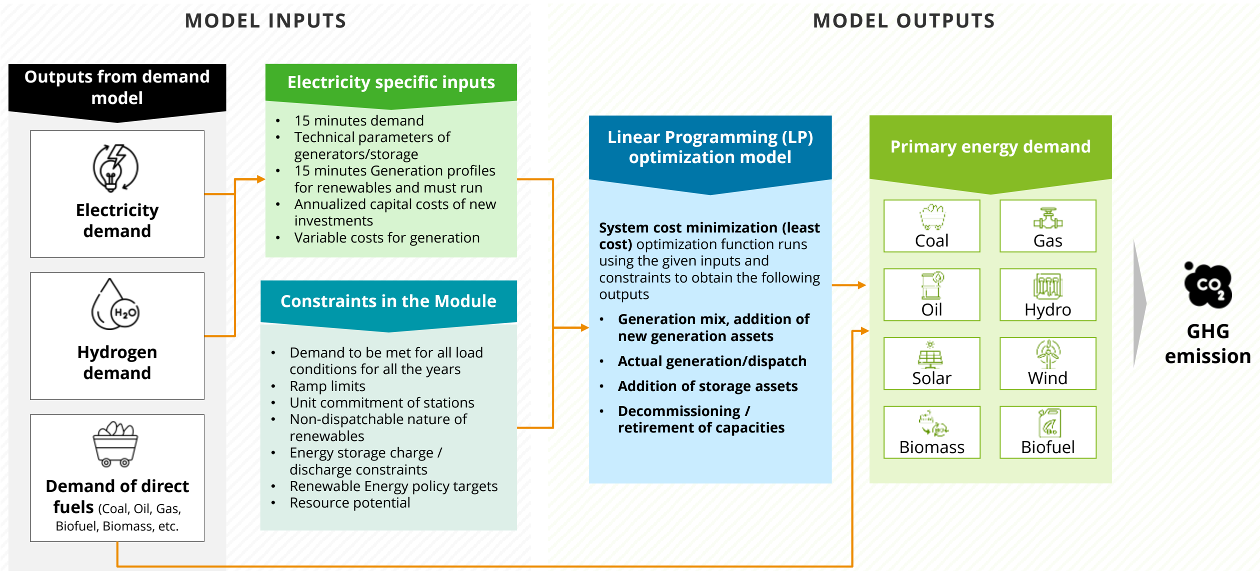


Figure 2: Methodology for supply modelling

2.3 Scenario development

This study has evaluated three scenarios to model energy demand, energy supply and energy related emission; the scenarios are Net Zero scenario, BAU scenario and an intermediate scenario.

	Scenario 1	**Scenario 2**
Scenario Description	**BAU scenario** with High adoption of fossil fuel due to slower uptake of renewables and new technologies	**Net Zero Scenario**; both demand and supply side efficiency are introduced. RE and Hydrogen uptake will be faster

[13] This scope of this study doesn't include transmission planning for integration of renewables. The capacity expansion model is simulated without any transmission constraint.

	Scenario 1	Scenario 2
Demand side measures	Moderate	Heroic
Supply side measures	Moderate to Low RE	High RE
Emissions level in 2070	**High**	**Low**

- **Scenario 1 - Business as Usual (BAU):** The BAU scenario represents a continuation of current trends without significant demand-side interventions or accelerated adoption of renewable energy. It assumes a moderate rate of electrification across various energy-intensive sectors, a gradual timeline for retiring thermal power plants, and a moderate level of penetration for renewable energy sources.
- **Scenario 2 - Net-Zero Scenario (NZS):** The Net-Zero Scenario is an optimistic pathway that envisions extensive electrification and rapid adoption of alternative energy sources and technologies, such as green hydrogen and battery storage. Under this scenario, all thermal power plants are expected to be retired by 2070, with no new thermal capacity being added after 2035. This scenario is most closely aligned with achieving net-zero emissions by 2070.

(Key assumptions of demand-supply modelling for each scenario are provided in the annexure.)

Understanding Net Zero Carbon

Net-zero carbon emissions (carbon neutrality) refers to a state when carbon emissions from energy consumption (coal, oil, and gas) equals the amount of carbon reductions achieved through carbon removal efforts, such as afforestation or new technologies such as carbon capture and storage (CCS).

In this context, it is important to understand that net-zero carbon is different from net zero climate change. Climate neutrality is an even stricter goal as it takes the non-CO2 greenhouse gases such as methane into account, and these have to be reduced to zero as well. These non-CO2 greenhouse gases are normally produced by agricultural businesses.

This study focuses on Net Zero Carbon emission

3 India’s emission landscape

Despite having much lower per-capita greenhouse gas (GHG) emissions compared to the global average, India is the world's third-largest GHG emitter[14]. The country faces the complex challenge of balancing rapid economic development with the need to reduce carbon emissions. As India's population and economy grow, it must manage rising energy demand while transitioning to a sustainable, low-carbon future.

India’s emissions are primarily driven by three sectors—power, industry, and transport—which together account for over 80% of the total GHG emissions. To address these challenges, the Indian government has introduced several policies and interventions aimed at reducing emissions. These include ambitious targets for expanding renewable energy capacity and promoting energy efficiency across buildings, industries, and hard-to-abate sectors. Other initiatives focus on encouraging electric vehicles, enhancing public transportation, improving freight efficiency to reduce energy consumption in the transport sector, expanding forest cover, and adopting sustainable land-use practices to create carbon sinks.

The power sector is the largest source of CO2 emissions in India, mainly due to its heavy dependence on coal, which accounted for more than 70% of electricity generation in 2022[15]. While fossil-fuel-based plants ensure energy security and provide grid stability to balance the intermittent nature of wind and solar power, the carbon intensity of India’s power sector is 725 g CO2/kWh, compared to the global average of 510 g CO_2/kWh[16]. This highlights the significant role of coal-based generation in the country’s GHG emissions, with the electricity sector historically contributing more than 40% of total emissions.

The industrial sector is the second-largest source of CO2 emissions in India, contributing around 30%. The iron and steel industry is the biggest industrial emitter, largely due to the reliance on coal-based blast furnaces rather than the less carbon-intensive gas-based direct reduction and electric-arc furnaces (using recycled scrap). The cement industry is the second-largest emitter within the industrial sector, primarily using coal and oil as fuels. Other significant contributors include the aluminium, fertilizer, and petrochemical industries. The growth of India’s industrial output, driven by macroeconomic growth and a focus on domestic manufacturing, has also increased the demand for reliable energy over the last two decades.

The transport sector accounts for 12-13% of India’s CO2 emissions and more than 40% of the country’s total oil demand. Since 2000, oil demand for road freight transport has tripled—the highest increase after China—with trucks responsible for over 45% of transport emissions. In the passenger vehicle fleet, India has a much larger share of two- and three-wheelers compared to developed countries. The rapid expansion of mobility is supported by an expanding road network and improved infrastructure.

Energy demand in the building sector, particularly in the latter half of the 2000s, has been driven by an increase in building floor area in both rural and urban areas, rising ownership of basic appliances, and greater use of refrigerators and air-conditioning units in urban areas.

It is crucial to note that three major fossil-based energy sources—coal, oil, and natural gas—have historically accounted for 72–75% of India’s primary energy requirements. With growing energy demand, the consumption of these fuels has also increased, leading to a rise in CO2 emissions. The illustration below provides a breakdown of fuel-wise emissions in India during 2013–22.

[14] UNEP (2023), Emissions Gap Record 2023 (access here), GoI (2022), India’s long-term low-carbon development strategy (access here)
[15] Source: Central Electricity Authority (CEA)
[16] India Energy Outlook, 2021

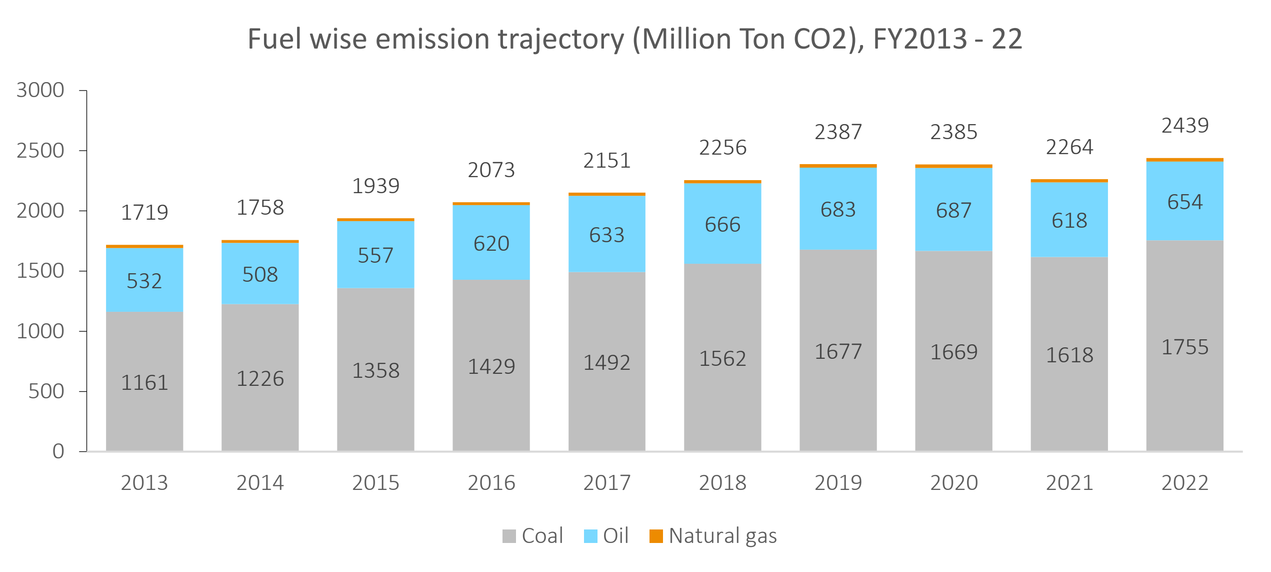


Figure 3 Fuel wise emission trajectory (Million Tonnes CO2) from FY2013-22

Source: Estimated; emission intensity – coal: 1.8 kg CO2/kg of coal, Oil: 3.5 kg CO2/kg of coal, Gas: 0.73 kg of CO2/kg of gas

Note: The above emission doesn't account for additional coal use for MSME sectors (~25 Mtoe)

India's energy-related emissions rose from approximately 1,719 million tonnes in 2013 to 2,439 million tonnes in 2022, with a temporary decline during 2020-21 due to the pandemic. Reducing carbon emissions is not just a national priority for India but also a global responsibility. Through consistent efforts and international collaboration, India has the potential to build a sustainable future characterized by cleaner air, healthier communities, and economic growth.

A sector wise break-up of emission from FY 13-22 is provided below:

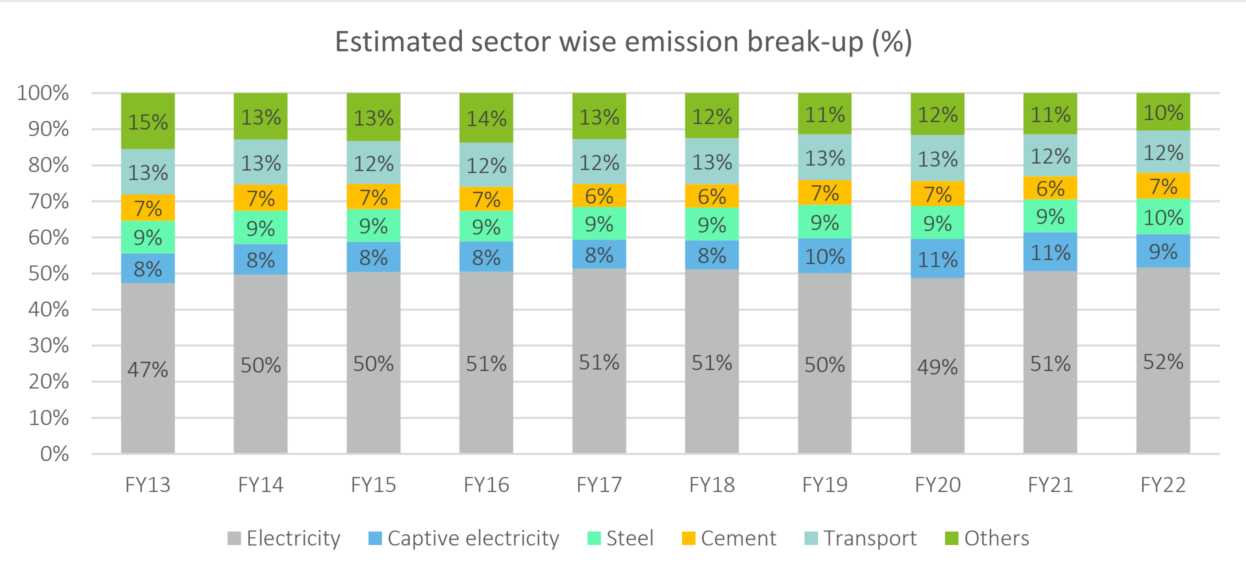


Figure 4 Sector wise emission break-up, FY13 – 22

Source: Estimated

Overall, strong economic growth, combined with adverse weather conditions, has led to increased energy consumption across all sectors, resulting in a rising trend in emissions. The electricity sector has historically been the largest contributor, accounting for over 50% of emissions. However, India's per capita emissions remain quite low at around 2 tonnes, which is less than half the global average of 4.6 tonnes.

4 India's energy demand modelling

The energy demand model visualizes different scenarios based on standard macro-economic assumptions including population growth of country, GDP growth, share of industry, services, agriculture etc., in the economy and trajectory for specific energy consumption, energy mix etc.

The demand-side modelling follows a bottom-up approach. The model involves all major sectors contributing to country's energy demand – Industries, transportation, cooking, agriculture, building (residential and commercial) and digital infrastructure (data centre and telecom).

Energy demand has been estimated across each of the sector and combined to determine the overall energy demand in India with a break-up of the different secondary and primary energy sources that are used to meet this energy demand.

4.1 India's macro-economic outlook

India is one of the fastest-growing large economy set to enter the high-middle-income club early next decade. India's current per capita GDP is ~USD 2300, and the country has an aspiration to attain "developed economy" status by 2047 ("Vikshit Bharat"), with per capita GDP reaching USD 14000 by 2047.

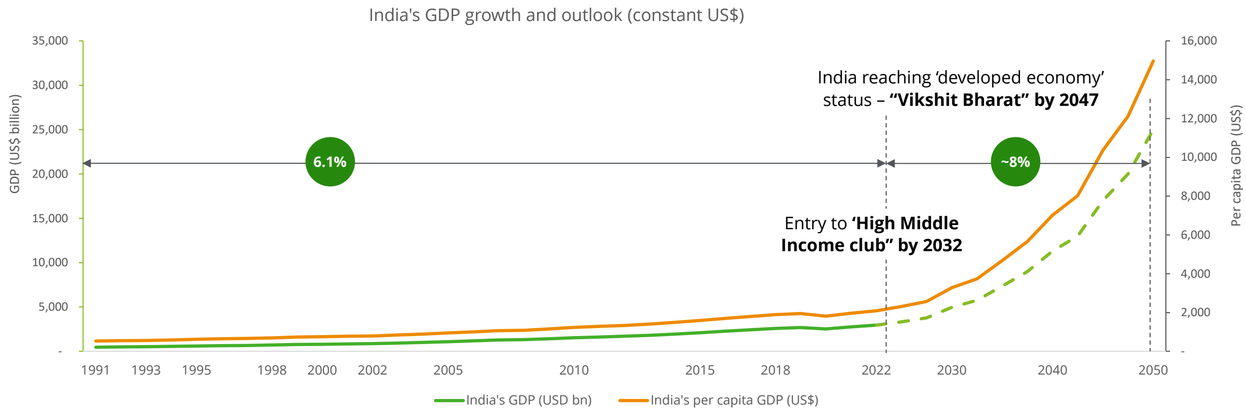


Figure 5: India's macro-economic outlook

India's population is expected to grow from 1.41 billion in 2022 to 1.67 billion in 2050 and 1.69 billion in 2070, as projected by United Nation[17].

Low per capita GDP, low urbanization, low median age, low manufacturing wage, low per capita energy consumption and an ambitious growth aspiration augur well for India to drive robust growth journey for next few decades. India is poised to become a USD 25 trillion economy by 2050 and nearly USD 60 trillion by 2070.

Emerging drivers of India's economic growth:

	Per capita GDP (US$)	Urbanization (%)	Median age (Year)	Manufacturing wage ($/hour)	Per capita energy consumption (GJ)
India	~2300	~36%	~30	~0.8	~26
Developed Nations	>14,000	>60%	>40	5 - 20	>70

[17] UN World Population Prospects 2022

4.2 Energy demand outlook in the Industry Sector

The industrial sector is projected to be the primary driver of energy growth in the coming decades. This study has estimated future energy demand for nine major energy-intensive sub-sectors—cement, steel, aluminium, fertilizer, refineries, chlor-alkali, pulp & paper, textiles, and digital infrastructure (data centers and telecom)—while grouping all other sub-sectors (including MSMEs) under a single category called "Others."

Energy demand for each sub-sector has been calculated using the methodology outlined in Section 2, accounting for technological advancements and improvements in energy efficiency up to 2070. The sources of final energy—such as solid hydrocarbons, liquid hydrocarbons, gaseous hydrocarbons, electricity, biomass, and hydrogen—have also been modeled to meet this demand.

Technological advancements will shape how industries fulfill their future energy needs while reducing emissions. There is no "silver bullet" solution; instead, industrial companies will need to explore a broad range of options to cut emissions and enhance energy efficiency.

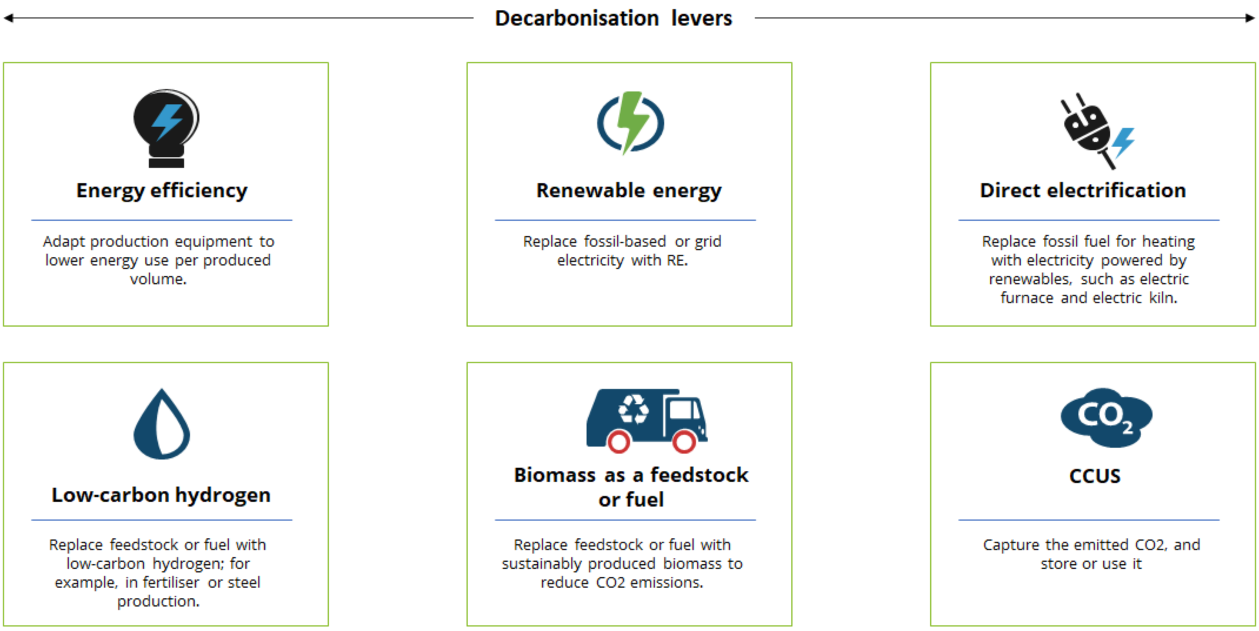


Figure 6: Illustration of decarbonization levers

- **Energy efficiency:** Energy efficiency is a continuous process. Manufacturers are focusing on operations excellence and adoption of digital monitoring tool to manage energy consumption. However, emission reduction potential from energy efficiency measures is limited to 5 – 15%[18]. Industries in the matured sectors typically have already seen improvements and can thus be expected to be at the low end of the range, whereas industries in evolving sectors may be at the high end.
- **Renewable energy:** Transition to renewables is becoming the most preferred options for most of the energy intensive industries to decarbonize the electricity sector. With reforms in regulations and policies, such as green open access, renewable corporate PPAs (through third party mode or group captive mode) are clearly visible. As of March 2024, India has ~20 GW of C&I renewable installed capacity[19]. Many industries and corporates also prefer buying renewable energy certificates to discount carbon emission. Apart from the sustainability agendas, major drivers for corporates to shift to RE include declining cost of renewables, emergence of energy storage to enable round-the-clock power and favorable regulations towards Renewables.
- **Direct electrification**: Electrification of process heat by leveraging low-carbon electricity is expected to emerge as a major decarbonization lever in the industry. For example, many furnace applications which use fossil fuel directly (e.g., steel, foundry etc.) can be replaced with electric furnaces powered by RE.
- **Low carbon hydrogen**: Use of low carbon hydrogen (mainly green) is being explored as a decarbonization agent in refineries, fertilizer and Steel sectors. There is a fast-growing acknowledgement that energy systems cannot be

[18] Source: Industry input, Deloitte analysis
[19] India RE Navigator (access here)

decarbonized by greening electrons (RE) alone; low-carbon hydrogen is emerging as a "Decarbonization Agent" for the hard-to-abate sectors where electrification is difficult to achieve.

- **Carbon Capture, Utilisation and Storage (CCUS):** CCUS is the most preferred decarbonization option in Cement sector; limited uptake is possible in Steel and Fertilizer industries. Currently, India is only operating few pilot scale projects in the Steel and Chemical sectors; both downstream carbon utilization and carbon storage will be critical to achieve scale.
- **Biomass as a feedstock:** Biomass or bio-fuel as an alternative fuel is gaining traction to reduce fossil fuel emission. Currently, majority of biomass used in the industrial sectors is in the Paper and Food industries. Going forward, some uptake is expected in the Steel and Cement sectors (co-firing with coal); however, key considerations include changes in the plant design and establishment of a reliable supply chain.

A Net Zero scenario would be defined by adoption of aggressive energy efficiency measures, breakthrough technologies and behavioural shift. The sectoral attributes in NZS and BAU are illustrated below:

Sector	NZS measures	BAU measures
Steel	Entire steel sector shall be decarbonized through H2-DRI and scrap recycling.	BF-BOF and Coal based DRI will steel continue to operate. H2-DRI penetration will be delayed – penetration of H2-DRI may be limited to 30 - 40% H2-DRI production by 2070 with 20% production through scrap recycling.
Cement	Higher electrification; Specific Energy Consumption (SEC) improvement from 0.67 TWh/Mn Ton to 0.59 TWh/Mn Ton driven by clinker substitution, energy efficiency and fuel switch.	SEC improvement will be in the same range; Indian cement players are in the top quartile amongst the global players.
Aluminium	SEC improvement by ~10%, based on global benchmarks.	SEC improvement by ~10%, based on global benchmarks.
Refinery	100% substitution of grey hydrogen with green hydrogen	Up to 40% substitution by green hydrogen
Fertilizer	Entire non-urea fertilizer will replace grey hydrogen with green. Urea production and consumption may gradually come down	Substitution in non-urea segment will be limited to 40-50%; Urea will continue to be dominant category in India's fertilizer mix.
Other industries	Rapid electrification; (up to 50% electrified) Aggressive energy efficiency adoption	Slower electrification (up to 30% electrified) Moderate adoption of energy efficiency
Building	Rapid electrification – Biomass-based heating (winter season – 3 months) will gradually reduce; adoption of energy efficient appliances, energy efficient building will increase rapidly	Same as NZS; Building sector is expected to transit rapidly towards electrification and energy efficiency even in BAU scenario.
Cooking	Transition to electric cookstoves, with some PNG.	Same as NZS; the sector will gradually move to electrification.
Passenger transport	Complete transition to low-carbon powertrain; Large adoption of EV with some penetration of FCEV	Lower adoption of electrification. ~60% adoption of electric vehicle in the private car segment; bus will be 100% electrified. FCEV will only be a niche segment.
Freight transport	50 – 60% low carbon powertrain – FCEVs and EVs	20 – 30% low carbon powertrain – FCEVs and EVs
Modal shift	Aggressive shift from private transport to public transport through efficient urban planning, infrastructure development	Moderate shift from private to public transport

Energy demand assessment for major sub-sectors in Net Zero and BAU scenario within industry sector is illustrated in following sub-sections.

4.2.1 Cement sector

India is the second-largest producer of cement in the world[20]. The current emphasis on infrastructure development in the country is expected to drive cement demand further. The cement production in India over the last decade had grown at a CAGR of ~4.8%. The sector is expected to follow a similar growth trajectory over the ongoing decade till 2030 as well (validated through the announced production plan of the major producers). In line with the global consumption of cement, the per capita consumption of cement in the country is expected to increase from 250 kg in 2022 to 800-850 kg per capita by 2050, driven by growth in infrastructure and construction activities[21]. Post 2050, the consumption growth is assumed to be flat or stagnated. Cement production is expected to reach 1300 – 1400 MTPA by 2050 from 350 MTPA in 2023[22].

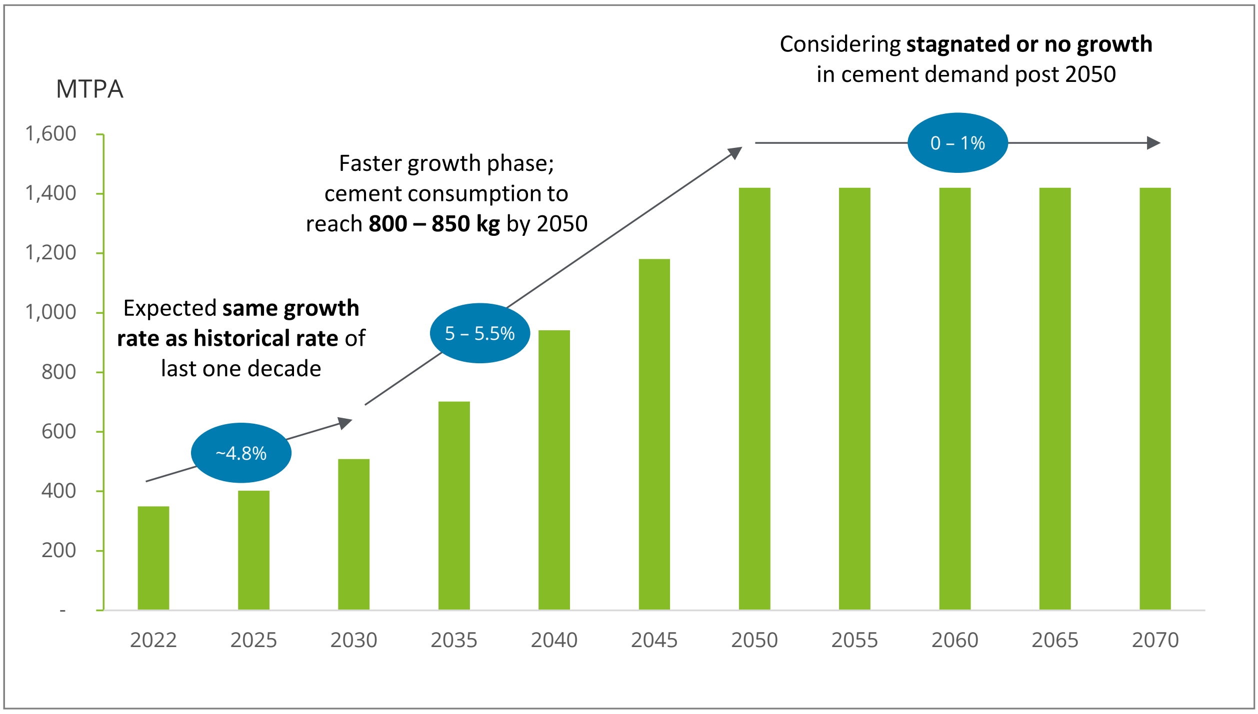


Figure 7: Cement sector growth trajectory

Technology landscape

Cement manufacturing is an energy and emissions intensive process. Raw materials such as limestone and clay are ground into fine powder and fed into rotary kilns where they are heated at a sintering temperature of 1,450 degrees celsius to produce clinker. Blending materials (usually gypsum) are then added to clinker and the resulting mixture, ground to a fine powder again, becomes the traditional Ordinary Portland Cement (OPC). The 'dirtiest' part of cement-making is the clinker production, during which CO2 is emitted from burning fossil fuels ('energy-related' or 'thermal' emissions) and from limestone calcination (called 'process' emissions). Technological interventions are critical to improve the energy efficiency and reduce emissions. There are broadly four ways to reduce energy and emission intensity in the cement sector.

Clinker substitution: The energy intensity in the production process can be reduced by lowering the clinker-to-cement ratio and substituting clinkers with additives such as steel slag, fly ash, waste gypsum etc.

Alternative fuels: In addition to clinker substitution, using alternate fuels such as Hydrogen and biomass can be effective in reducing the emissions footprint for cement production. In long term, under the Net-zero scenario the share of fossil fuels is expected to decline, driven by use of biomass and hydrogen substituting coal. The share of coal could be reduced to ~60-65%, with share of biomass and hydrogen in the final energy mix of 20% and 5% respectively. Hydrogen is expected to be introduced into cement kiln around 2035 and can reach up to 5% of total energy mix by 2050. Considering easy access to biomass in India, it can be introduced in cement kilns much earlier around 2025-27 and has potential to substitute ~20% of coal use by 2040. In addition to alternative fuels, improvement in green power mix is another prominent decarbonization initiatives.

[20] IEA
[21] Current per capita cement consumption of India is 250 kg while the global per-capita consumption is 550 kg; China's consumption is 1200 kg
[22] A correlation has been established from China's growth story from 1998 to 2020.

Traditional energy efficiency technologies: Traditional energy efficiency technologies hold potential of 5 – 10% reduction in specific energy consumption. However, Indian cement players are amongst the most energy efficient manufacturers in the world. Major interventions include implementation of Waste Heat Recovery System, increasing grinding system efficiency, use of high efficiency clinker coolers, efficiency improvement in kiln and preheater, burner retrofit, use of efficient drives and appliances etc.

Currently, the specific energy consumption (SEC) to produce one million ton of cement is 0.67 TWh[23], and more than 85% of the energy required is met through coal. The SEC is expected to decline to ~0.59 TWh by 2035 – 40, driven by lowering the clinker to cement ratio from 0.70 to 0.60 and implementing energy efficiency measures.

Carbon Capture technology: The cement production process has inherent process emissions of CO2 during the process of conversion of limestone to cement clinker. Nearly 50% of total emission in cement industry is process emission which is difficult to decarbonize through fuel shift. This could correspond to over 300 million tonnes per year for India for the expected capacity in 2070, even with clinker substitution and a complete switch to alternative fuels. Hence, carbon capture and storage would play an important role in the future in decarbonizing the cement production.

However, large scale deployment of CCS is challenged with economic, technological, and ecological barriers. Most CCUS projects in cement plants globally are in the development stages. Heidelberg Materials' plant in Brevik, Norway is poised to be the world's first operational carbon capture facility by end of 2024[24].

Multiple CCUS technologies could potentially be applied in the cement industry. Recent developments suggest four offer early promise:

Post combustion: Flue gas is mixed with a solvent like amine or ammonia that dissolves pollutants to leave a high concentration of CO2 for capture. The industry is working on membrane-based CO2 liquefaction to function alongside solvents and reduce the need to use steam, which isn't often available in cement plants. Brevik, Norway (Heidelberg) will be the first project to prove viability. Bigger post combustion projects are expected in Canada (Heidelberg) and Germany (Cemex).

Oxyfuel: Pure oxygen is injected into the kiln rather than air. This is a precombustion solution that requires plant modification as the process is integrated with the kiln. The concentration of CO2 in the exhaust gas rises to 70% or higher, making it easier to capture. The process is being tested by the Catch4Climate consortium on a project called CI4C at Schwenk's Mergelstetten plant in Germany. Multiple larger scale oxyfuel CCUS projects are expected to go live in 2027-28.

Calcium looping: This solution uses limestone or burnt lime to absorb CO2 from flue gases in a carbonator to create calcium carbonate. This is then transferred to a calciner where it releases CO2 for capture. This is in nascent stage and there are no planned industrial-scale projects due before 2030.

Direct separation: This process is also known as indirect calcination. The technology heats limestone directly, rather than in a calciner. This keeps process and manufacturing emissions separate, allowing the former to be captured. The solution was proven by Heidelberg Cement.

In addition, in the initial years, economics of CCUS may not be favourable with an estimated levelized cost of capture and storage is USD 60 – 120 per ton of CO2.[25]

Final energy consumption and energy mix in NZS

The split among different final energy sources is illustrated below. Biomass and green hydrogen are expected to substitute 20 – 25% of final energy demand by 2050.

[23] Thermal SEC: 3084 MJ/ton of clinker; Electrical SEC: 76 kWh/ton; Clinker to cement ratio is 0.70
[24] https://www.brevikccs.com/en
[25] https://www.iea.org/commentaries/is-carbon-capture-too-expensive

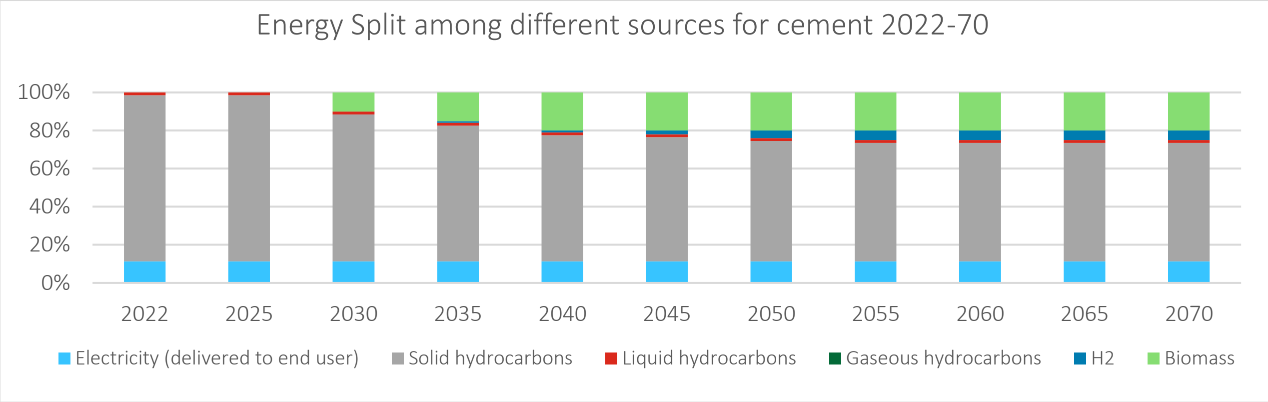


Figure 8: Fuel wise energy split for Cement, NZS

Final energy demand in the cement sector is expected to increase from ~240 TWh in 2022 to 300 – 320 TWh by 2030 and 800 – 850 TWh by 2050. Post 2050, energy demand is expected to be flat.

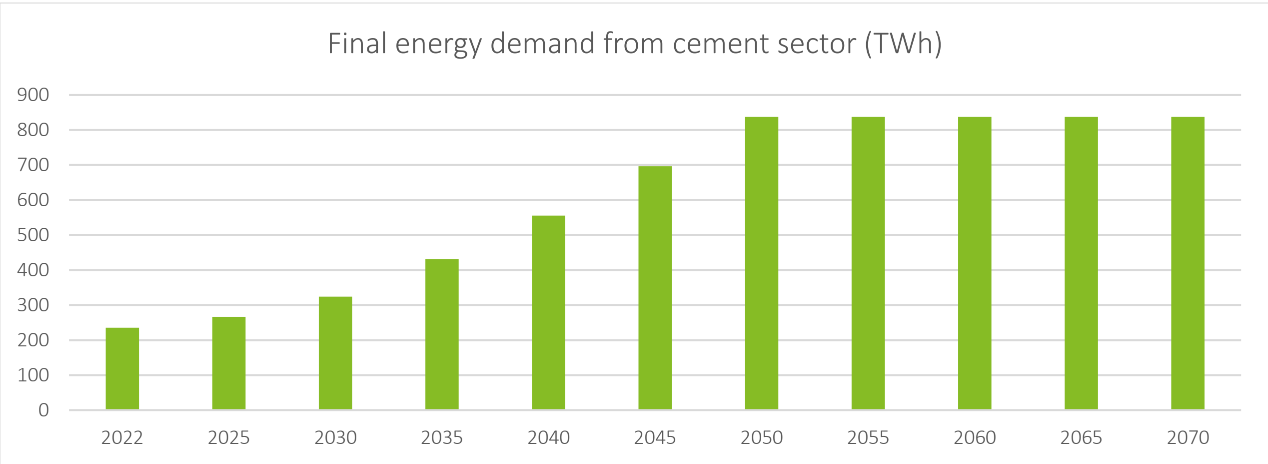


Figure 9: Final energy demand for Cement sector

Final energy consumption and energy mix in BAU

In BAU scenario, biomass penetration is expected to be lower than NZS; biomass penetration is likely to be limited to ~5% of total energy mix. However, considering performance of Indian cement manufacturers, specific energy consumption improvement will likely to be same in both NZS and BAU scenario. Green hydrogen penetration is considered within 5% only (same as NZS).

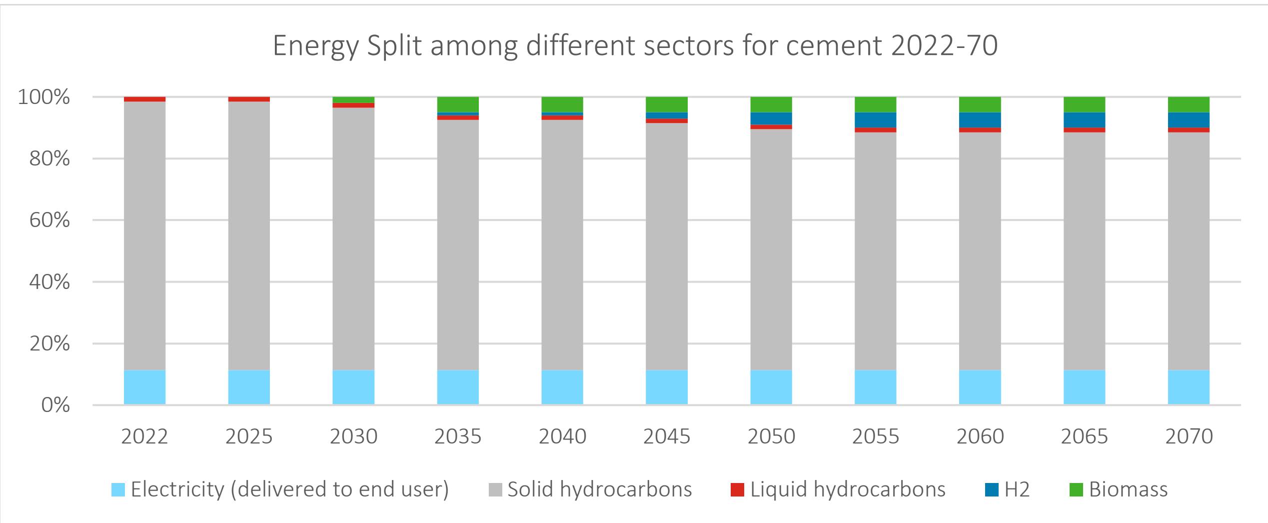


Figure 10: Fuel wise energy split for Cement sector, BAU

4.2.2 Steel sector

India is world's second largest producer of crude steel after China. The steel production capacity of the country has increased by over 45% since FY15[26]. In 2022, India's steel consumption was around 106 million tons, and the per capita steel consumption stood at 77 kgs, which is much lower than global average of 240 kg – 640 kg in China, 980 kg in South Korea, 310 kg in EU, 230 kg in Thailand, 130 kg in Vietnam and 110 kg in Brazil. The import of steel has gone down from 7.4 million tons in 2010 to 4.7 million tons in 2022. On the contrary, export of steel has increased from 4 million tons in 2010 to 18 million tons in 2022. Total consumption of steel has grown at a CAGR of 3.6% since 2010.

Steel demand is greatly influenced by construction activities and industrial manufacturing. In a growing developing economy, steel and cement demand are highly corelated. Based on the reference taken from China and few other countries, the demand model has considered a cement to steel production ration of 2.2 by 2050 and in the long term, by 2070, the ratio would decline to 2.0, driven by technological interventions in the construction industry. In addition, likewise cement, the steel sector future growth is also correlated with China's steel growth story between 2000 - 2020. With these assumptions, the steel demand is expected to grow at a rate of 6 - 7% till 2050 with the demand in 2050 reaching 600 - 650 million tons. Post 2050, demand growth rate is expected to decline, and the total demand may reach 700-750 million tons by 2070.

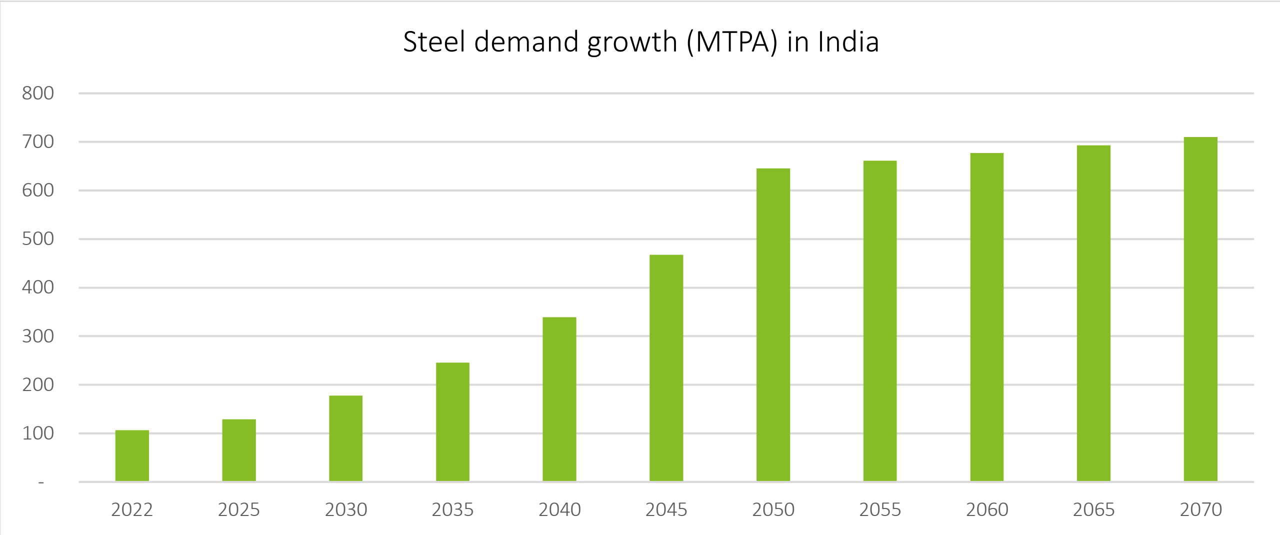


Figure 11: Projection of steel demand growth

Technology landscape

The study has assessed following major steelmaking pathways: Blast furnace-basic oxygen furnace (BF-BOF) route, Direct reduction of iron-induction furnace (DRI-IF) route, Direct reduction of iron-electric arc furnace (DRI-EAF) route, Scrap iron – induction furnace (Scrap-IF) and Direct reduction of iron by Hydrogen. In India, currently almost half of the steel is produced mostly through Blast furnace-basic oxygen furnace (BF-BOF) route; DRI route has a share of around 40-45% and remaining through Scrap-IF. However, of the large steel plants in India, nearly 70 percent are Blast Furnaces and Basic Oxygen Furnaces (BF-BOF).

The BOF route primarily uses hot metal and scrap to produce steel. In this process, the hot metal from the blast furnace is charged into the basic oxygen furnace along with some additives. Highly pure oxygen gas is injected into this furnace from the bottom, which further oxidizes the remaining carbon and other elements – such as silicon, manganese, phosphorus, and sulfur – to produce liquid steel with the desired carbon content. The liquid steel is typically cast into semifinished steel products such as slabs, blooms, and billets via the continuous casting route or teemed into large ingots.

The second most prevalent route of steel production is the Direct Reduced Iron (DRI) coupled with Electric Arc Furnace. The heart of the process lies in the direct reduction of iron oxide, achieved by heating the ore to high temperatures within a furnace and introducing a reducing gas such as carbon monoxide. This chemical reaction yields pure, solid metallic iron, paving the way for high-quality steel. Popular methods like the Midrex Process, HYL Process, and MIDREX® Shaft Furnace Technology showcase the versatility of DRI production. Noteworthy advantages include its lower greenhouse gas emissions, better energy efficiency, and the flexibility to adapt to varying production needs. DRI

[26] Ministry of Steel, Press release (access here)

finds its place as a vital feedstock for electric arc furnaces, ensuring a cleaner, more sustainable path for steelmaking. India extensively uses coal-based DRI as opposed to natural gas-based DRI, which is more common across the world.

Electric furnaces are of two types: electric arc furnaces (EAF) and induction furnaces (IF). These furnaces produce the heat required to melt, primarily, sponge iron and/or scrap steel, and any required additives, to produce crude steel. Some EAFs in India take a mix of hot metal, sponge iron, and scrap, as the charge, depending on the availability of scrap, the required composition of steel, and a few other process parameters. Typically, EAFs are employed by larger plants, while smaller plants and independent scrap steel processors use IFs. While IFs are available in smaller sizes and are more economical to install, there is little control over the resultant steel quality, as IFs cannot refine steel.

The Steel industry has a share of ~10 percent in the total emission in the country. India's steel industry is more energy and emissions intensive than international benchmarks due to the following factors:

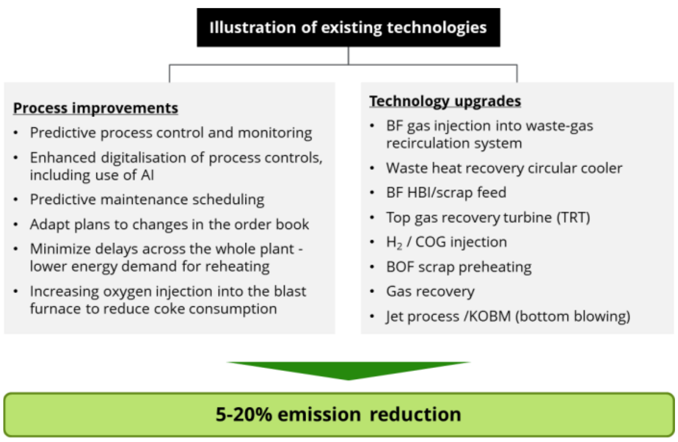
- Nearly 50% of steel production is through BF route where coal is the major source of energy
- Presence of many small production facilities
- Heavy reliance on coal for DRI furnaces
- Low quality of domestic coal
- Relatively old stock of blast furnaces in the country
- A low proportion of scrap in the total metallic input

According to the IEA[27], the Indian steel sector's emission intensity is 2.2–2.4t of CO2 per tonne of crude steel produced, which is higher than the international benchmark. Of the direct emissions, coal contributes nearly 90 percent of the total emissions mainly because of its use in coke ovens, blast furnaces, and coal-based direct reduction furnaces.

In a net-zero scenario, Steel sector decarbonization is crucial. **Two (2) major drivers for steel sector decarbonization are Hydrogen based DRI (H2-DRI) coupled with EAF and increased circularity by recycling scrap steel**. In the H2-DRI process, iron ore undergoes direct reduction at high temperature using hydrogen gas as the reducing agent, typically sourced from renewable or low-carbon hydrogen sources. This process emits only water vapor as a byproduct, drastically reducing greenhouse gas emissions compared to traditional methods. Hydrogen-based DRI not only offers a cleaner alternative but also ensures very high energy efficiency. As the industry pivots towards decarbonization, this technology stands as a beacon of progress, aligning steelmaking with the goals of a carbon-neutral future. Direct injection of Hydrogen in the blast furnace is likely to be limited to smaller scale[28]. Another important lever is increased use of scrap steel in Induction Furnace (IF). India is expected to generate significant amount of steel scrap in the coming decades, which can be utilized in induction furnaces to produce crude steel.

Due to unfavourable economics, uptake of large scale H2-DRI is expected only after 2035. In the Net Zero scenario, India is assumed to start commercial H2-DRI production from 2035 and gradually increase its share. By 2045, it is assumed that 80% of incremental production will be through H2-DRI and rest 20% through scrap recycling. No new capacity addition of BF-BOF or fossil fuel based DRI is expected after 2040. All blast furnaces and fossil based DRI units are expected to be retired between 2065-70. In addition, all new blast furnaces should be designed for 5-10% biomass co-firing and the existing units be retrofitted for 5-10% biomass firing to replace highly polluting coking coal.

Traditional energy efficiency measures and process improvement related measures will also be critical in the operating BF-BOFs and DRI units. They have potential of 5-20% emission reduction, based on current level of penetration.



In the Indian context, only limited retrofitting of BF-BOF or DRI units with CCS is considered in the net zero scenario due to challenges associated with storage of CO2, economics of CCS and limited downstream application with captured carbon. Cost of carbon capture for steel industry varies between USD 45 – 100 per tCO2. While there are few pilot scale plants currently operating, commercial scale adoption is not expected. However, blast furnaces are long-lived assets with life of nearly 40 years. Hence, there may be a need to retrofit the residual capacity of BF-BOF furnaces in 2070 in order to meet the net zero goal.

[27] Iron and Steel technology roadmap: IEA

[28] The optimal amount of hydrogen and its impact on furnace performance need further investigation. There are also challenges in scaling up hydrogen injection from experiments to real-world operations.

Final energy consumption and energy mix in NZS

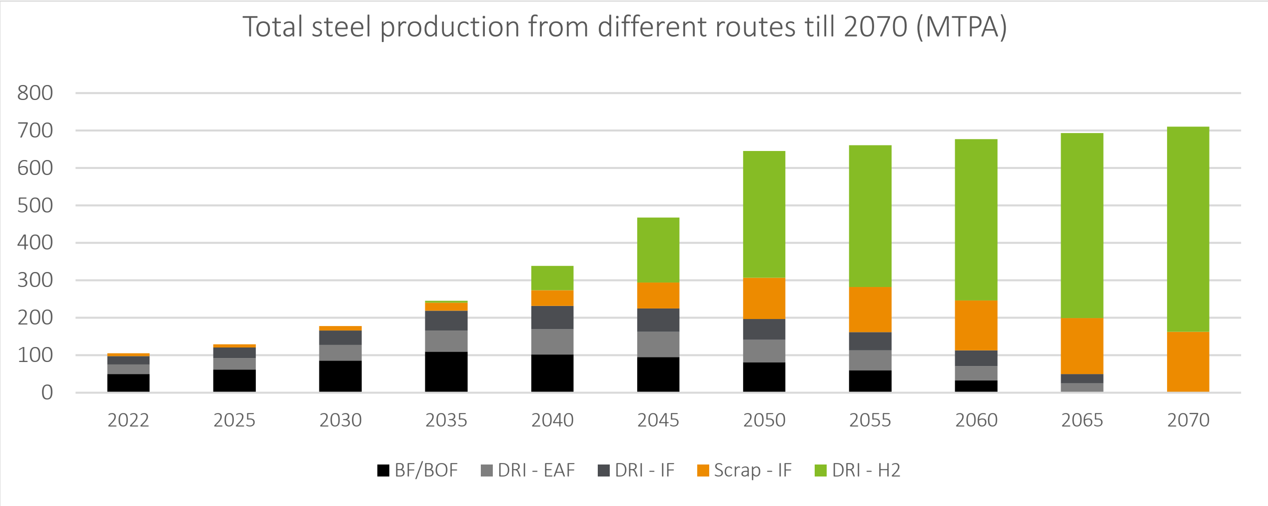


Figure 12: Total steel production from different technological routes till 2070 (MTPA), NZS

Final energy demand in the steel sector is expected to increase from ~600 TWh in 2022 to 2300 – 2400 TWh by 2050 and 2100 - 2200 TWh by 2070. Energy consumption is expected to be plateaued despite increase in production due to higher energy efficiency induced through recycling and adoption of H2-DRI.

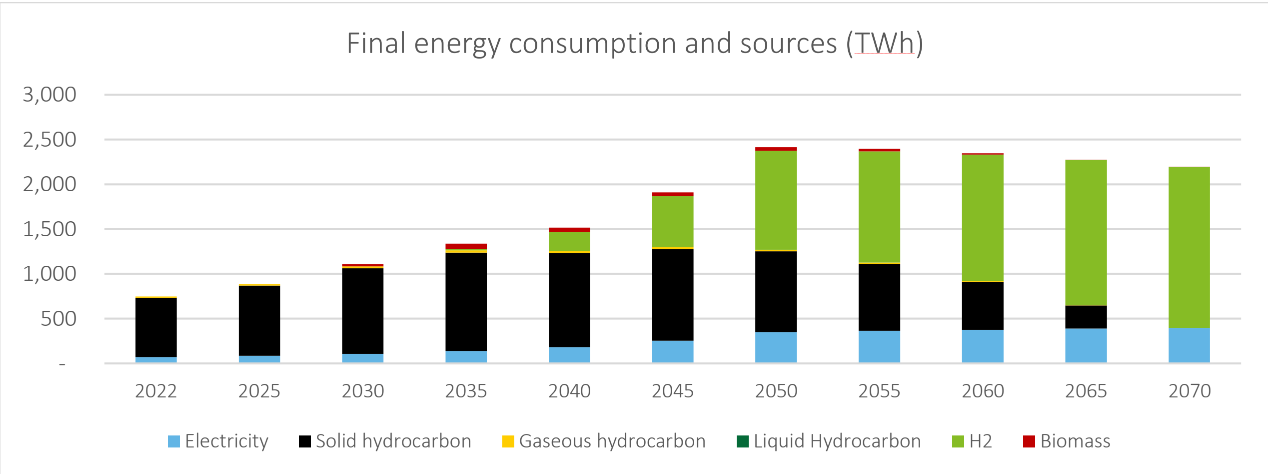


Figure 13: Final energy consumption for Steel sector, NZS

Existing blast furnaces and coal based DRI units are expected to start retiring from 2040 and being replaced by H2-DRI and Scrap-based Induction furnaces.

Globally, most of the large steel manufacturers are committed to achieve net zero by 2050, by replacing or retrofitting existing BF-BOF and coal or gas-based DRI with H2 DRI or gas based DRI with CCS

Company name	Country	Net zero commitment
Thyssenkrupp	Germany	Net zero by 2050
Arcelor Mittal	Luxembourg	Net zero by 2050, and, in Europe, the target is to reduce CO2 emissions by 30% by 2030 over 2018.
Salzgitter	Germany	No net zero target; 50% emission reduction by 2030
Tata Steel NL	Netherland	Net zero by 2045
Emirates Steel	UAE	Net zero by 2050
US Steel	USA	Net zero by 2050
POSCO	Korea	Net zero by 2050
Nippon Steel	Japan	Net zero by 2050; 30% emission reduction by 2030 from 2013 level

Company name	Country	Net zero commitment
JFE	Japan	Net zero by 2050; 30% emission reduction by 2030 from 2013 level

Source: Company announcements

Final energy consumption and energy mix in BAU

In the BAU scenario, Steel sector is not expected to be decarbonized fully. It is expected that capacity addition of BF-BOF and coal based DRI will continue to happen till 2050. By 2070, share of H2-DRI is expected to be in the range of 25 – 30% while scrap-based steel melting may contribute another 20%. Therefore, 50 – 60% of steel production is expected to use fossil fuel in 2070.

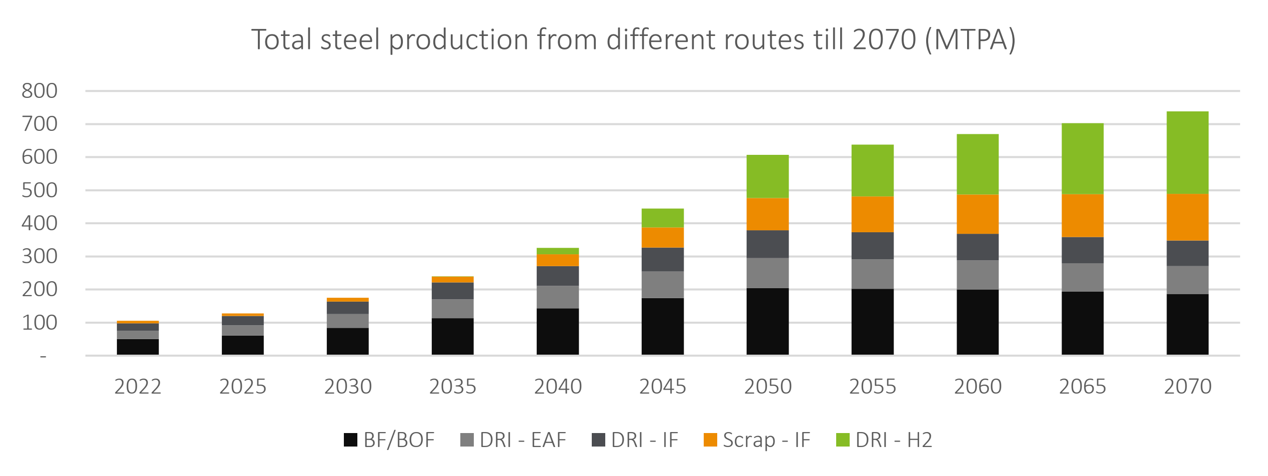


Figure 14: Total steel production from different routes till 2070, BAU

Final energy demand in the steel sector is expected to increase from ~600 TWh in 2022 to 2300 – 2400 TWh by 2050 and 2600 - 2700 TWh by 2070.

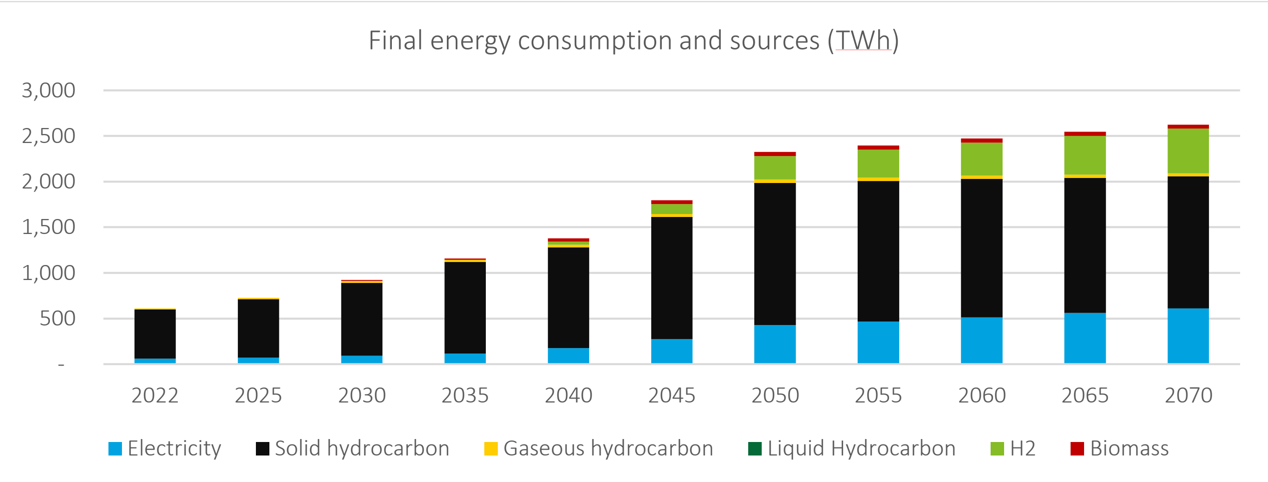


Figure 15: Final energy demand for steel sector, BAU

Full decarbonization of the steel sector would require rapid uptake of H2-DRI and adoption of circularity in steel making process. It is expected that H2-DRI will gain industry acceptance by 2035, and post-2035, large scale adoption is expected. However, availability of high-grade iron ore (64%+ Fe) required for H2-DRI operation and continuous supply of steel scrap should be ensured to enable above two technologies.

4.2.3 Aluminium sector

India is the second largest aluminium producer in the world, after China. However, the gap between India and China's production of primary aluminium is significant – in FY 22, China produced nearly 40 Million Tons whereas India's production was limited to ~4 Million Tons. India's per capita consumption of aluminium in 2022 stood at 4.1 kg as compared to the per capita global consumption of 14 kg. In 2022, per capita consumption of Aluminium in China was 28 kg, in US – 15 kg, in EU – 14 kg and in Korea – 42 kg.

India's primary aluminium production in the last decade between 2010-22 has grown at a CAGR of 8.4% while the consumption has grown at a CAGR of ~4.6%. The industry is characterized with large amount of import of scrap to produce scrap based secondary aluminium and significant export of primary aluminium. Low import duty of 2.5% is one of the major drivers for scrap import.

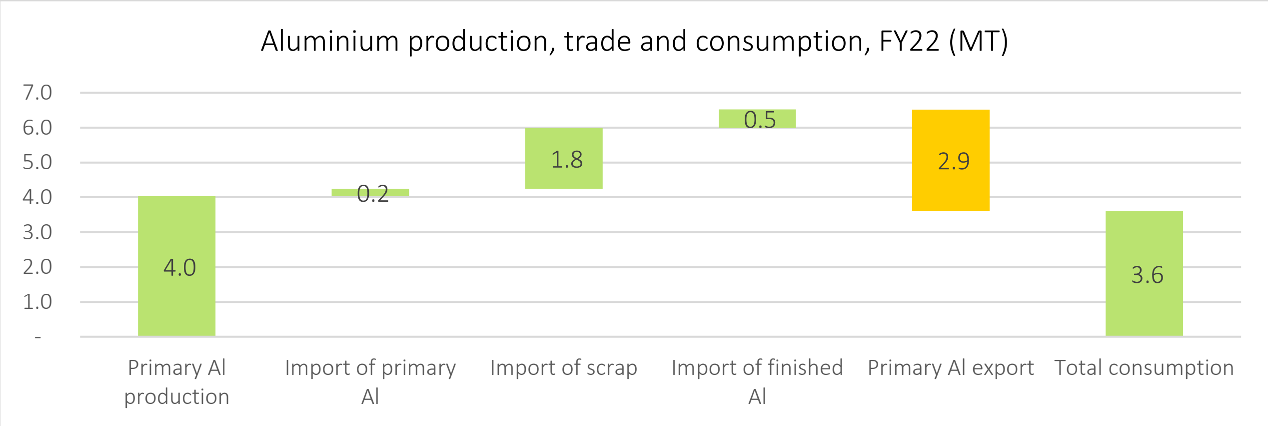


Figure 16: Aluminium production, trade and consumption, FY22

Going forward, industrial demand for aluminium is expected to increase multi-fold, driven by preference towards light weight material in manufacturing sector, EV manufacturing and growth in industrial packaging sector. The per capita aluminium demand in India is expected to reach around 14-15 kg by 2050, which is in line with global average as well as current demand in EU, USA and Turkey. After 2050, the demand growth is expected to slow down, and the production is expected to grow at a rate of 1-2% every year till 2070. Aluminium production in India is expected to grow steadily from ~5.8 Million Ton in 2022[29] to 11-12 Million Ton by 2030, 22 – 24 Million Ton by 2050, and 32 – 36 Million Ton by 2070.

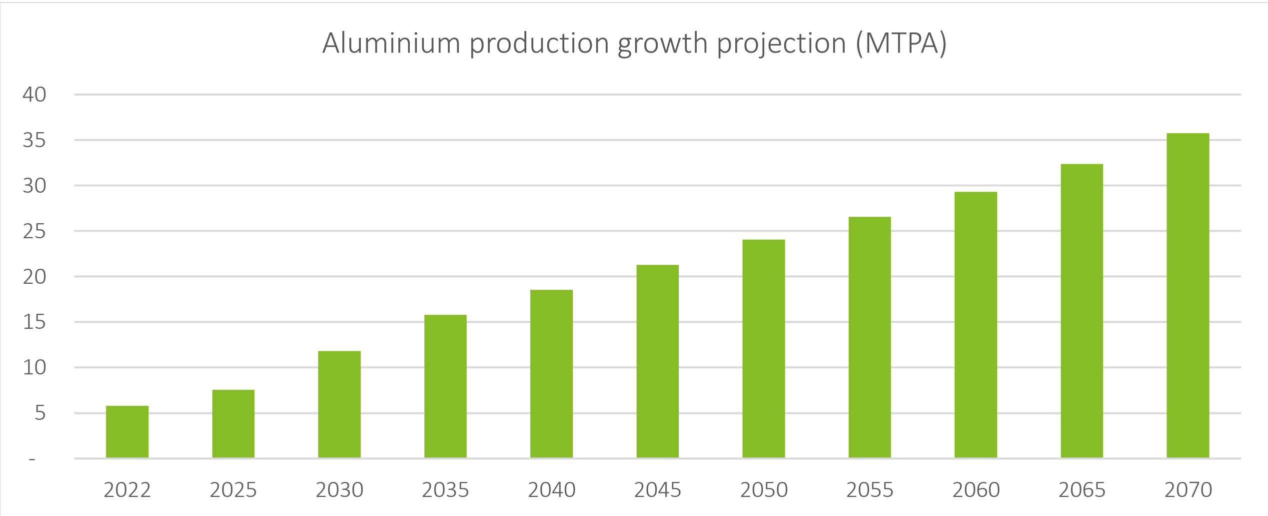


Figure 17: Aluminium production growth projection

Technology landscape

Aluminium production is an energy-intensive process. In India, carbon intensity of primary aluminium production is 17–19 MT CO_2 per ton of production, due to the significant use of coal in generating captive power. In the primary production process, alumina refining and smelting are the most energy-intensive processes, accounting for more than 90 percent of direct emission. Future of aluminium production will be driven by adoption of renewable energy for the smelting process, fuel switch in the alumina refining process and adoption of novel low-emission technologies, such as "inert anode technology". Going forward, secondary aluminium production is also expected to increase, which is 100% electrified and consumes 90% less energy than primary aluminium production.

Energy efficiency will play an important role in reduction in specific energy consumption of primary aluminium production. In the long term, based on global references (e.g. Norsk Hydro, Norway), **the SEC is expected to reduce from 19.6 TWh per MT of production in 2022 to ~18.90 TWh per MT by 2040.**

[29] This includes both Primary and Secondary Aluminum – 4 MT Primary and 1.8 MT secondary Al

Final energy consumption and energy mix in NZS and BAU

Final energy consumption for the Aluminium sector is expected to increase from ~83 TWh in 2022 to 140 – 150 TWh in 2030, 230 – 250 TWh by 2050, and 300 – 330 TWh by 2070.

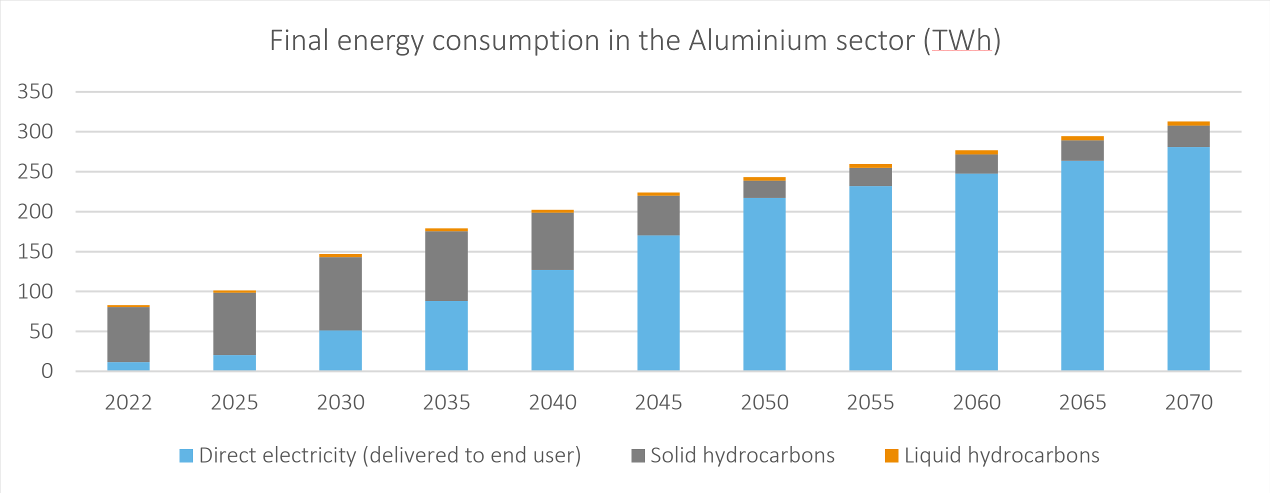


Figure 18: Final energy consumption for Aluminum

Note: Coal used for captive power generation is considered under the head of solid hydrocarbon

In future, the entire electricity demand, which is ~90% of total energy demand, can be decarbonized by using renewable energy; another ~10% is likely to be met through coal which is required for process heat in alumina refining process. As an intermediate measure, biomass can be cofired with coal in captive power plant if the supply chain can be ensured.

In the BAU scenario also, similar SEC improvement and grid electrification is expected due to maturity of technology and increasing reliability of the grid.

4.2.4 Fertilizer sector

India is world's second largest consumer and fourth largest producer of fertilizers[30]. India's fertilizer production has grown at a CAGR of 1.7% with an annual production of 35 million tons in 2010 increasing to 43 million tons in 2022. Government initiatives like direct income support schemes from both central and state governments have also bolstered farmer liquidity, enhancing their ability to invest in fertilizers.

Future production growth scenario for the fertilizer industry is likely to be subdued due to increased efficiency in agricultural processes and advent of nano fertilizers. Future growth is assumed at a CAGR of 1% till 2050 and the growth saturates after 2050[31]. India's fertilizer demand stands at 64 million tons in 2022 and the future production is expected to be around 80 - 90 million tons by 2050.

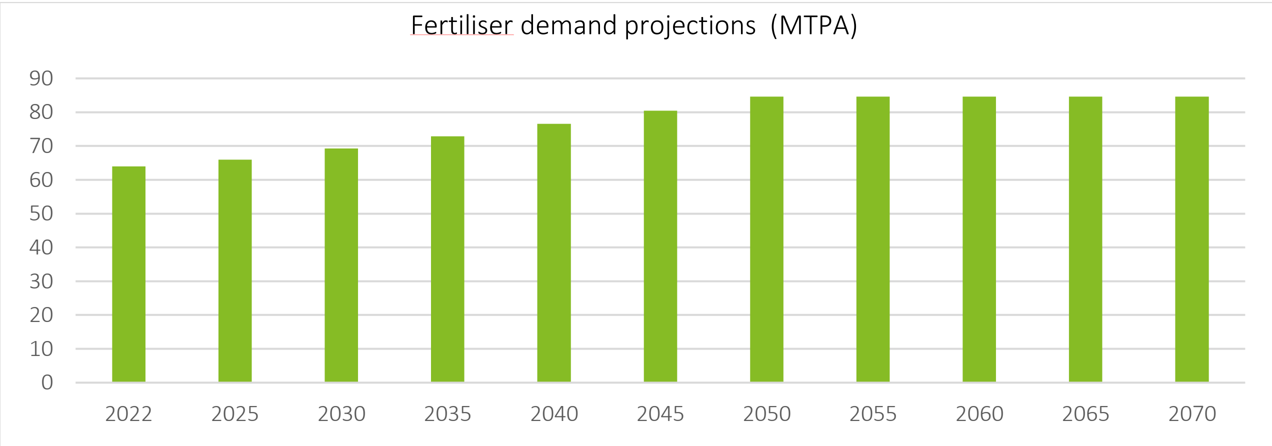


Figure 19: Fertilizer demand projection

[30] USDA Report (access here)

[31] In reality, fertilizer production growth has not been linear

Technology landscape

The industry largely has three types of fertilizers – Nitrogenous fertilizers, Phosphorus and Potassium based fertilizers. Product wise chemical fertilizers are classified into Urea, Diammonium Phosphate (DAP), Single Super Phosphate (SSP), Muriate of Potash (MOP) and other Complex fertilizers like Calcium Ammonium Nitrate (CAN) and various grades of NPK Fertilizers (Fertilizers having different grades of Nitrogen (N), Phosphorus (P), and Potassium (K)). Urea is the most consumed fertilizer in India; nitrogenous fertilizer and DAP constitute more than 90% fertilizer consumption in India.

Currently, in fertilizer production process, gaseous hydrocarbons (natural gas) accounts for the maximum amount of energy usage, with a share of more than 90%. In manufacturing of nitrogenous fertilizer, Ammonia is a major input ingredient. The ammonia production process is emission intensive as it uses natural gas as the feedstock to produce hydrogen. Theoretically, each ton of ammonia produced emits 2.0–2.2 ton of CO2 into the atmosphere. In India, total consumption of ammonia is 18–19 million tons; ~95 percent of this is used in the fertiliser industry.[32]

Green Hydrogen can decarbonise 100 percent ammonia required for DAP and complex fertilisers (NPK) production. In case of urea, decarbonisation potential is likely to be limited to 15–20 percent, due to process challenges. Nearly 75% of nitrogen fertilizer consumption in India is in the form of urea (NH_2CONH_2), which has carbon it's molecular structure. Typically, the carbon in urea's molecule is obtained by re-using the carbon dioxide (CO2) emitted by natural gas-based ammonia production (later the CO2 gets emitted in the field when mixed with soil). Using CO2 from other sources is theoretically an option, but it implies a prohibitive cost increase in addition to green ammonia costs. Therefore, integrated ammonia-urea plants are difficult to be completely decarbonized using green hydrogen. Other nitrogen fertilizers, such as NPK compounds, ammonium phosphate, ammonium sulphate etc. can be decarbonized by substituting grey hydrogen with green hydrogen for ammonia production. **However, in future, there is a possibility of DAP and complex fertilisers substituting Urea to address the emission related challenges.**

Currently, share of direct electricity in fertilizer production is 2 – 3%, which can be decarbonized through sourcing of renewable energy.

Final energy consumption and energy mix in NZS

In a net-zero scenario, green hydrogen is expected to contribute 35 – 40% of final energy mix by 2050 and 70 – 80% by 2070[33], as illustrated below.

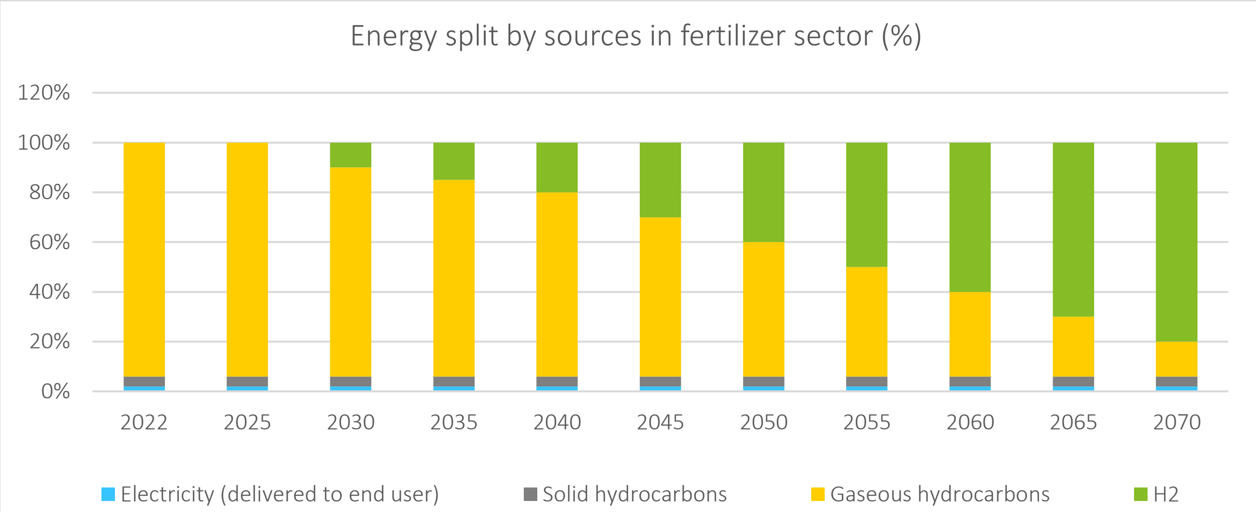


Figure 20: Energy split by sources in fertilizer sector

With implementation of energy efficiency measures and adoption of green hydrogen, the specific energy consumption in the fertilizer industry is expected to decline from 6.90 TWh per million tons (MT) of production in 2022 to 6.40 – 6.50 TWh/MT by 2050 and saturate at this level in the long term.

The final energy consumption in the fertilizer industry is expected to increase from ~300 TWh in 2022 to 500 – 550 TWh by 2050. Technologies such as Carbon capture and adoption of low-carbon hydrogen will act as a catalyst in this sector.

[32] Industry input; Secondary research
[33] This substitution would be possible due to two reasons – 1) there will be a shift from Urea to NPK and 2) external sources of low-cost CO2 would be available due to maturity of CCUS technology; alternatively, fertilizer companies may also consider deploying Carbon Capture technology while continuing with their SMR units.

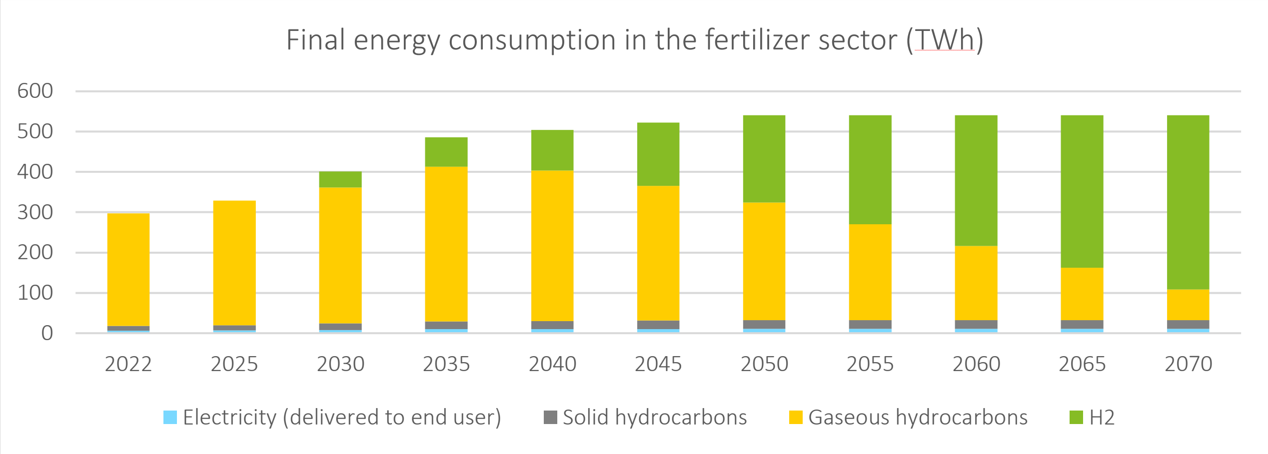


Figure 21: Final energy consumption in the fertilizer sector, NZS

Final energy consumption and energy mix in BAU

In BAU scenario, green hydrogen penetration is expected to be limited to 20 – 25% by 2050 and 25 – 30% by 2070 due to challenges associated with process modification, especially Urea production. In BAU scenario, Urea is expected to continue as the mainstay fertilizer in the country. As a result, Natural Gas will continue to be the largest contributor of the energy mix.

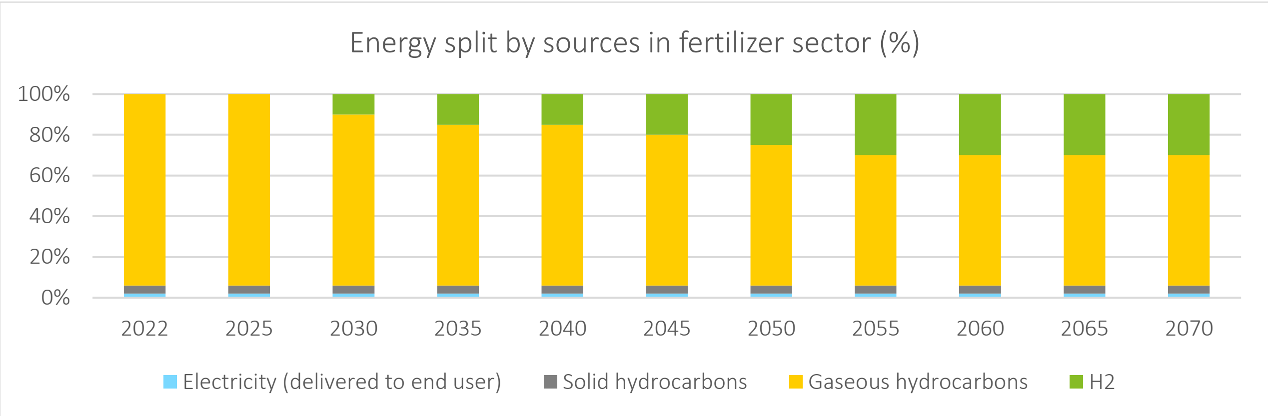


Figure 22: Energy split by sources in fertilizer sector, BAU

In BAU scenario, the final energy consumption in the fertilizer industry is expected to increase from ~300 TWh in 2022 to 550 – 600 TWh by 2050.

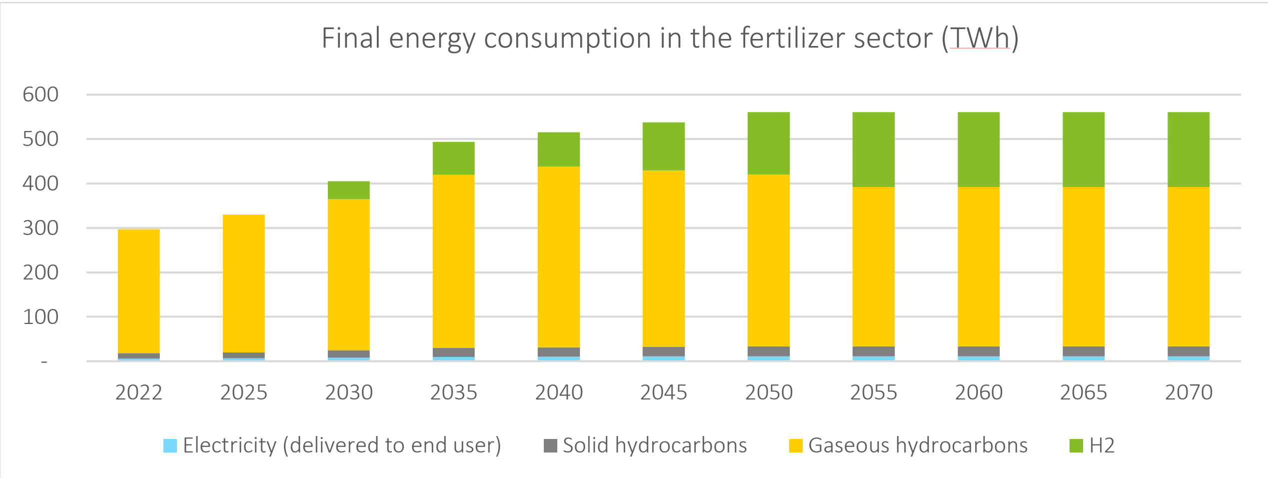


Figure 23: Final energy consumption in Fertilizer sector, BAU

4.2.5 Textile sector

India is one of the major textiles hubs of the world; it is the world's second largest producer of textiles and garments and has nearly 4% share in the global textile market[34]. With the emergence of other more economical textile manufacturing hubs in other developing nations, such as Bangladesh and Vietnam, the production growth is expected to steadily decline in the long term. However, the specific energy consumption of the sector is expected to see sharp decline (15 – 30%) due to various energy efficiency measures and higher electrification. The sector is expected to exhibit a growth of 3.5 – 4.0% between 2024 – 30, 2 – 3% between 2030 – 50 and 1 – 2% between 2050 – 70.

Final energy consumption and energy mix in NZS

Only about one-third of the final energy demand of the segment is met through electricity currently, fossil-fuels are still the major source of energy with nearly 70% share in total energy mix, which is used for generating process steam. In the long run, with technological innovation in the space of electric boiler, nearly 70 – 80% of heating requirement (mainly in processes like drying and heat-setting) can be electrified.

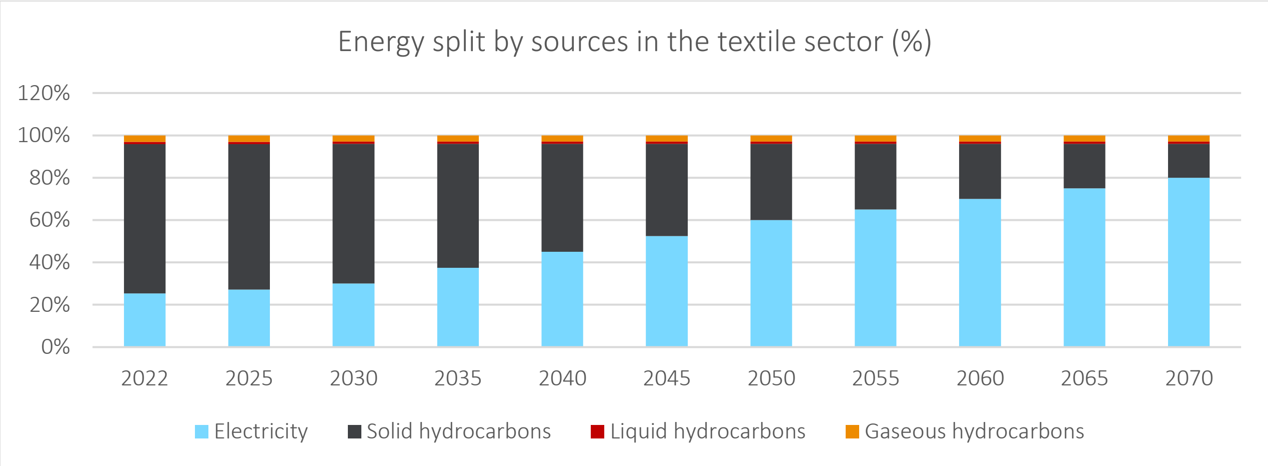


Figure 24: Energy split by sources for textile sector

The final energy consumption in the textile sector is expected to increase from ~160 TWh in 2022 to 270 – 300 TWh in 2050 and 330 – 350 TWh in 2070. Gradually, share of coal will decline as the electrification will intensify.

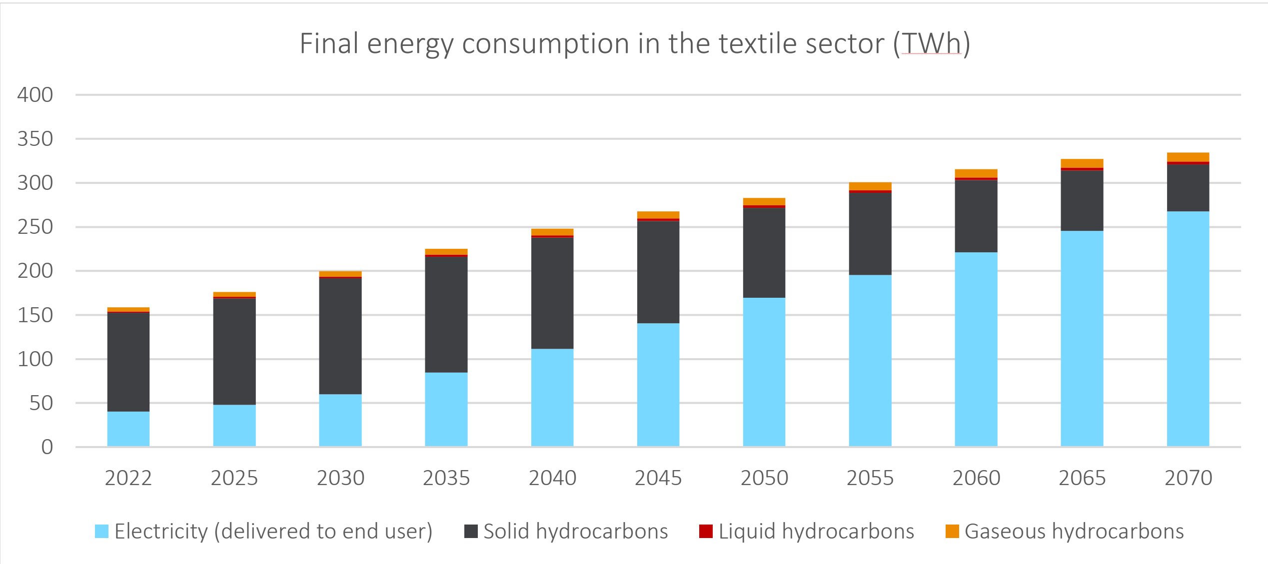


Figure 25: Final energy consumption in the textile sector

Final energy consumption and energy mix in BAU

In the BAU scenario, the textile sector may see 5 – 10% lower electrification of heat. The final energy consumption is expected to increase from ~160 TWh in 2022 to 300 – 320 TWh in 2050 and 350 – 380 TWh in 2070. Gradually, share

[34] CII (access here)

of coal will decline as the electrification will intensify. The traction towards electrification is already visible from the large players.

4.2.6 Chlor-alkali sector

The chlor-alkali industry consists of the production of three inorganic chemicals - Caustic Soda (NaOH), Chlorine (Cl2) and Soda Ash (Na2CO3). Caustic soda and chlorine are produced simultaneously while soda ash is produced during a different process. India's chlor-alkali industry has grown at a CAGR of ~3% over the last decade with production increased from 2.4 million tons in 2011 to ~3.2 million tons in 2022. With growth in the Aluminium, Pulp & Paper, Textile and other chemical sectors (where soda ash and caustic soda are used as feedstock), the chlor-alkali sector is expected to witness a decent growth over next few decades. Production growth from 2024 – 2050 is assumed at a rate of 2.5 – 3.0%.

The specific energy consumption of the segment is expected to decline from 3 TWh/million tons of chemical production in 2022 to 2.20 TWH/MT by 2070, driven by higher electrification and increased energy efficiency. This sector holds potential for nearly 100% electrification by electrifying the entire the process heat generation.

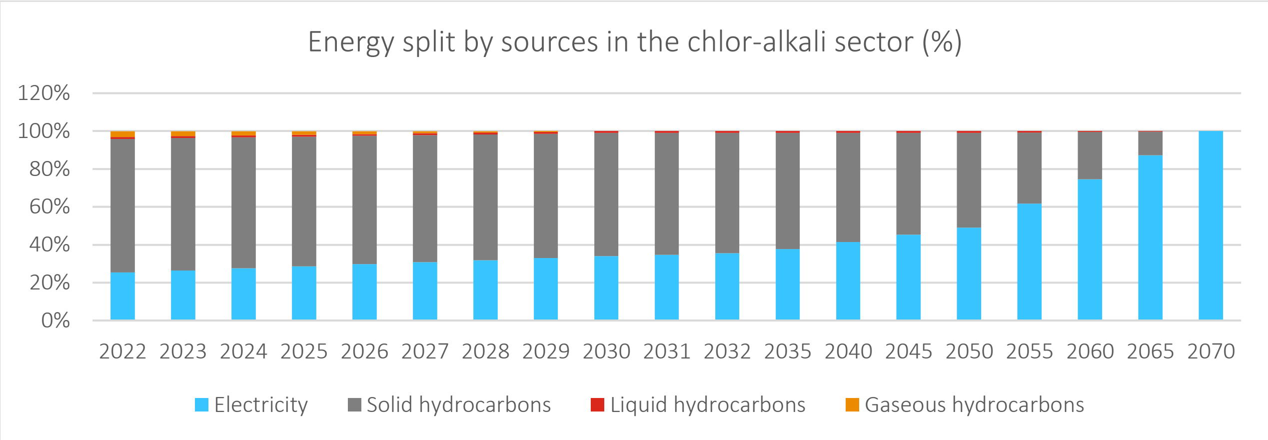


Figure 26: Energy split by sources in the chlor-alkali industry

The final energy consumption in the sector is expected to increase from ~10 TWh in 2022 to 16-18 TWh by 2050 and it may further reduce due to increased electrification.

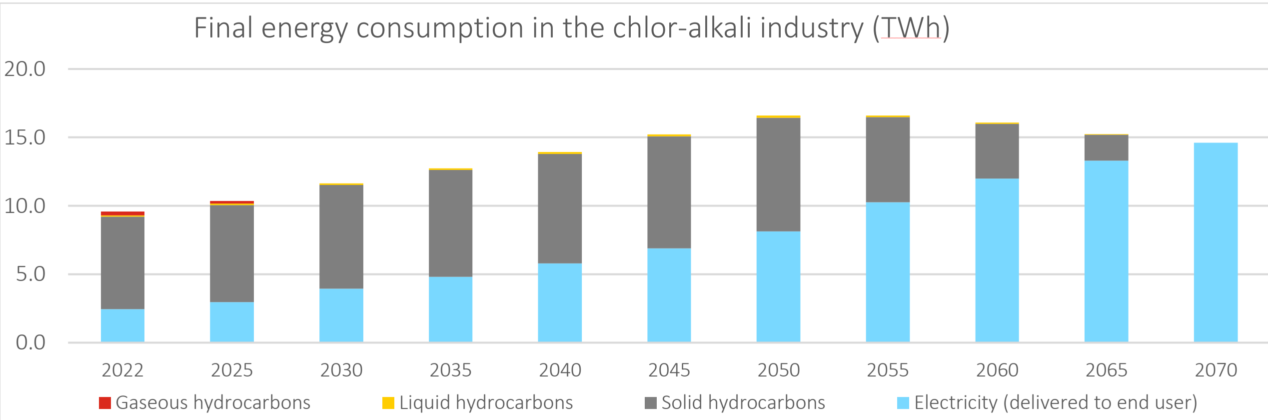


Figure 27: Final energy consumption in the chlor-alkali industry

4.2.7 Refineries

The energy demand in the refineries is a function of the total liquid hydrocarbon consumption. For example, gas demand in the refineries is nearly 3% of the total liquid hydrocarbon consumption in energy terms. In addition, internal consumption of liquid hydrocarbons in the refineries is nearly 6% of the total liquid hydrocarbon demand of the country. In 2022, around 40-45 TWh (~4 Mtoe) of liquid hydrocarbons were needed to produce petrochemicals.

Final energy consumption and energy mix in NZS

Final energy consumption by the refinery sector is expected to peak around 2035 – 40, rising to 330 – 350 TWh from ~270 TWh in 2022. From 2040 onwards, the energy consumption is expected to decline driven by increasing focus towards low carbon fuel in the transportation sector.

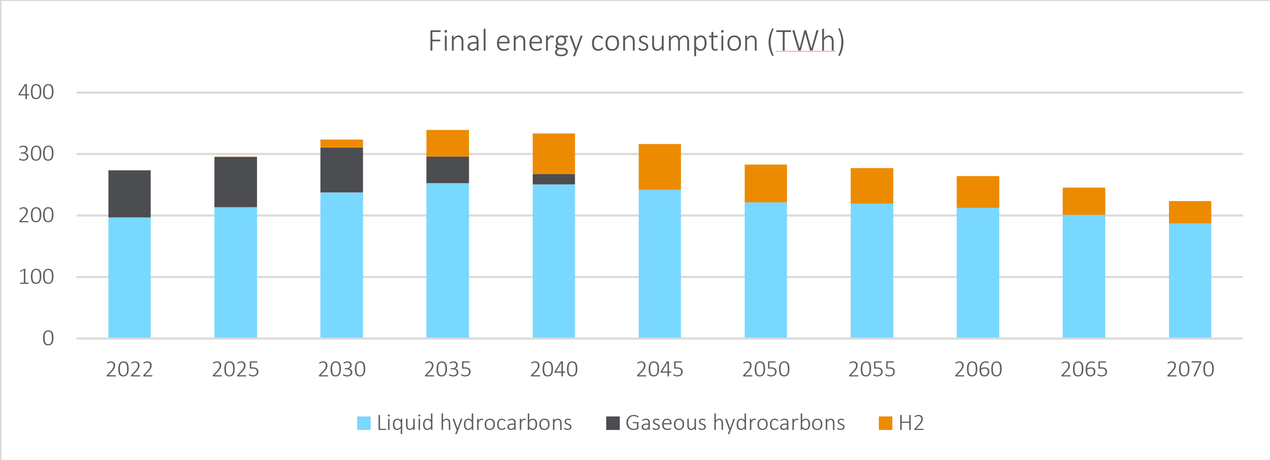


Figure 28: Final energy consumption for Refineries, NZS

Technology landscape

With around 250 MTPA refining capacity, India is the second largest refiner in Asia and the fourth largest in the world (after USA, China and Russia). The refinery industry in India currently processes a large amount of crude oil, with final products being used in transport and industry. Crude oil accounts for around 30% of the primary energy demand in the country, with more than 80% of it being imported. Hydrogen is mainly used for desulphurisation, with different products allowing different levels of sulphur, based on regulations and industry requirements. The demand for hydrogen increases with the requirement of lower sulphur content in the refined products. New regulations and policies (such as the BS-VI Standards) mandate lower sulphur requirement in transportation fuels and **this is expected to be one of the key drivers for increase in demand for hydrogen in this sector.**

In refineries, hydrogen is predominantly used in two chemical processes:

- **Hydrotreating** – It involves mixing a hydrocarbon feedstock with hydrogen and a catalyst to remove sulphur and nitrogen.
- **Hydrocracking** – It involves mixing a heavy hydrocarbon feedstock with hydrogen in the presence of a catalyst, to crack into lighter fractions for use as a blend-stock into jet fuel (kerosene) or diesel (distillate) or for use in fluid catalytic cracking (gasoil).

In earlier years, naphtha was the main fuel for producing hydrogen, which was used for hydrotreating and hydrocracking processes. Over time, naptha has been replaced by natural gas reformation. The natural gas reforming units are typically built on-site to meet the overall demand for hydrogen at the refinery over the course of its lifetime. The illustration below depicts the hydrogen value chain in the refinery, major consumption points as well as the overall process flow.

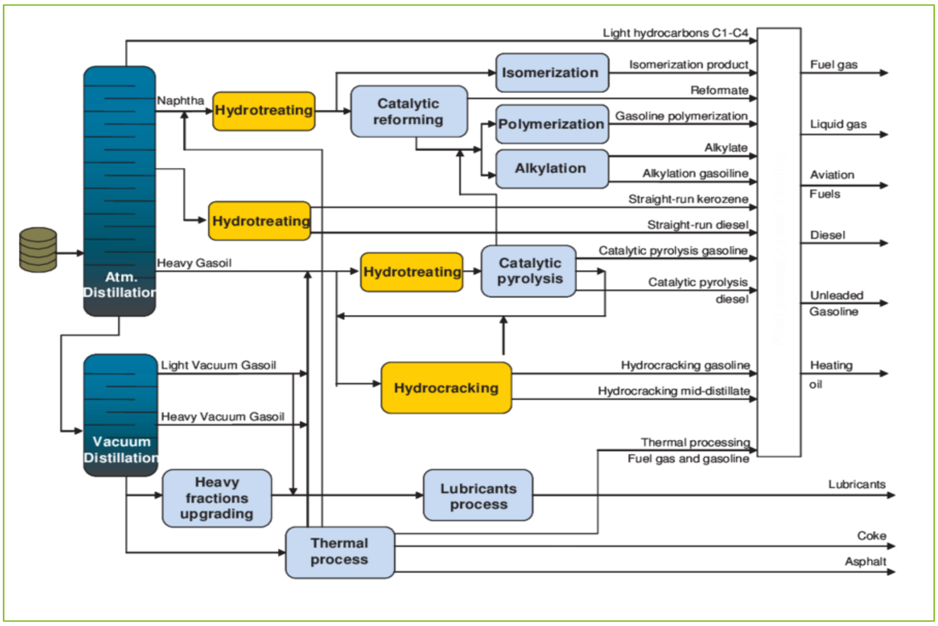


Image source: Sciencedirect

Adoption of green hydrogen by replacing grey hydrogen (NG or naptha based) for hydro-treating and hydro-cracking process could be an important decarbonization lever for the industry. While adoption of green hydrogen is expected to start around 2030, 100% penetration is expected around 2045 – 50.

Final energy consumption and energy mix in BAU

In the BAU scenario, penetration of green hydrogen is expected to be limited to 25-30% by 2050 and 40-45% by 2070. Also, final energy consumption in the refinery sector in BAU scenario is expected to be higher than NZS due to higher demand of liquid hydrocarbon.

Final energy consumption is expected to grow to 500 – 550 TWh by 2050 and 450 – 500 TWh by 2070

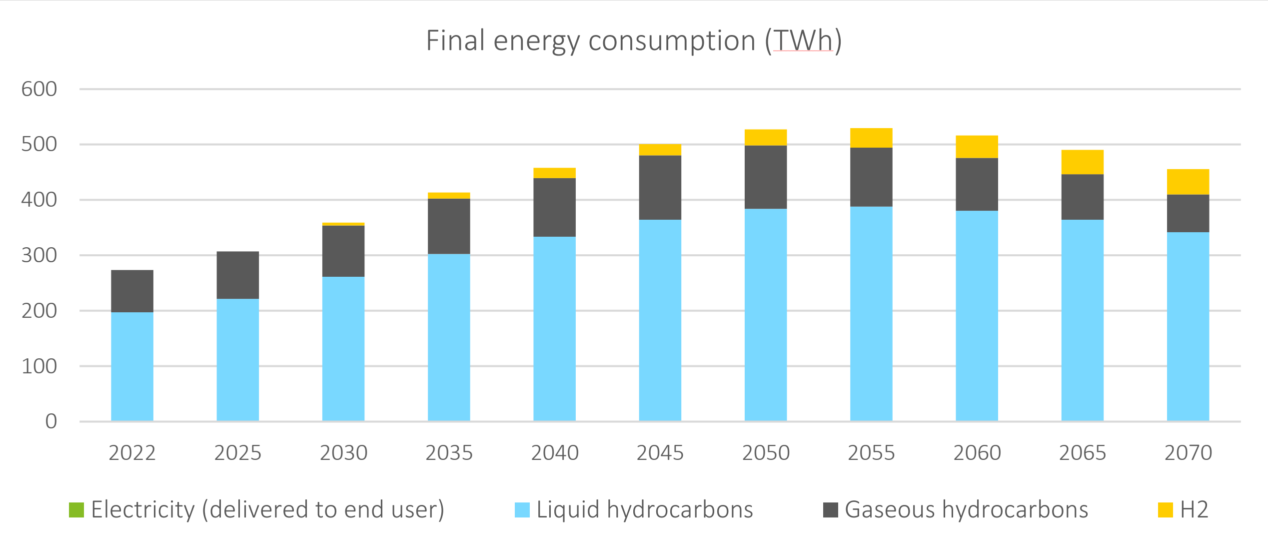


Figure 29: Final energy consumption in Refineries, BAU

4.2.8 Paper and pulp industries

India is one of the world's largest producers of paper and produces around 4% of the world's paper[35]. India's current installed capacity is ~27 Million Tons and produced ~22 Million Tons in 2022. India's per capita paper consumption is ~14 kg compared to a global average of ~57 kg. Driven by the growth of packaging industry, India's paper consumption is expected to grow multi-fold in the future - the per capita consumption may increase to 30 – 32 kg by 2050 (50 – 55 Million Ton) and has potential to reach 45 - 50 kg by 2070 (70 – 75 Million Ton).

The industry has witnessed significant improvement in energy efficiency in the last one decade. However, based on globally available best practices, there is a potential of 15-20% reduction in Specific Energy Consumption (SEC) in India's paper industry. **The decline in SEC will be underpinned by increased electrification of heat, penetration of energy efficient equipment and drives, recovery of waste heat and use of recycled paper**. The SEC is expected to decline to 6.20 TWh per Million ton of production in 2050 from 6.50 TWh per Million ton in 2020.

Presently, the energy requirement in the sector is mostly met by fossil fuels with a share of 80-85% and remaining by electricity. In the long term, electrification will increase and biomass is expected play a pivotal role in replacing the fossil fuel (mainly coal).

Final energy consumption and energy mix in NZS and BAU

The final energy consumption in the paper industry is expected to grow form ~140 TWh in 2022 to 360 - 380 TWh by 2070. Share of biomass may reach 20% of final energy consumption by 2050 while share of electricity would increase incrementally.

[35] UNIDO Report (access here)

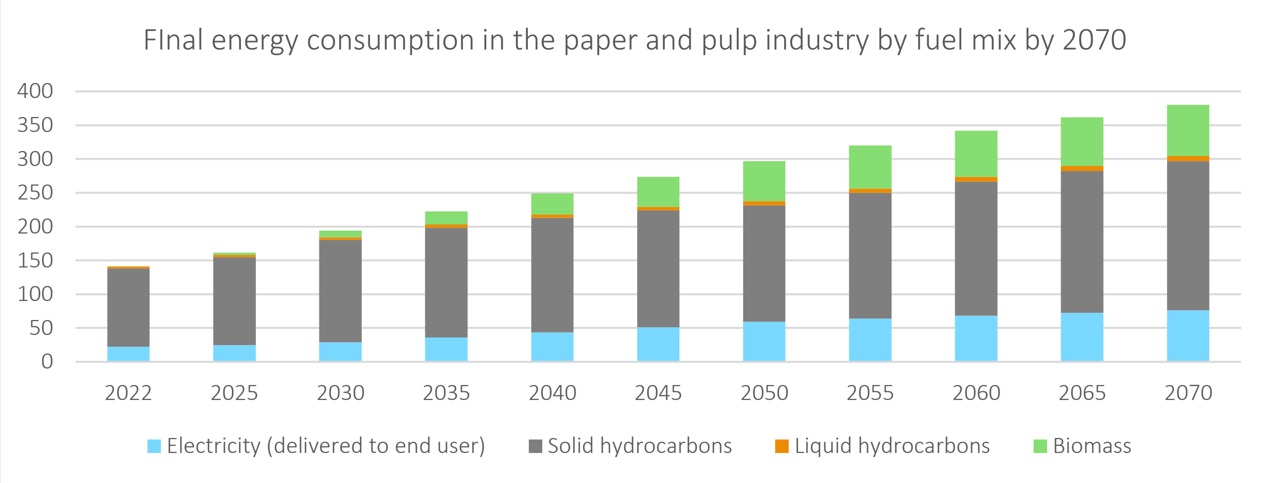


Figure 30: Final energy consumption in the paper and pulp industry

Similar improvement in SEC and energy mix is assumed for BAU scenario also.

4.2.9 Other industries

The energy consumption by all the remaining industries have been combined and bucketed together under the head of 'other industries'. These include MSMEs and other industries, such as sugar, glass, chemicals (other than refineries and fertilizer), capital goods etc. The total GVA added by these industries in 2022 was ~ INR 28 trillion. The growth of these industries has been pegged with India's projected GDP growth with a declining elasticity with respect to GDP.

As per industry benchmark, total cost of energy spend for these group of industries is 15-20% of revenue, which translates to an SEC of 30 - 34 TWh per INR trillion of GVA; this is expected to improve continuously till 2050 to 27-29 TWh per INR trillion and saturate after that.

The current energy mix is dominated by fossil-fuels with a share of 70-75%, with remaining contributed by electricity (20-25%) and biomass (2 – 5%). However, in the long run, large scale electrification is expected to improve the energy efficiency; average contribution of electricity in the final energy consumption is expected to be 60 – 70%. Also, with the availability of a hydrogen market and ecosystem, 4 – 5% energy consumptions (medium to high temperature heat) may be contributed by Hydrogen also.

Final energy consumption and energy mix in NZS

Estimated final energy consumption is expected to grow from ~900 TWh in 2022 to 2400 – 2500 TWh by 2070.

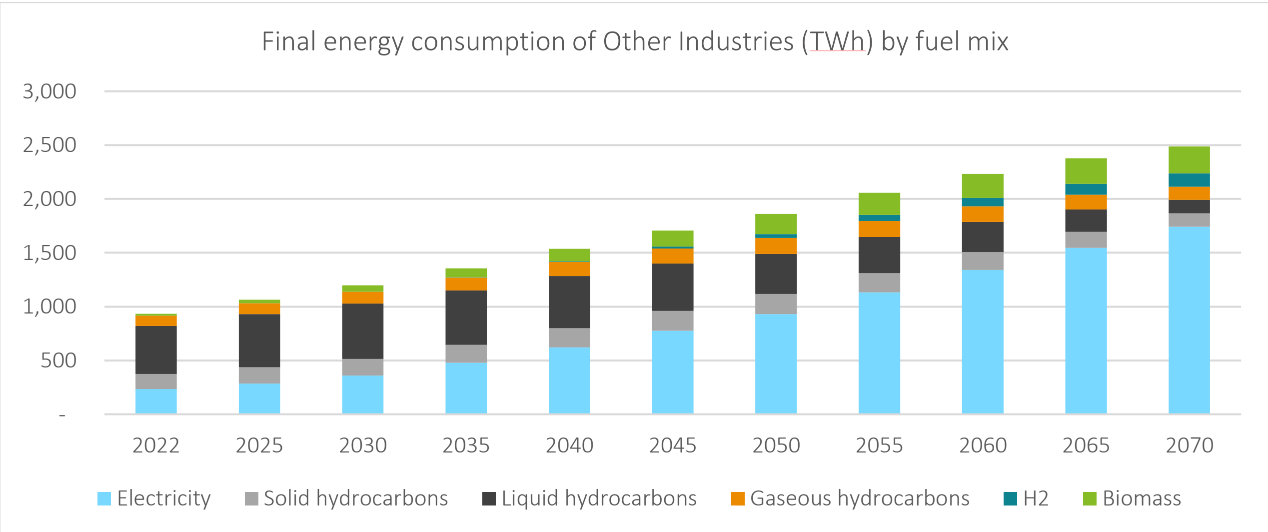


Figure 31: Final energy consumption in Other industries, NZS

Final energy consumption and energy mix in BAU

In BAU scenario, the energy efficiency improvement is expected to be 5 – 10% lower than the NZS and penetration of Hydrogen is not envisaged. Estimated final energy consumption is expected to grow from ~900 TWh in 2022 to 2600 – 2700 TWh by 2070.

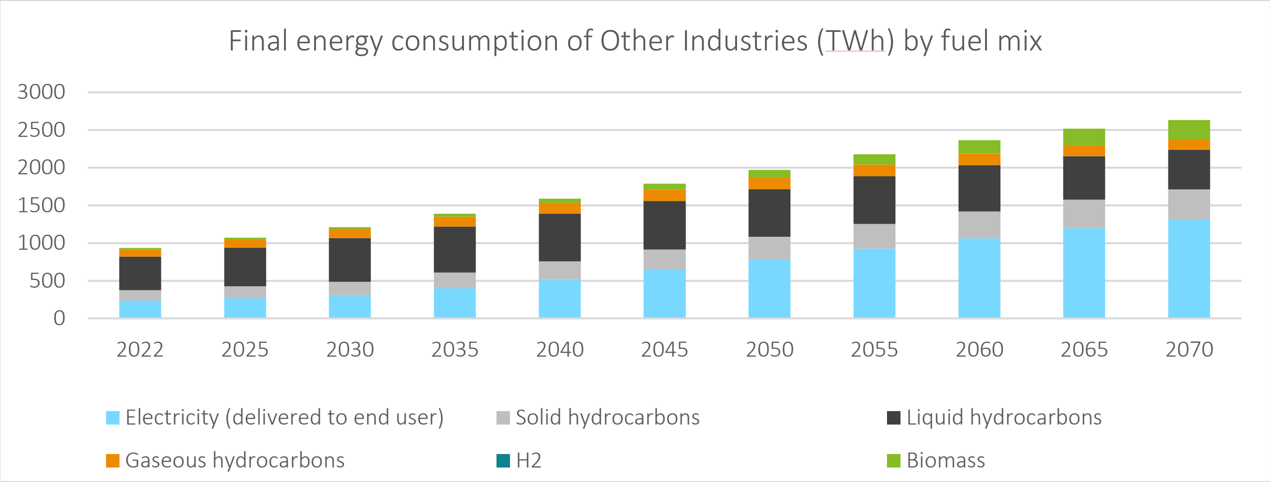


Figure 32: Final energy consumption in Other industries, BAU

4.3 Transportation sector

The transport sector is the third largest carbon emitter (12–13 percent) in India, after power and industries, making it an important pillar for the energy transition. A high dependence on oil to meet this demand presents major roadblocks to achieving India's decarbonization aspirations. Importantly, the transport sector accounts for nearly 50 percent of the total oil demand in India[36]. Oil demand for road freight transport in India has tripled since year 2000, highest after China. Vehicle ownership per capita has grown five-fold since the year 2000, with particularly significant growth in the fleet of two- and three-wheelers. The rapid growth of mobility has been enabled by the expanding road network in India, which increased from 33 lakh km in 2000 to 67 lakh km in 2024[37].

With increasing demand, disposable income, and industrial and commercial activity, India is expected to witness a rapid rise in both passenger and freight transport demand, and this will create an increase in CO2 emissions share in the overall emission mix. Therefore, the country should take an integra[ted approach towards decarbonizing the transport sector by making a transition to low-carbon powertrain technologies. This includes biofuel blending with conventional fuel in the short term and eventually a complete transition to Battery Electric Vehicles (BEV) and Fuel Cell Electric Vehicles (FCEV).

This study has considered a layered approach to transportation which involves initiatives to meet transport demand, improve accessibility, competitiveness, and environmental conditions. The net impact of all these initiatives can broadly be categorized across following these levers:

- ✓ **Avoid** the need to travel or reduce trip lengths.
- ✓ **Shift** towards efficient modes.
- ✓ **Improve** operational or vehicle/fuel efficiency of transport system or enabling zero emission vehicles.

These levers will be applied to both passenger and freight transportation and are detailed in the subsequent sections. The below chart summarizes the key decarbonisation initiatives in each vehicle segment between the present day and 2070.

Transport decarbonization in a Net Zero Scenario

		Pathways for Transport transition		
	Decarbonization potential	2022 - 32	2033 - 50	2051 - 70
Passenger transport	Car	• Moderate uptake of BEVs; 15 - 20% penetration by 2030	• Gradual increase of BEV and FCEV • Last sale of ICE vehicle between 2045 – 50	• Complete transition to BEV (90 – 95%) and FCEV (5 -10%)
Passenger transport	2W/3W	• Moderate uptake of Electric 2W/3W; 20 - 50% penetration by 2030	• Rapid increase of Electric 2W/3W • Last sale of ICE vehicle between 2035 – 40	• 100% electrification to achieve by 2050 - 55
Passenger transport	Bus	• Slow uptake of BEVs; 5 - 10% penetration by 2030	• Gradual increase of BEV and FCEV • Last sale of ICE vehicle around 2050	• Complete transition to BEV (80 – 90%) and FCEV (10 – 20%)
Passenger transport	Rail	• 100% electrification by 2030	• 100% electrified	• 100% electrified
Passenger transport	Aviation	• Blending of green aviation fuel in low quantity	• ~50% use of green fuel	• Near 100% transition to green fuel
Freight transport	Heavy and Light Commercial Vehicle	• Diesel to continue as the dominant fuel	• 40 - 50% fleet to convert to BEV and FCEV • Diesel and CNG to form rest	• 60 - 70% fleet to convert to BEV and FCEV • Diesel and CNG to form rest

Figure 33: Pathways for transport transition in India by 2070, NZS

4.3.1.1 Passenger transport

In India, total passenger transport demand was nearly 7,200 billion passenger-kilometres (BPKM) in 2022, with a per capita demand of ~5100 passenger km/year. This demand was estimated through a bottom-up approach incorporating registered vehicle data from official dashboard such as the 'Vahan' Portal, and then applying vehicle occupancy rates

[36] Estimated
[37] Invest India (access here)

and annual vehicle utilization to the registered motor vehicle data. Industry standards and research articles[38] were referred to adopt vehicle utilization, occupancy factors and carrying capacity for various modes. Further validation of this transport demand was carried out by comparing the estimated fuel consumption with actual fuel consumption data from the MOPNG.

The passenger transport demand is expected to grow to 10,000 – 11,000 BPKM by 2030, 23,000 – 24,000 BPKM by 2050 and 26,000 – 27,000 BPKM by 2070, driven by economic and population growth along with urbanisation. For estimation of passenger demand, this study has considered passenger transport demand elasticity with respect to GDP declining from 0.90 in 2022 to 0.25 by 2050 to 0 by 2070[39]. **Efficient urban planning** through innovative concepts like Transit Oriented Development, Mixed land use planning and integrated transport and spatial planning, logistics optimization and travel demand management can reduce the need for distance travelled and reduce motorized travel demand.

Modal shift is another important consideration for transport decarbonization. It can be considered along two areas – *from private to public/shared modes of transport and from road to railways* since these are more carbon efficient modes of transportation. A modal shift away from personal transport modes to public transport will reduce the growth in number of private vehicles on road and congestion and subsequently help in emissions reductions. High quality and safe non-motorized and mass-transit public transport infrastructure and services will provide wide range of alternatives to private motorized vehicles. Currently, public road transport (buses, omni buses and taxis) accounts for 30 - 32% of the passenger road traffic. This share is expected to increase in a low-carbon scenario.

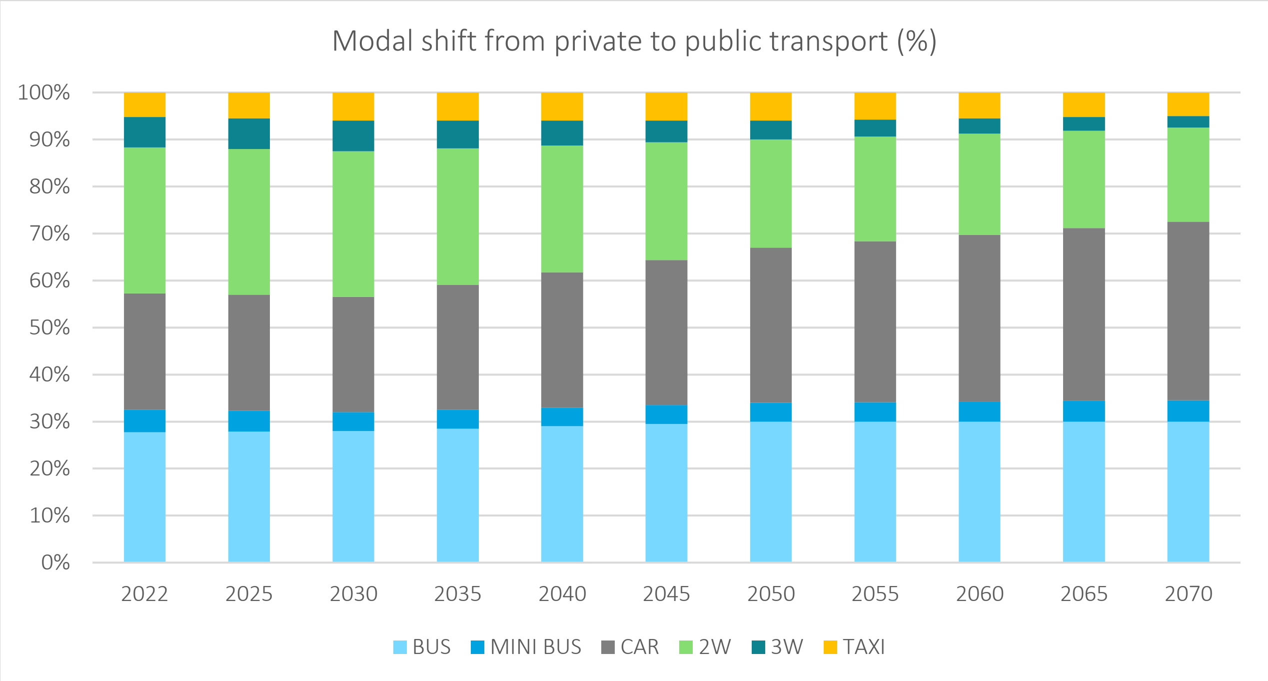


Figure 34: Modal shift for Passenger transport

In addition, **Modal shift from road to rail transport has significant potential to reduce carbon emissions.** This is especially so because majority of the rail network in the country is expected to be electrified soon. High quality railway infrastructure and services provide a viable alternative to road transport. Aggressive push to complete all identified railway projects, modernization of railway, signaling, track technology, rakes, locomotives, station buildings, outsourcing of operations, improving quality of service, digitalization can facilitate the modal shift towards railways. The completion of passenger high-speed lines and metro lines could relieve congestion, ensure high-quality railway services, and ensure an alternative to road and air transport. In 2022, the modal shares of road, rail, and air transport were 85%, 13%, and 2% respectively. This study considers that share of rail and air may increase to 20 – 22% and rest will be contributed by Road.

[38] Literature review was conducted, referring various reports and analysis from credible think-tanks and organizations, such as NITI Aayog, ICCT, reports from Ministries, India Rail Plan etc.
[39] Elasticity declines due as passenger transport demand saturates ~15k pkm similar to other developed countries

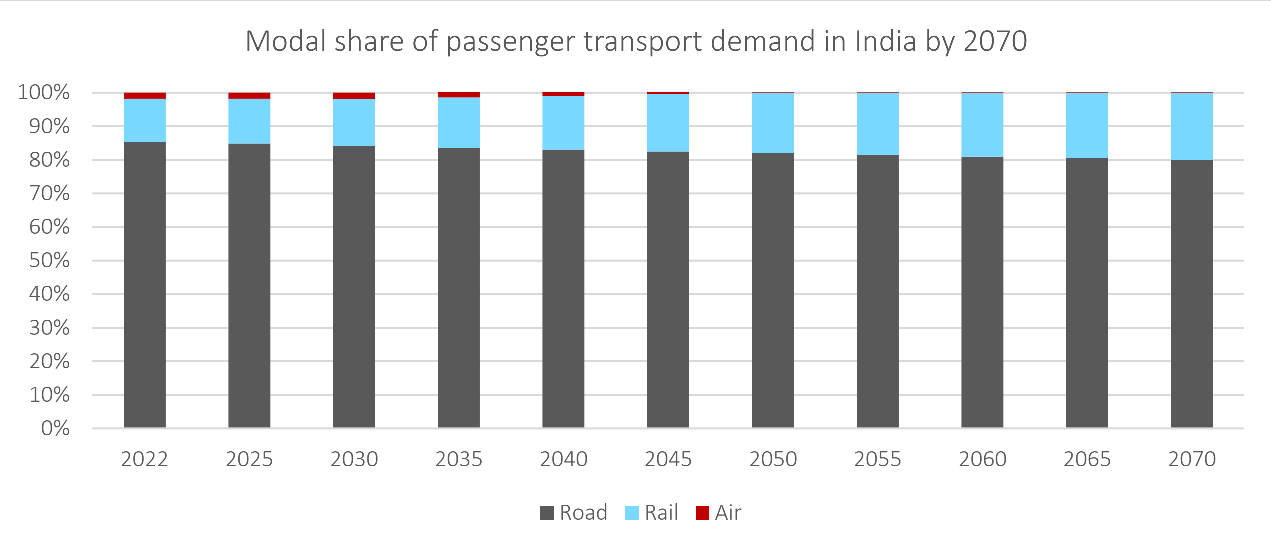


Figure 35: Modal share of Passenger transport

Shift to low-carbon powertrain and expanding charging infrastructure are crucial for transport decarbonization. **While there have been a range of policies that support the increased adoption of a wide variety of electric vehicles, electrification of road transport has been largely limited to two and three wheelers on a larger scale.** Higher cost of vehicles, novelty of technology and lack of abundant charging infrastructure have been observed to be some of the reasons for limited penetration of electric vehicle technology.

However, going forward, the country should focus on accelerated adoption of Battery Electric Vehicle and building adequate charging infrastructure to drive transport decarbonization. While Fuel Cell Electric Vehicle (FCEV) is another option for low-carbon powertrain, sub-optimal efficiency may restrict its adoption in large scale. This study considers adoption of 100% low carbon powertrain technology by 2070.

In NZS, final energy consumption is expected to grow from ~800 BU in 2022 to 1300 – 1400 BU by 2050 and getting stagnated thereafter. Increase in transport demand is expected to be offset by the improvement in efficiency from fleet electrification (75-80% BEV efficiency vis-à-vis 25% ICE efficiency).

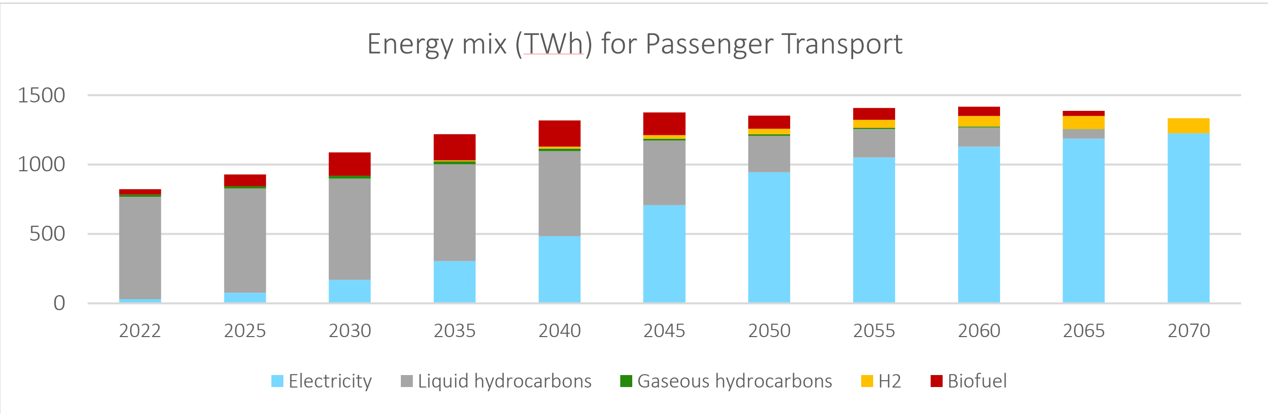


Figure 36: Energy mix for Passenger transport, NZS

Pairing electrification with alternative low-carbon fuels has the potential to decarbonize the transport sector. The government mandated the leapfrogging of vehicle fuel standards from Bharat Stage-IV to Bharat Stage-VI for all new vehicles sold starting April 2020. This standard is in line with Euro-6. Moreover, a comprehensive National Policy on biofuels was approved in 2018 that envisages a target of 20 percent blending of ethanol with petrol and 5 percent blending of biodiesel in diesel by 2030. The Government has been pushing for adoption of compressed natural gas for transport over the last decade resulting in greater adoption of CNG for three wheelers, buses, and cars. Further adoption of LNG and CNG for road transportation and LNG for shipping can be instrumental in reducing carbon intensity of transportation where electrification is not feasible or economical. Improvement in vehicle technology and fuel technology will help in further improving fuel efficiency

4.3.1.2 Freight transport

India's freight demand is directly correlated with the GDP growth. The freight demand in 2022 in the country was estimated to be 2750 Billion Ton – km (BTKM), and the elasticity with respect to GDP was~1.40. With the growth in industrialization and economic activities, this demand is expected to grow multi-fold while the elasticity is likely to decline. This study has considered an elasticity of 0.35 by 2050 and 0.1 by 2070, which is inline with the developed nations. Freight demand is expected to grow from 2750 BTKM in 2022 to 7500 – 8000 BTKM by 2050 and 9000 – 10000 BTKM by 2070.

Efficient infrastructure planning could be a major enabler for optimization of energy requirement for freight movement. Development of greenfield expressways and multi modal logistics parks can help in efficient handling of freight by lowering overall freight costs and time, cutting warehousing costs, reducing vehicular pollution and congestion, improving the tracking and traceability of consignments through infrastructural, procedural, and information technology interventions. In addition, consolidation of freight enabled by technological interventions like big data, blockchain and analytics can help in improving load factors and better utilization of freight vehicle trips. In addition to planning, emphasis on non-motorized transport along with adequate supporting infrastructure can help in reducing the overall demand for motorized transport.

Modal shift from road to rail transport has significant potential to reduce energy consumption. Currently, ~72% of freight transport demand is addressed through road, followed by train (~22%) and shipping (~6%). Majority of the rail network in the country would be electrified, inducing higher energy efficiency. High quality railway infrastructure and services would provide a viable alternative to road transport. Aggressive push to complete all identified railway projects, modernization of railway, signalling, track technology, rakes, locomotives, station buildings, outsourcing of operations, improving quality of service, digitalization can facilitate the modal shift towards railways. For freight, dedicated freight corridors can help in increasing the freight carrying capacity of the rail network and reduce congestion. Further, they are designed to carry heavier loads thereby improving utilization. **In addition to railways, water-based transportation can offer significant opportunities for decarbonization**. Shipping constitutes a mere 6% of the total freight transport demand at present. Development of additional freight terminals, improving port connectivity, modernization of ports, and port linked industrialization projects could be useful steps in improving the use of shipping for freight transport. Moreover, the Maritime India Vision-2030, a 10-year blueprint with the aim of overhauling the Indian maritime sector, envisaging Rs 3 lakh crore investment in port projects, shipping, and inland waterways categories. To harness the potential of Inland waterways, government has come out with lot of initiatives viz. creation of National Waterways, Inland Vessels Bill, Dredging Policy for IWs, promoting private participation in terminal operations and maintenance, etc.

The country has potential to increase the share of Rail in overall freight demand from ~22% in 2022 to 40 – 45% by 2050; shipping share also could be increased to 10 – 12% during the same period.

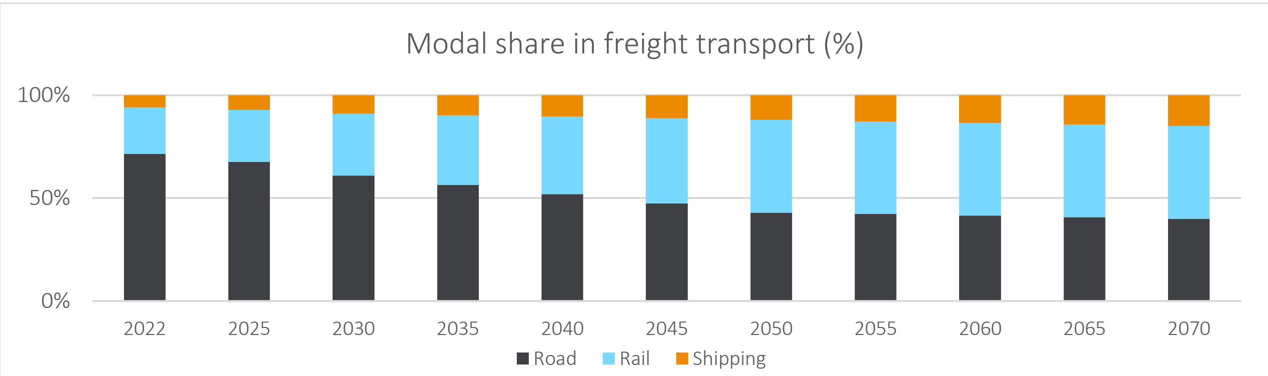


Figure 37: Modal share in freight transport

Along with the modal shift, adoption of new and efficient transportation technology would impact the energy footprint of freight transport. In a low-carbon scenario, 40 – 50% of the entire LCV and HCV fleet is expected to transit to BEV and FCEV by 2050, with rest to be met through Diesel, CNG and LNG. The share of BEV and FCEV is likely to increase further to 60 – 70% by 2070.

The Shipping sector is expected to fully transit to green hydrogen based fuel by 2070. In the transition period, LNG will play a crucial role to reduce emission footprint by substituting diesel.

The final energy consumption from freight transportation is expected to increase from ~550 BU in 2022 to 1100 – 1200 BU by 2050 and 1400 – 1500 BU by 2070. While actual freight demand would increase by ~4x by 2070, energy demand would follow a lower growth trajectory due to increase in energy efficiency driven by electrification of fleet.

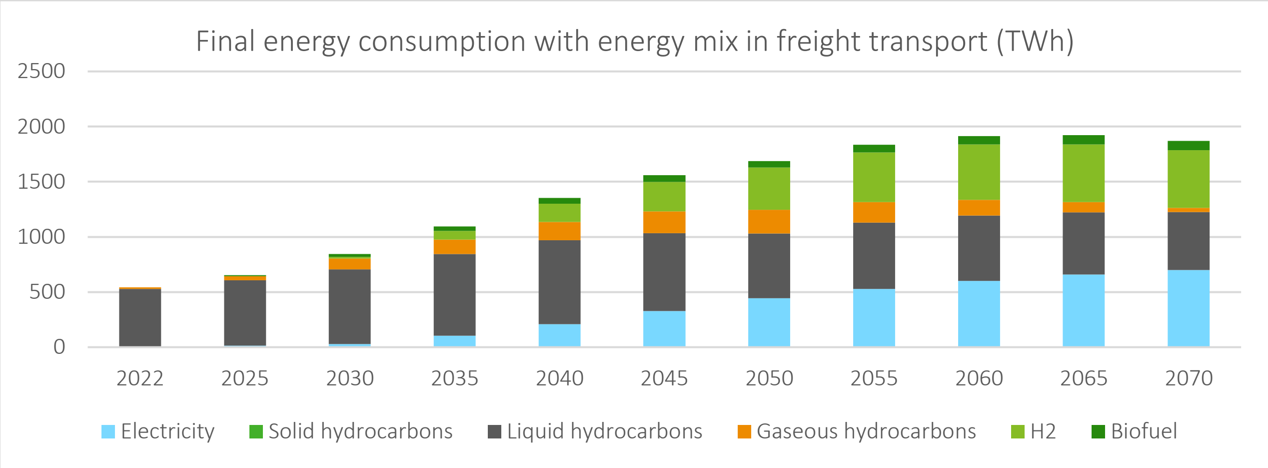


Figure 38: Final energy consumption in Freight transport, NZS

The transport sector is required to transition completely to low-emission technology, such as Battery Electric Vehicle (BEV), Fuel Cell Electric Vehicle (FCEV), Hydrogen Combustion Engine (H2-ICE), and biofuel to achieve transport transition. Widespread development of charging infrastructure and efficient urban planning are keys to transition to low carbon transport.

Key recommendations include the following:

- Public-Private Partnership (PPP) to set up charging infrastructure and hydrogen refueling system
- Central and state governments to focus on efficient urban planning that has the potential to reduce the distance travelled and motorised travel demand
- Investment to be channelised in railways (augmentation and modernisation), freight corridors, mass public transit, etc., to drive modal shift
- The future policy endeavours to account for the potential supply chain and geo-political risks associated with import dependence of critical minerals, such as lithium and cobalt.

Transport decarbonization in BAU Scenario

Pathways for BAU scenario is expected to be lenient with respect to decarbonization, as illustrated below:

Pathways for Transport transition

	Decarbonization potential	2022 - 32	2033 - 50	2051 - 70
Passenger transport	Car	• Moderate uptake of BEVs; 10 - 15% penetration by 2030	• Gradual increase of BEV – 40% EV by 2050	• Gradual increase of BEV – 60% EV by 2070; 5% FCEV by 2070
Passenger transport	2W/3W	• Moderate uptake of Electric 2W/3W; 20 - 30% penetration by 2030	• Rapid increase of Electric 2W/3W	• 100% electrification to achieve by 2070
Passenger transport	Bus	• Slow uptake of BEVs; 5 - 10% penetration by 2030	• Gradual increase of BEV and FCEV • ~30% penetration 2050	• Complete transition to low carbon technology - BEV (80 – 90%) and FCEV (10 – 20%)
Passenger transport	Rail	• 100% electrification by 2030	• 100% electrified	• 100% electrified
Passenger transport	Aviation	• Blending of green aviation fuel in low quantity	• ~50% use of green fuel	• Near 100% transition to green fuel
Freight transport	Heavy and Light Commercial Vehicle	• Diesel to continue as the dominant fuel	• Diesel and CNG are dominant fuel	• 10 - 15% are BEVs/FCEVs

Figure 39: Transport decarbonization pathways for BAU scenario

Passenger transport

In BAU scenario, the final energy consumption is expected to grow from ~800 BU in 2022 to 2200 – 2300 BU by 2050, thereafter reducing to 1800 – 1900 BU by 2070.

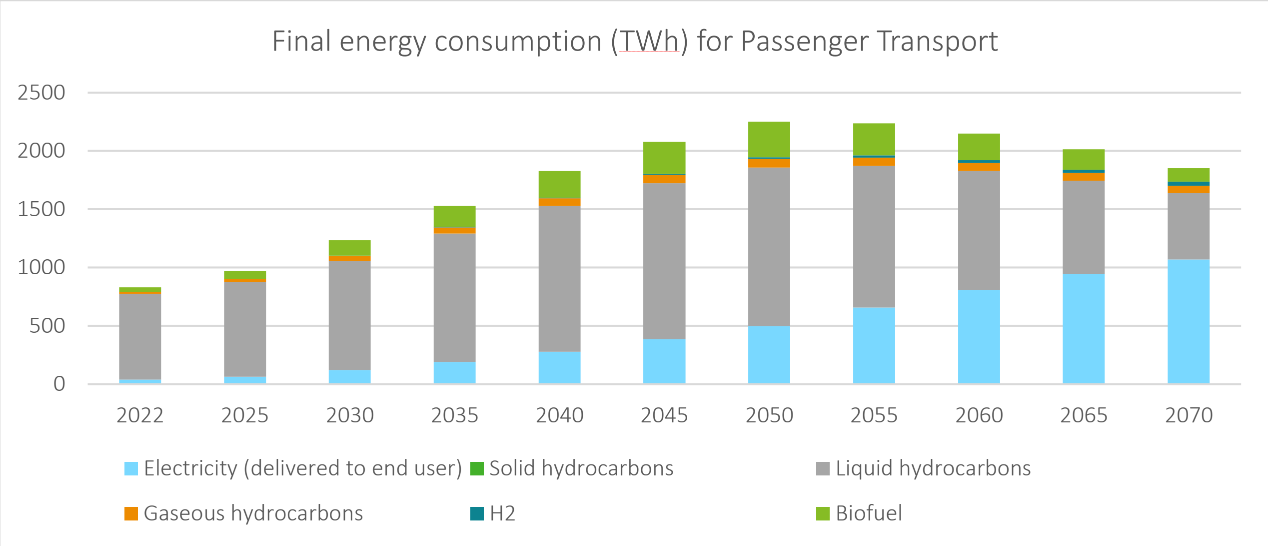


Figure 40: Final energy consumption for Passenger transport, BAU

Freight transport

The final energy consumption from freight transportation is expected to increase from ~550 BU in 2022 to 2300 – 2400 BU by 2050 and 2800 – 2900 BU by 2070, much higher than the energy consumption estimate in the NZS.

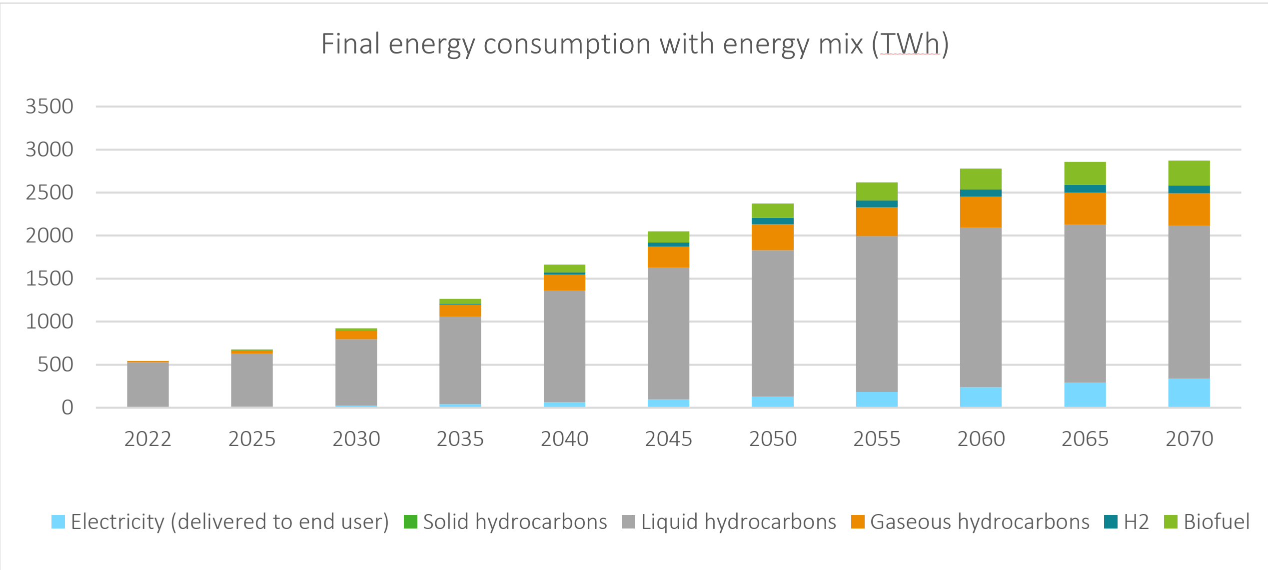


Figure 41: Final energy consumption for Freight transport, BAU

4.4 Cooking sector

At present, about half of rural households and a small percentage of urban households depend on biomass for cooking. Primary source of fuel used for cooking determines the energy required for cooking as well the health impacts due to cooking activities. Even to this day, an estimated 660 million Indians remain without access to modern and clean cooking fuels and technologies[40].

Energy demand from cooking currently accounts for 10 percent of the total energy demand but is expected to reduce to around 3 percent by 2070 owing to fuel switching and efficiency improvements. While the government has extended measures to improve the availability of liquified petroleum gas (LPG) for cooking and provided fiscal incentives to

[40] World Energy Outlook, 2021

encourage adoption in poor households (Pradham Mantri Ujjawala Yojana or PMUY and Pratyaksh Hanstantrit Labh or PAHAL), LPG penetration in rural areas remains only partial (50 percent). Affordability remains a key impediment to large scale adoption of cleaner cooking fuels like LPG despite such incentives due to availability of cheap biomass and constraint in distribution network of LPG.

Alongside the increasing use of LPG in rural areas, there has also been growth in the use of pipeline natural gas (PNG) in urban areas through the city gas distribution network. The government now has plans to expand this city gas distribution network to cover 70 percent of all households by 2030. Fuel switching to modern fuels and technologies will be more prominent in case of rural areas due to their heavy reliance on tradition biomass for cooking.

On the other hand, urban areas could see some shift towards piped natural gas and electricity for cooking owing to their convenience and efficiency. Availability of pipeline infrastructure and reliable electricity supply will be key imperatives for facilitating this transition. In addition to the fuel used for cooking, the efficiency of the cooktop/ stoves has a direct impact on fuel consumption. Improvement in quality of cooktops can further help in reducing emissions from cooking. Electrification of cooking would be required in the longer term to ensure net zero emissions from the cooking sector. While electric cooktops provide increased safety and incur low operational costs, the adoption in India has remained low due to the high upfront cost of induction cooktops. India must pursue a strategy of gradually shifting away from gas as the source of clean cooking. This has already been pursued in cities such as San Francisco, which have banned the use of natural gas in newly constructed buildings. Electrification would also provide India the benefit of improved energy security since the country imported nearly 60 percent of LPG and 50 percent of its natural gas in 2020.

Final energy consumption and energy mix in NZS

Overall energy split and the final energy consumption in the cooking sector in a net zero scenario is illustrated below:

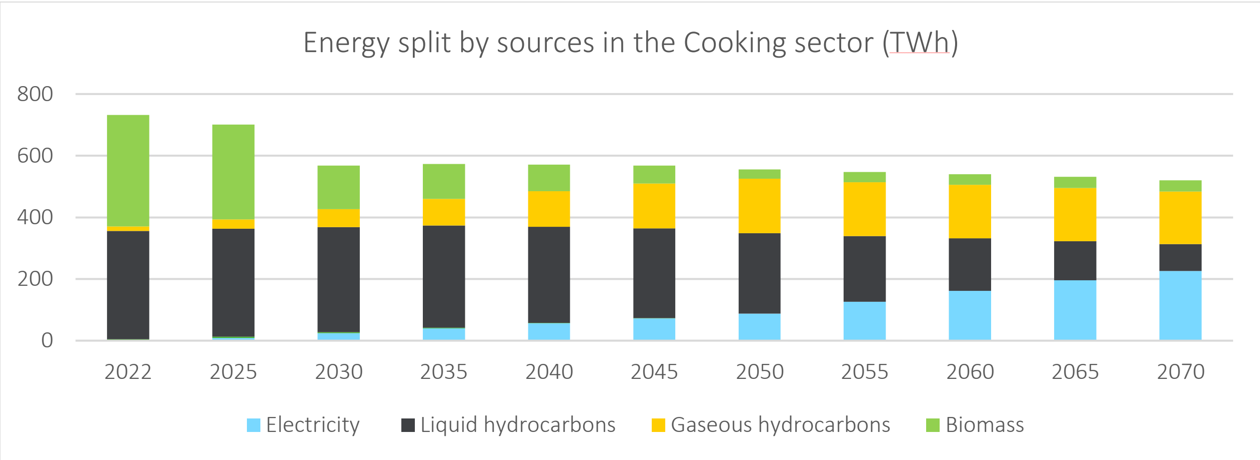


Figure 42: Energy split by sources in Cooking sector, NZS

Penetration of cooking technologies

Rural area

- Currently, cooking in rural areas of India is largely dependent on biomass (40 – 45%) and LPG (50 – 55%). Biomass based cooking comes with significant inefficiency in energy conversion. It is expected that large share of biomass and LPG will be substituted through electrification and piped natural gas (PNG). Share of electricity and PNG may reach 40% in 2050 and 80% in 2070.

Urban area

- Currently, cooking in urban areas is dominated by LPG (80 – 85%), followed by PNG (~10%). Urban areas will also see substitution of LPG with PNG and electrification. Urban area may continue with a higher PNG share due to established CGD networks in many of the major cities. Both PNG and electricity are expected to contribute ~60% of total cooking energy in urban areas by 2050, and 80% by 2070.

In a Net Zero scenario, entire cooking sector, in both rural and urban areas, is expected to transit to electric cookstoves and PNG. Use of biomass and LPG will be very limited. This would require Government push in the form of enacting innovative policy and a behavioural shift from the residential consumers.

Final energy consumption and energy mix in BAU

In the BAU scenario, level of electrification will be moderate vis-à-vis NZS. Oil and PNG will be dominant fuels.

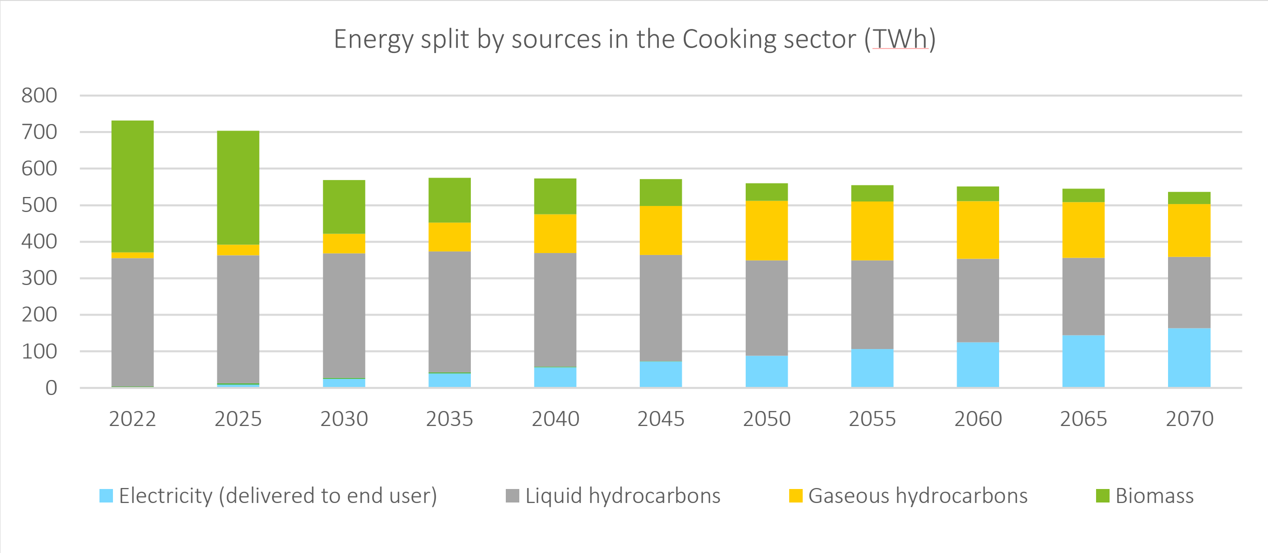


Figure 43: Energy split by sources in Cooking sector, BAU

4.5 Agriculture sector

The declining share of agriculture in the economic output of the country and continued dependence on traditional farming techniques have resulted in a relatively smaller growth in the agricultural energy demand over the last few years. From the perspective of emissions as well, agriculture accounted for less than 2 percent of total GHG emissions in 2022. Irrigation pump-sets and tractors account for most of the energy requirement in the sector in the form of electricity and diesel respectively. While the impact of the sector from an emissions perspective is limited, attempts can nonetheless be made to improve the carbon intensity of the sector. Inefficient irrigation practices lead to unnecessary use of water and energy, and conversion of the existing diesel pumps to off-grid solar pump will reduce the emission footprint

Improvements in reliability of electricity supply and expansion of micro irrigation practices along with agricultural demand side management can help in reducing dependence on diesel fuel. To improve agricultural productivity and reduce dependence on diesel for pumping, the Government has enacted the Pradhan Mantri Kisan Urja Suraksha Evam Utthaan Mahaabhiyan (PM-KUSUM) scheme aimed at ensuring energy security for farmers and increasing energy supply from renewable energy sources. This includes setting-up of decentralized ground mounted grid-connected renewable power plants up to 2 Mega Watt (MW) capacity, installation of stand-alone solar agriculture pumps and solarization of 1 Mn grid-connected agriculture pumps.

Further, efficiency improvement of tractors can also help in reducing energy demand. National Policy on Biofuels, has directed to utilize sugarcane and its by-products, surplus rice, maize, damaged food grains and non-edible seeds to produce biodiesel and ethanol. This further creates an opportunity to reduce the emissions to an extent, as burning of agricultural residue will reduce, and petrol and diesel will be blended with biofuels.

Projected energy split in the agriculture sector from 2022 – 70 for both NZS and BAU scenarios is illustrated below:

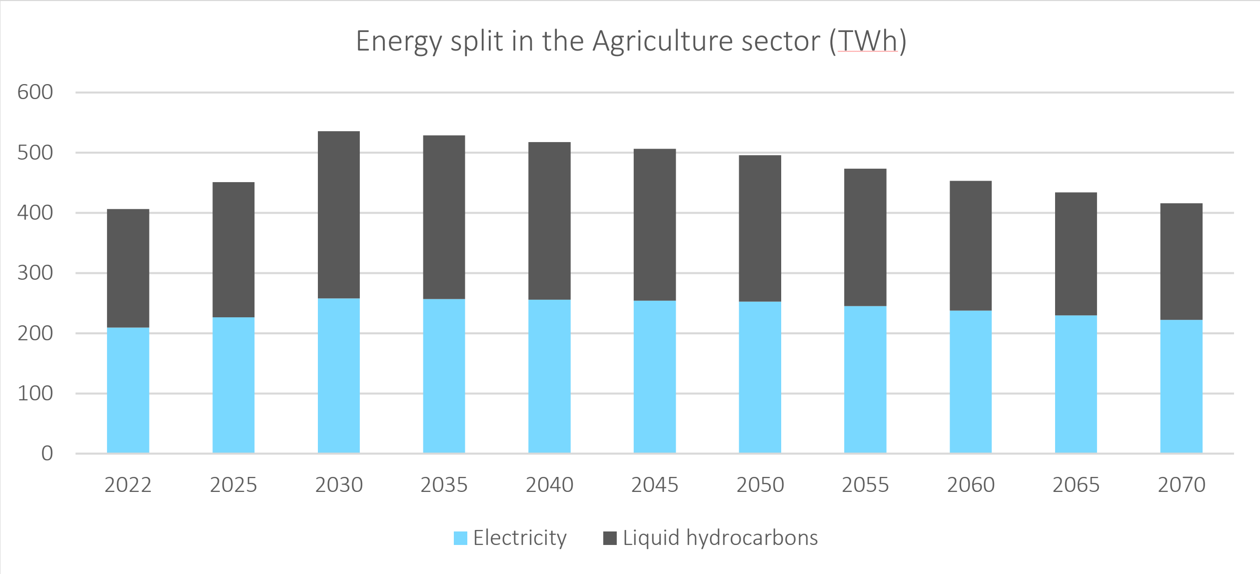


Figure 44: Energy split by sources in Agriculture sector

Agricultural pumping demand is expected to increase between 2024-30. However, post 2030, the demand is likely to be stagnated and energy demand is expected to decline due to improvement in pump efficiency.

Tractor demand is also expected to increase from ~11 Million in 2023 to ~16.5 Million in 2032 to achieve saturation thereafter. Diesel demand from tractors has been estimated considering 60% of tractors in use at a time and utilization of 500 hours annually.

4.6 Buildings sector

The rising energy demand from the residential segment comes primarily due to urbanization, replacement of existing building stock with new construction and increasing appliance ownership with air conditioners emerging as the single most significant source of electricity demand in the buildings sector. Residential sector currently accounts for ~5 percent of the total energy demand which is expected to go up to 11-12 percent by 2070. The thrust towards public housing has resulted in large scale replacement of informal living settlements which has not only impacted the residential energy demand but also created demand for modern building materials like cement, steel, iron etc.

Electricity consumption is buildings sector is expected to rise significantly due to increasing cooling load and electrification of heating in rural areas during winter seasons. Electricity requirement for residential buildings is expected to increase from 450 TWh in 2023-2024 to nearly 1600 TWh even under the Net Zero Scenario, and to nearly 1800 TWh under the Business-as-Usual Scenario.

The growth in energy demand from this sector could be restrained by energy efficiency improvements in appliances particularly those with higher rating as well as through thermally efficient building designs. While the government has made steps in the direction of energy efficiency for appliances including standardization and labelling for appliances, distribution of energy efficient energy buildings, household electrification to reduce dependence on traditional biomass and oil and energy conservation codes for buildings, stringent implementation of these measures is warranted. For example, state level implementation of Energy Conservation and building codes are critical for large scale implementation of these code on the ground. A significant volume of India's building stock is yet to be built and therefore provides an opportunity to optimize the future cooling requirements and thermal performance of residential buildings through energy efficient design.

Rooftop solar could be a potential alternative to meet the residential and commercial energy demand of the country. However, achieving scalability in the rooftop segment is a major challenge. Out of the total 1400 GW of solar power for grid electricity, nearly 200 GW could be met through a combination of rooftop solar and off-grid agricultural pumps.

Key considerations for energy demand growth in the residential building sector:

- Energy demand growth will be directly proportionate with the population growth. Further, per capita housing space will increase in both rural and urban areas due to economic development and increase in per capita income.
- Annual growth is energy footprint is assumed to be flat 1% between 2024 – 70, mainly driven by cooling load and increased ownership of appliances. Cooling load is expected to increase from ~7% in 2023 to ~20% of total residential building load by 2070.

In the commercial segment, energy conscious commercial buildings design will be key to reducing cooling loads. In order to realize the net-zero goals and decarbonization strategies, more stringent implementation of energy conservation as well as incentivizing energy efficient equipment will be critical. Energy demand from commercial establishments currently account for 2 percent of the total energy demand which is met almost entirely through electricity. The commercial electricity accounted for ~11% of the total electricity demand in 2022. This demand from commercial sector is expected to grow in the coming years due to the anticipated growth in sectors like hospitality, retail, and Information technology. Moreover, commercial activity in rural India is expected to pick up pace owing to improved electricity access, reliability, and infrastructure.

Energy Performance Index (EPI) in Indian commercial establishments is between 100 to 150 kWh/sq. m/year. Within the overall commercial energy demand, almost 50% is accounted for by cooling demand from air conditioners; therefore, energy conscious building design would be critical for reducing the cooling load. While the Government has instituted measures for energy efficient design of commercial building spaces, higher upfront investment and low demand of energy efficient buildings by developers and owners pose challenges in larger uptake of energy conscious building designs. Technical and financial capacity barriers further inhibit adoption of such designs.

Key considerations in the commercial building segment are:

- The major growth segments in the commercial building sector are Retail, Hospitals, Hotels, Office spaces, Educational institutes, Assembly placed and warehouses.
- The current share of air-conditioned floor space is 20 – 25%, which is likely to increase significantly (55 – 60%) by 2070, driven by economic development and adverse weather conditions.
- Growth in commercial floor space is also expected at a CAGR of 2 – 2.5% between 2022 – 70.
- By 2070, 40 – 50% of commercial buildings are expected to be compliant with ECBC norms, driving overall energy efficiency in the building segment.
- Use of DG sets is likely to be eliminated by 2030, driven by increased reliability of electricity grid and focus on decarbonization of electricity used (Scope – 2 emission reduction)

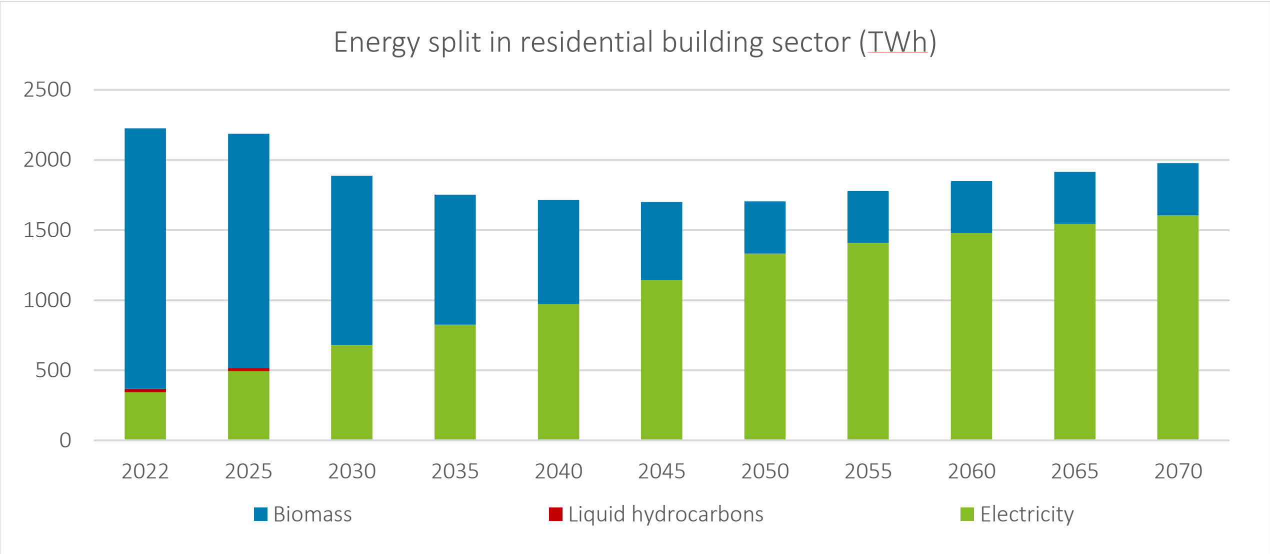


Figure 45: Energy split by sources in Residential Building sector

Overall energy consumption is roughly the same between 2025 and 2070 since increase in electricity use compensates the decline in biomass use. However, there is a complete shift in the form of energy used. Biomass consumption for the residential sector is expected to decrease due to shift to electricity for heating and cooking purposes. As per IEA, India consumed over 1800 TWh of biomass in 2022 for heating and cooking. This high number is due to the very low efficiency of biomass used for traditional forms of heating and cooking.

Gradually, this source of energy will be substituted by electric heating, inducing additional energy efficiency. Therefore, total demand is expected to decline till 2040, and then it will again start increasing due to additional energy demand driven by cooling load, population growth and improvement in lifestyle.

Overall, electricity demand for residential sector is expected to increase from ~350 TWh in 2022 to 1500 – 1600 TWh by 2070.

For commercial building sector, energy demand is expected to be fully electrified by 2030. Overall electricity demand is expected to increase from ~130 TWh in 2022 to 400 – 450 TWh by 2070. The growth in energy demand will be driven by increase in cooling load and growth in commercial buildings area due to economic growth.

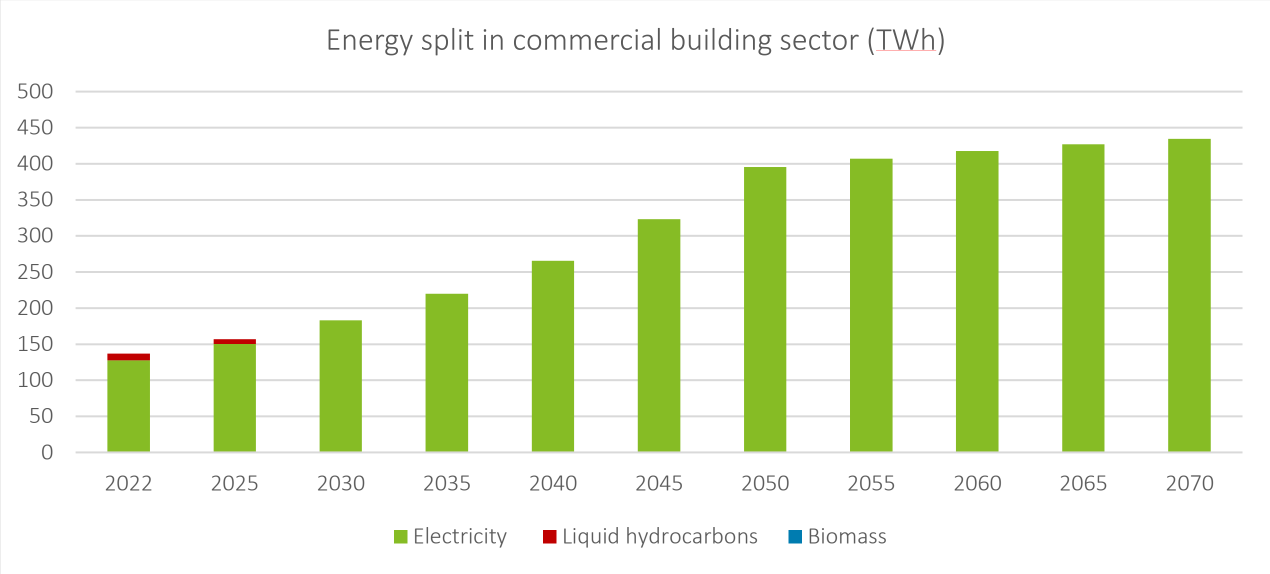


Figure 46: Energy split by sources in Commercial building sector

Cooling load is likely to be the major growth driver of energy in both residential and commercial segment. In the Residential segment, cooling load is expected to increase from 6-8% of final energy consumption to 20-22% by 2070; in the commercial building segment, the cooling load is expected to increase from 20 – 25% in 2022 to 30 – 35% by 2070.

4.7 Digital infrastructure

Telecom sector and data centres are expected to be new source of energy demand in the coming decades. As per IEA, globally, data centre electricity consumption in 2022 was 240-340 TWh, or around 1-1.3% of global final electricity demand. This excludes energy used for cryptocurrency mining, which was estimated to be around 110 TWh in 2022, accounting for 0.4% of annual global electricity demand[41].

Exponential growth of digital services will drive the growth in data centre energy demand. While datacenter capacity is constructed for a multitude of reasons, local population can be an interesting proxy to determine potential growth of a local market. In comparison of global cities, concentration of data center in Indian cities is much lower.

Table 1: Data center concentration in Indian cities

City	People/MW
Kolkata	2900000
Delhi-NCR	300000
Hyderabad	200000
Pune	250000
Chennai	150000
Mumbai	70000
Bengaluru	64000
Beijieng	50000
Tokyo	50000
Sanghai	40000
Chicago	25000

[41] https://www.iea.org/energy-system/buildings/data-centres-and-data-transmission-networks

City	People/MW
London	22000
Singapore	14000

Source: Estimated

Currently, in India, total capacity of data centre is ~1 GW, which is expected to grow to ~6 GW by 2030, ~50 GW by 2050 and ~100 GW by 2070. The exponential future growth of data centre is expected to be driven by proliferation of AI/ML based technology and the energy load would come from requirement of cooling.

In the telecom sector, growth of Base Transceiver Stations (BTS) will drive the energy demand. The growth of BTS is expected to be ~6% between 2023 – 35 (based on historical CAGR) and ~3% from 2035 – 50, achieving saturation thereafter.

Overall energy demand from telecom sector and data centre is expected to increase from ~100 TWh in 2022 to 800 - 900 TWh by 2070, which is ~10% of the electricity demand. The entire demand is likely to be met through electricity. Use of DG sets to power telecom towers has already reduced in urban areas and is likely to be eliminated gradually due to growing reliability of the grid.

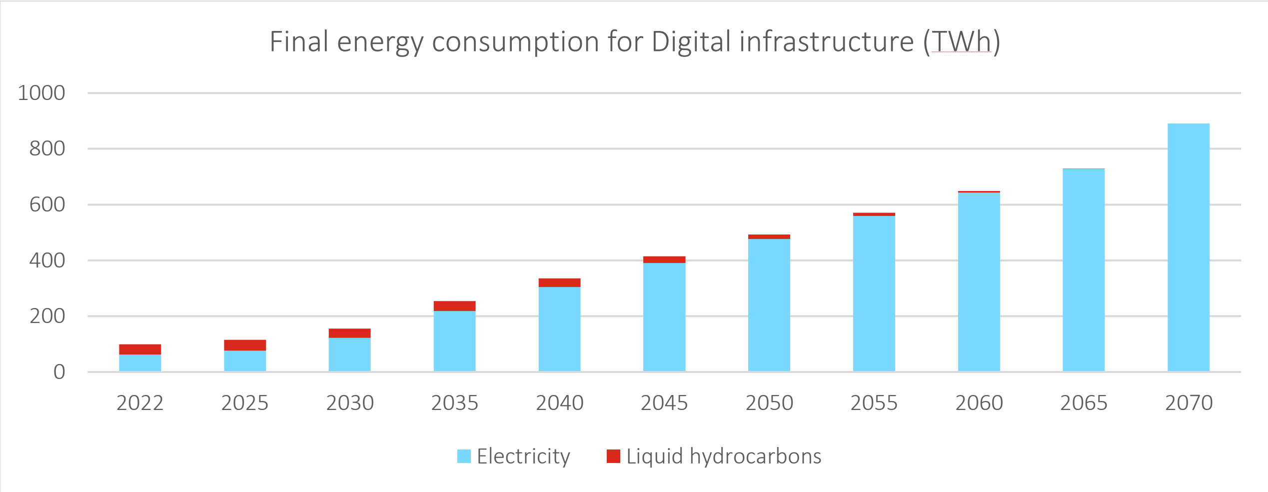


Figure 47: Final energy consumption for Digital Infrastructure

4.8 Summary of sectoral energy demand

In the NZS, the final energy consumption growth in India is expected to be limited within 80-90% by 2070. Final energy consumption is estimated to reach 14000 - 14500 TWh (1200 – 1250 Mtoe) by 2070; industry sector would contribute 50 – 55%.

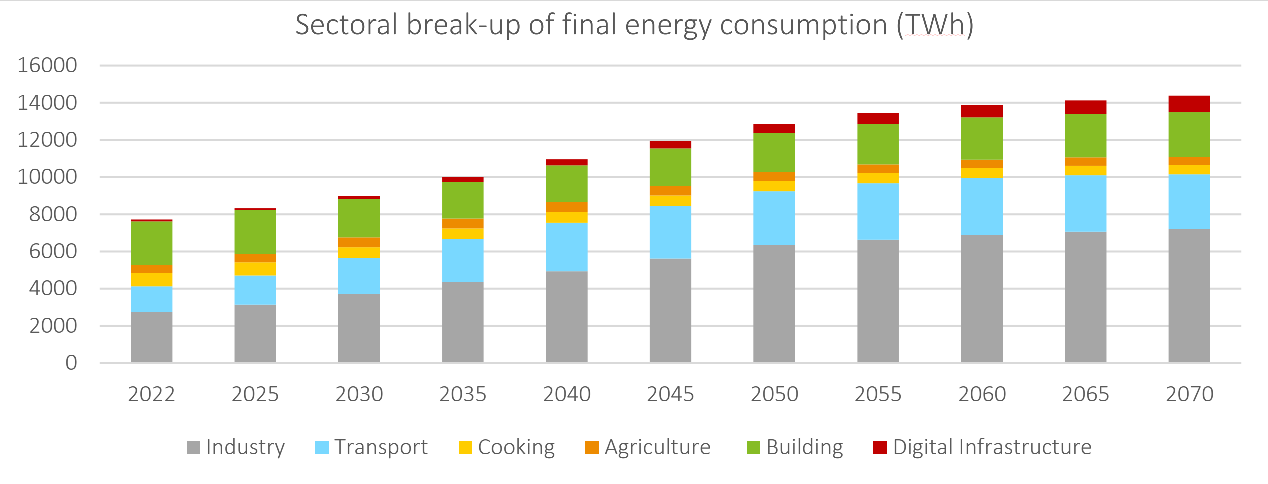


Figure 48: Sectoral break-up of final energy, NZS

The India energy model suggests total final consumption of energy grows at 2.0% over 2022-30E, ~1.8% over 2030-50E, before slowing to 0.5% over 2050-70E.

Key takeaways:

- Reduction in energy consumption is pivotal to achieve Net Zero; final energy demand by 2070 is expected to be contained within ~2x of current final energy demand.
- Industry sector will drive the growth with 50 – 55% share in final energy demand, followed by transport (18 – 22%) and Building (16-18%) by 2070.
- Final energy growth is expected to plateau by 2055, driven by higher energy efficiency as well as slower economic and industrial growth.
- Transport energy demand will see moderate growth due to efficiency improvement in EVs and modal shift and behavioral changes (LiFE interventions).
- Cooling load for building sector will drive the final energy consumption:
    - Residential: Cooling load is expected to increase from 6% in 2022 to 20-22% by 2070
    - Commercial: Cooling load is expected to increase from 20% in 2022 to 30 – 35% by 2070

In BAU scenario, the energy demand will be 15 – 20% higher than the NZS, reaching 17000 – 18000 TWh (1400 -1500 Mtoe) by 2070. The increase in demand is due to lower energy efficiency and electrification[42] in BAU scenario than NZS.

Projected sectoral break-up of final energy consumption in BAU scenario is illustrated below:

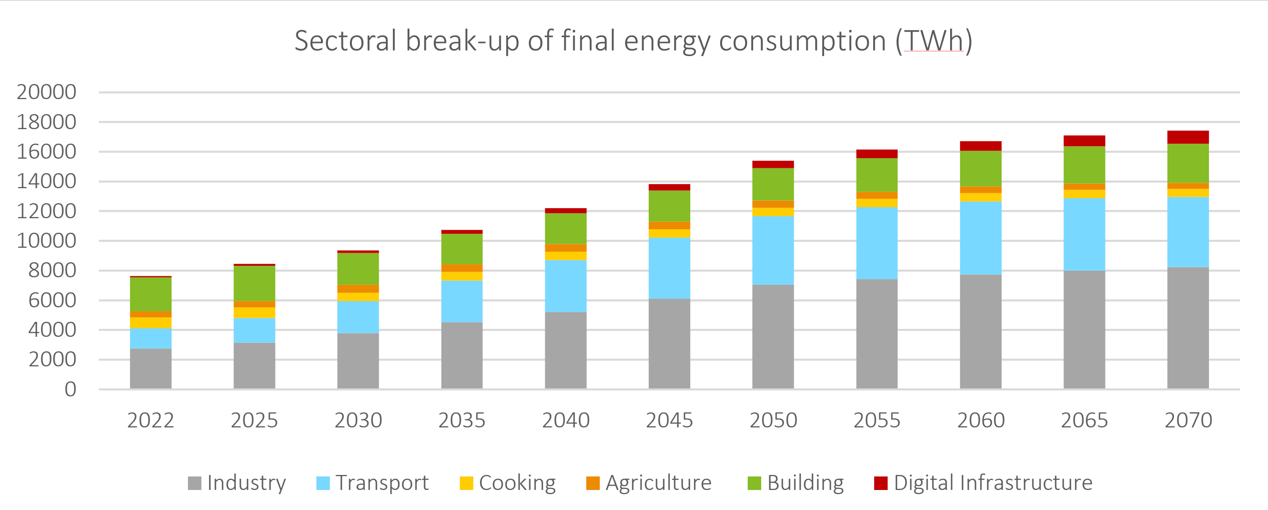


Figure 49: Sectoral break-up of final energy, BAU

The energy model suggests total final consumption of energy grows at 2.6% over 2022-30E, ~2.5% over 2030-50E, before slowing to 0.6% over 2050-70E. The growth rate is expected to be higher than NZS.

Key takeaways:

- Final energy demand by 2070 is expected to be ~2.3x of current final energy demand, 15 – 20% higher than NZS.
- Direct electrification and investment in energy efficient technologies across sectors will be lower than NZS.
- Industry sector will drive the growth with nearly 50% share in final energy demand, followed by transport (22 – 25%) and Building (10-12%) by 2070.
- Final energy growth is expected to plateau by 2055, driven by increasing adoption of energy efficiency as well as slower economic and industrial growth in later years.
- Transport sector is expected to see moderate penetration of Zero Emission Vehicle, leading to higher energy consumption than NZS.
- Building and Cooking sectors are expected to fully transit to electrification and PNG even in BAU scenario.

[42] With direct electrification, energy conversion efficiency increases

In NZS, Direct electricity and Green Hydrogen are expected to be major sources of energy by 2070, contributing 65 – 75% of total demand. Coal and Oil will have limited application in industry and transport.

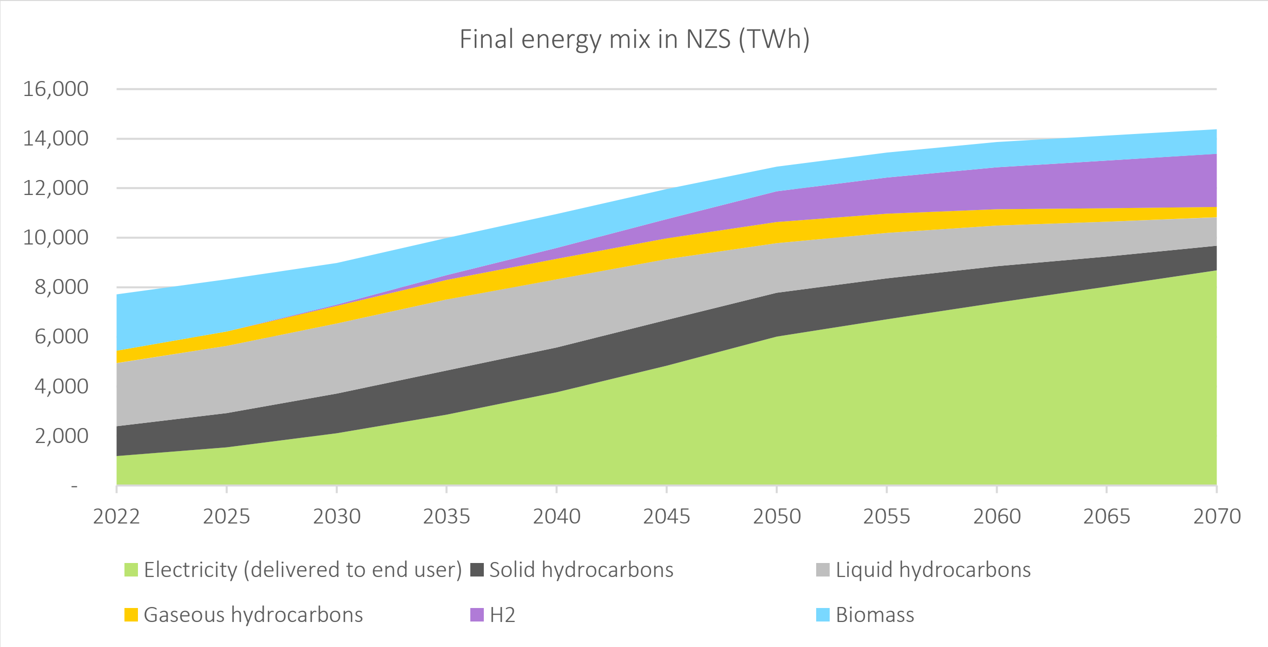


Figure 50: Final energy mix, NZS

Growth of electricity is expected to be much faster than the total final energy growth - ~7% between 2022-30E, ~5% between 2030-50E, before slowing to ~1.5% between 2050-70E. Direct electrification in industry (mainly process heat), transport (conversion of ICE vehicle to BEV), building (electrification of heating) and cooking (adoption of electric cookstove) sector will drive the growth of electricity. Hydrogen will find application in hard-to-abate industry sectors, such as steel, refinery, fertilizer and cement, and transport. In Indian context, green hydrogen is not considered as a preferred fuel for power generation.

Coal will continue to be used in certain industry sectors, such as Cement, Petrochemical and certain MSME sectors. Oil will have limited application in heavy duty transport, shipping and aviation sector. Use of biomass as a final energy will reduce due to aggressive electrification of cooking and building sector.

In BAU scenario, adoption of direct electricity and green hydrogen will be lower than NZS, limiting it to 45-50% of total final energy demand. Coal, Oil and Gas will contribute another 40-45%.

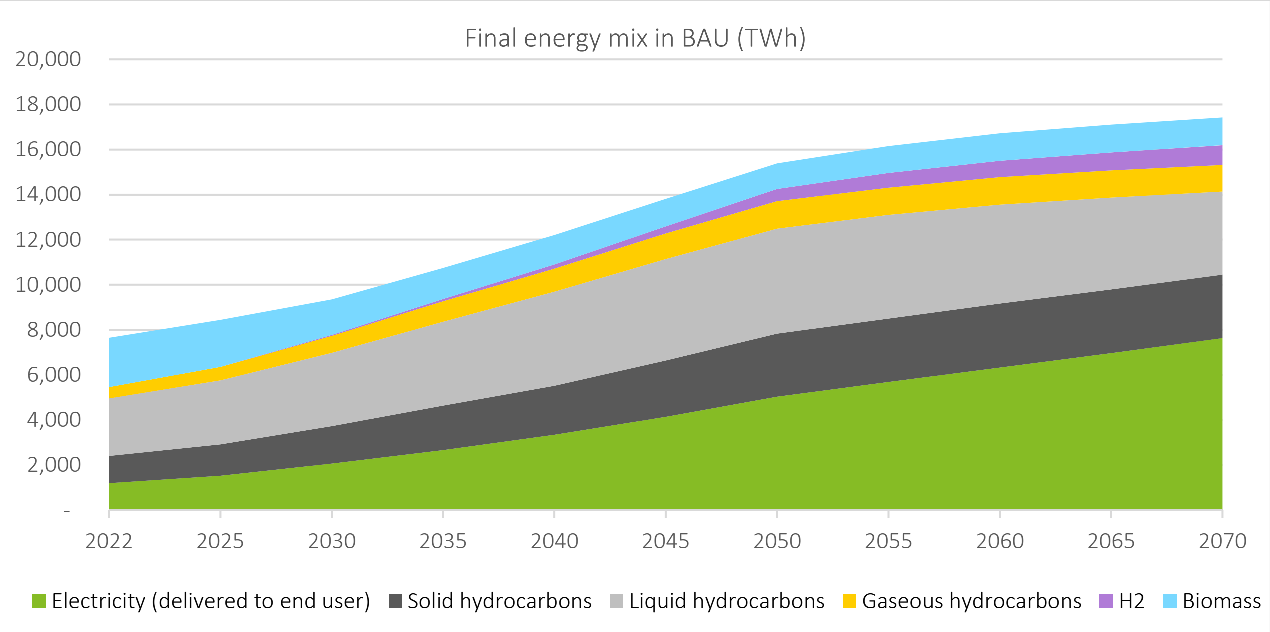


Figure 51: Final energy mix, BAU

Growth of electricity is expected to be much faster than the total final energy growth - ~6.3% between 2022-30E, ~4% between 2030-50E, before slowing to ~1.8% between 2050-70E. Electrification in industry and transport sector is expected to be lower than NZS.

Adoption of green hydrogen led decarbonization will be moderate in the hard-to-abate industry sectors and transport. Significant quantum of coal will continue to be used in industry sectors, such as Steel, Cement, Petrochemical and MSME sectors. Oil will have application in freight vehicles, shipping and aviation sector. However, use of biomass as a final energy will reduce due to aggressive electrification of cooking and building sector.

In the NZS, Green Hydrogen demand is expected to reach ~30 Million Tons by 2050 and 50 - 55 Million Tons by 2070; adoption is likely to pick up post 2030. The electrolyser demand may reach 200 – 250 GW by 2050 and 450 – 500 GW by 2070.

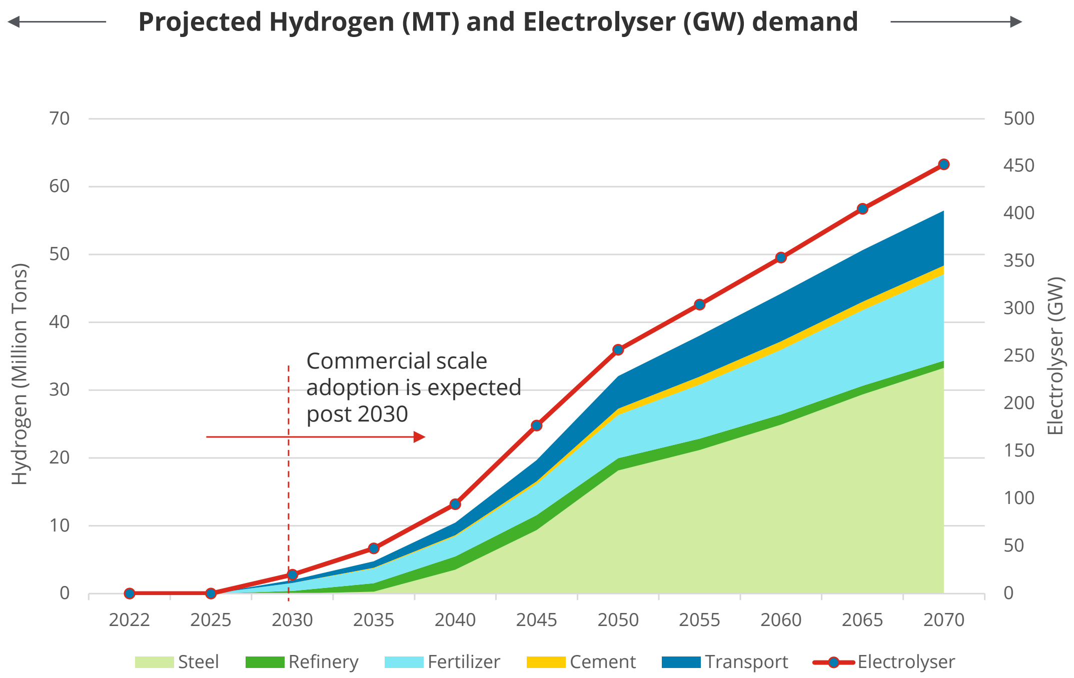


Figure 52: Green hydrogen demand till 2070, NZS

Note:

1. Hydrogen production for export will be addition to this demand.
2. Electrolyser demand shown here is only for production of hydrogen for industrial decarbonization. Additional demand will be unlocked for producing hydrogen as seasonal storage.

Key takeaways:

- Hydrogen will find major applications in Steel, Fertilizer, Refinery, Transport and Cement sector. Major uptake of hydrogen is expected after 2030 once the cost parity is achieved and ecosystem is developed.
- **Steel sector** is expected to emerge as the largest consumer of green hydrogen; by 2070, H2-DRI based steel production is expected to contribute 75 – 80% of total steel production.
- **Refinery and Fertilizer** may transit to green hydrogen by 2050; increased production of complex and phosphate-based fertilizer (Diammonium Phosphate) will drive hydrogen adoption in fertilizer sector[43].
- **In transport**, freight vehicle is expected to see higher adoption due to higher energy density and higher payload capacity. However, passenger vehicle is expected to see limited adoption (15-20%) through a mix of FCEV and H2 engine (H2-ICE).
- **Cement and 'Other' sector** may see penetration of green H2 up to 5% of total energy consumption, mainly as an alternative fuel co-fired with coal and gas.
- **Power sector** is not expected to create a sizeable demand of hydrogen. Hydrogen based gas turbines are expected to see commercial maturity around 2035-40; however, their uses are likely to be limited as "seasonal storage".
- **Introduction of an aggressive carbon tax and policy driven sectoral mandates** are expected to drive hydrogen adoption

[43] Currently, Urea is the dominant fertilizer in India. Urea can't be decarbonized completely through green hydrogen due to process related challenges while complex fertilizer and DAP can substitute 100% grey hydrogen with green.

Developing a robust ecosystem by establishing a domestic supply chain and hydrogen infrastructure is crucial. While the PLI scheme for electrolysers is expected to provide an initial boost to the domestic supply chain, equal emphasis should be placed on manufacturing Balance of Plant (BOP) equipment, such as compressors, dispensers, and electrical components. According to an analysis, the alkaline electrolyser system has the potential for 100% indigenization, while the PEM system can be indigenized up to 70-80%. The government (central or state) could encourage manufacturers to set up indigenous facilities for BOP equipment and related ancillaries.

Currently, the infrastructure needed for hydrogen transport and storage is lacking. Beyond just manufacturing electrolysers and producing hydrogen, policies should be designed to facilitate capital investment in developing hydrogen infrastructure, expanding the network, and retrofitting existing gas infrastructure. Since the National Hydrogen Mission (NHM) focuses on hydrogen exports, it is essential to assess the readiness of ports for exporting green ammonia or other hydrogen carriers.

In the BAU scenario, Green Hydrogen demand will be lower than NZS. Demand is expected to reach ~12 – 15 Million Ton by 2050 and 23 - 25 Million Tons by 2070. The electrolyser demand may reach 100 – 120 GW by 2050 and 200 - 220 GW by 2070.

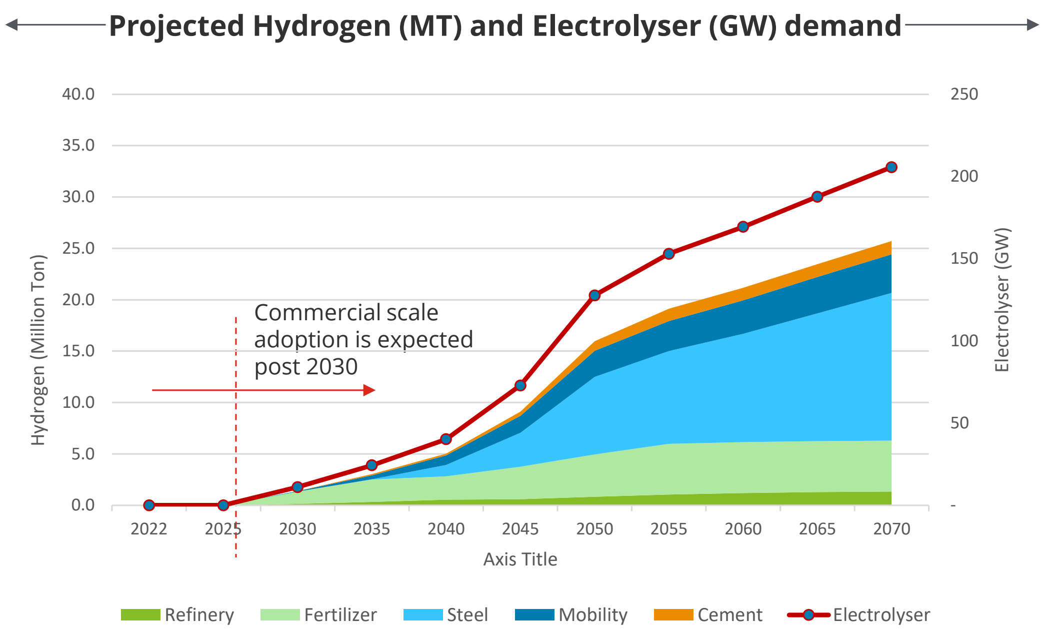


Figure 53: Green hydrogen demand till 2070, BAU

Key takeaways:

- Pace of adoption of green hydrogen may be slower in the absence of cost parity and policy drivers, such as carbon tax and sectoral mandates.
- **Steel sector** is expected to be the largest consumer in BAU scenario also.
- **Refinery and Fertilizer** may transit to green hydrogen by 2050; increased production of complex and phosphate based fertilizer (Diammonium Phosphate) will drive hydrogen adoption in fertilizer sector[44].
- **In transport**, freight vehicle is expected to see higher adoption due to higher energy density and higher payload capacity. However, passenger vehicle is expected to see limited adoption (15-20%) through a mix of FCEV and H2 engine (H2-ICE).
- **Cement and 'Other' sector** may see penetration of green H2 up to 5% of total energy consumption, mainly as an alternative fuel co-fired with coal and gas.

[44] Currently, Urea is the dominant fertilizer in India. Urea can't be decarbonized completely through green hydrogen due to process related challenges while complex fertilizer and DAP can substitute 100% grey hydrogen with green.

- **Power sector** is not expected to create a sizeable demand of hydrogen. Hydrogen based gas turbines are expected to see commercial maturity around 2035-40; however, their uses are likely to be limited as "seasonal storage".
- **Introduction of an aggressive carbon tax and policy driven sectoral mandates** are expected to drive hydrogen adoption

While the use cases for green hydrogen in the BAU scenario are expected to be similar to those in the NZS, its adoption will be lower due to less aggressive decarbonization efforts by the government and corporations. Consequently, achieving commercial parity and ecosystem development is likely to be delayed.

4.9 LiFE interventions

India is the first country to include Lifestyle for Environment-LiFE mission in its NDCs to combat climate change. On the occasion of the UN Climate Change Conference (UNFCCC COP26), Hon'ble Prime Minister of India had introduced the mission of "LiFE (Lifestyle for the Environment)" to engage individuals in mitigating the adverse effects of climate change. This initiative encourages a lifestyle that focuses on mindful and deliberate utilization of resources. These interventions introduce behavioural changes to reduce energy consumption[45].

Following 'LiFE measures', with an impact on overall energy demand, should be implemented in order to achieve India's net zero goals and objectives.

- **A behavioural shift from personal transport modes to public transport** will reduce the growth in number of private vehicles on road and subsequently help in emissions reductions. High quality and safe non-motorized and mass-transit public transport infrastructure and services will provide wide range of alternatives to private motorized vehicles.
- **In the cooking sector, gradual movement from traditional biomass to LPG to PNG to electric cookstoves is another important behavioural shift that holds potential for cooking related emission reduction**. Traditional biomass has a very low conversion efficiency of 12 – 13%, which can be improved significantly to 60-90% through shift to gas and electricity.
- In the residential segment, adoption of energy efficient appliances and shift from biomass-based heating to electrified heating would improve energy conversion efficiency.
- In the commercial segment, **energy efficient building/green building** holds potential to reduce the emission footprint.

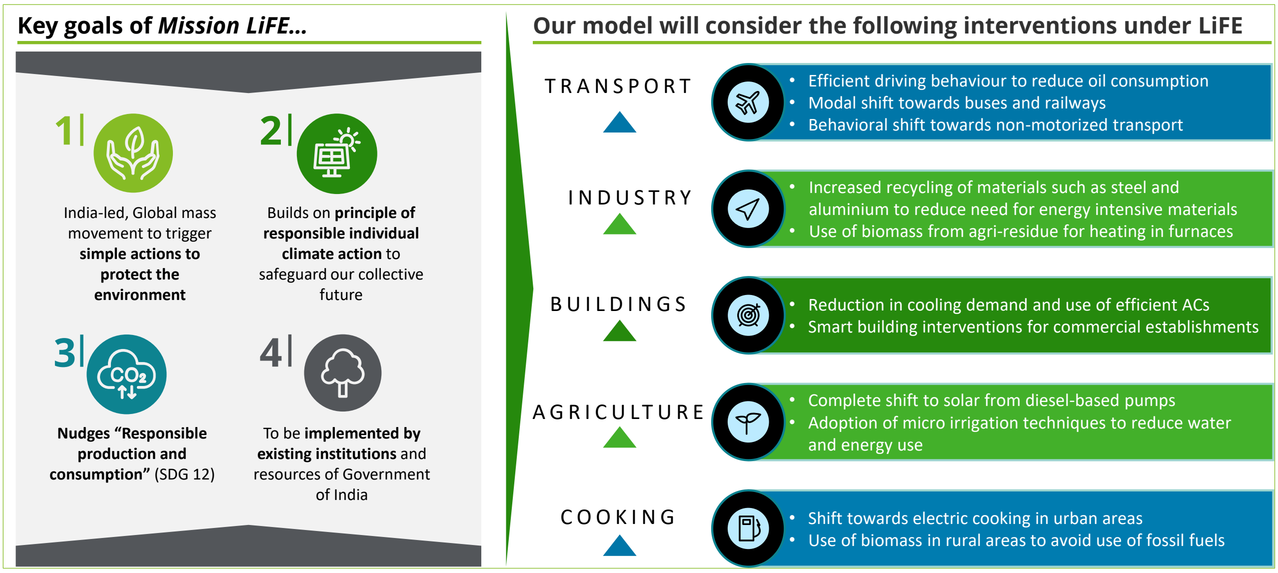


Figure 54: Principles of LiFE

Changing our lifestyle, however, is not easy. Our habits are deeply ingrained in our daily lives and are continually reinforced through several elements of our environment. Therefore, a 'pull effect' is required for this transition by introducing economic incentives and easy access of resources. Following interventions can be considered to accelerate the transition:

Transport sector interventions:

- Innovative planning of cities based on transit-oriented development, mixed land use planning and integrated transport and spatial planning.
- Development of infrastructure for railways and electrification of rail transport
- Investment in development of adequate stock of public transport
- Extension of fiscal incentives for adoption of electric vehicle and development of adequate charging infrastructure

[45] https://amritmahotsav.nic.in/lifestyle-for-environment-life.htm#:~:text=On%20the%20occasion%20of%20the,adverse%20effects%20of%20climate%20change.

Cooking sector interventions:

- Expansion of Geographical areas covered under city gas distribution.
- Investment in the downstream LPG distribution network
- Incentives for electric cookstoves, especially in rural areas, to accelerate the transition from biomass to electrification.

Building sector interventions:

- Promoting use of energy efficient lights and appliances (e.g., LED light) and defining SOPs for energy efficient use of appliances (e.g., keeping temperature of Air Conditioners to 24 deg.)
- Implementation of regulations that encourage energy-efficient construction and subsidies for the usage of sustainable materials in residential and commercial buildings.
- Setting of minimum energy performance standards for commercial buildings
- Fiscal support and financing schemes for making upfront investments in energy efficient commercial infrastructure. Incentives such as tax benefits and grants further encourage developers to embrace green building practices.

While it is difficult to measure the impact of LiFE objectively, in a populus country like India, collective impact of LiFE initiatives can lead to transformative shift in the energy consumption pattern.

5 Supply side assessment

Approach for supply side modelling is elaborated in the Section 2.2. The projected electricity demand in all sectors is fed as an input to the Optimization Module, which determines generation capacity expansion/retirement along with optimal dispatch to meet the electricity demand. Based on the overall electricity demand estimated, the supply side is simulated to meet the demand using a **Linear Programming (LP) optimization model**.

The generation mix is determined based on least cost optimization using an Integrated Resource Planning model. The model also takes into consideration the policy targets and allocations made by the Government for various end use sectors and the fuel/ technology adoption within those.

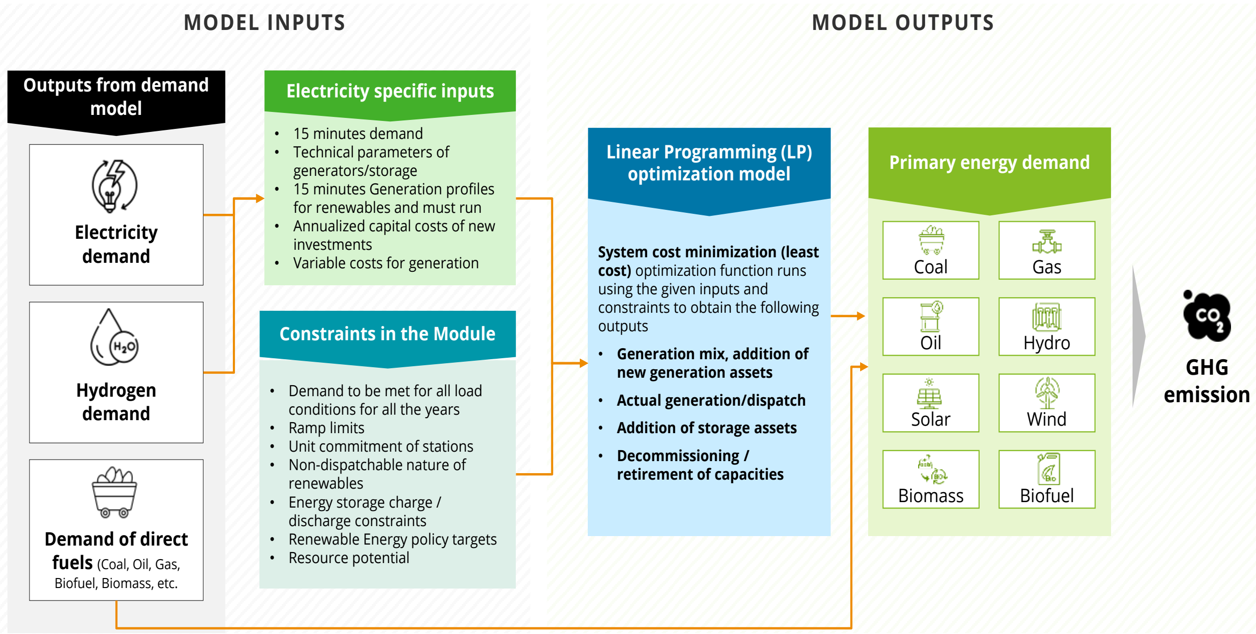
Understanding "Integrated Resource Planning"

The aggregate electricity demand and the expected trajectory of transmission & distribution (T&D) losses are passed on to the electricity supply model. The model optimizes the electricity system to satisfy specified electricity demands at the optimal costs. The study used Deloitte's proprietary least-cost Integrated Resource Planning (IRP) model which runs on an hourly (with option for 15 min time-block) resolution for each modelled year. The IRP works on a framework based on a **Linear Programming (LP)** formulation which is an internationally recognized methodology used for supply side optimization.

The future demand obtained is projected on an hourly (with an option for 15 min time-block) resolution based on historic load patterns and policy changes envisaged. Supply side data, assumptions, technical parameters, and constraints are fed into the model as variables. **The LP model, written in python, minimizes the overall system cost, including capital costs, operations and maintenance costs, fuel costs, transmission cost, etc. and is solved using commercial optimization algorithms**.

Based on supply side modelling, fuel mix for each type of energy source has been evaluated ("the source"). Emission intensity of various type fuels have been modelled and sector wise emission for each year through 2070 have been estimated. Emission intensity factors have been obtained from emission databases in the Indian context.

An illustration of the methodology for supply side model is provided below:



The results of the supply side modelling exercise depend not only on how accurately the mathematical modelling is done to mimic the physical system but also on how realistic the model assumptions are. Key assumptions are illustrated in the subsequent chapter.

5.1 Model assumptions

5.1.1 Peak demand projections and selection of representative days

The overall electricity demand growth is obtained from the demand modelling for both BAU and NZ scenarios. The peak demand growth projection is considered similar with the overall electricity demand growth in the near term; however in the long term, a lower growth rate is considered. Electricity demand growth (obtained from the demand side model) and the peak demand growth trajectory are illustrated below.

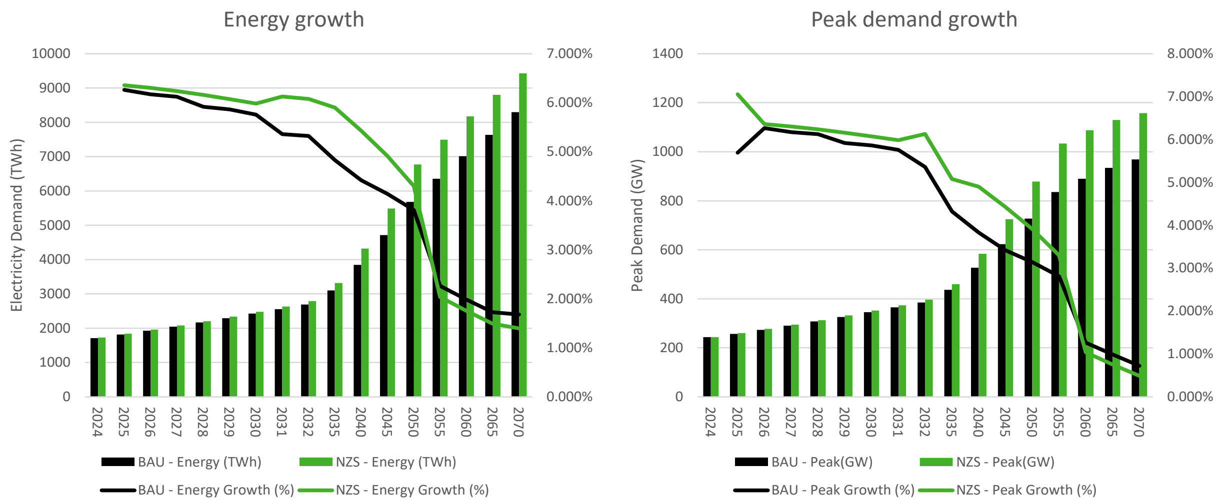


Figure 55: Electricity and peak demand growth

For modelling, 31 representative days are simulated for each year instead of simulating for all 365 days of the year. The representative days were obtained by using "k-means" clustering of net demand, which is an industry standard methodology for long-term capacity expansion models. Following figure illustrates the projected demand load duration curve and the load duration curve for the representative days considered.

Figure 56: Projected demand load duration curve and the load duration curve for the representative days

5.1.2 Existing capacities and key parameters for thermal generators

India's current power generation mix is heavy on thermal generators – coal and Gas. The data for existing coal and gas capacities is obtained from the latest available CEA database[46]. The coal plants are segregated based on the technology and the variable cost of generation as shown in in the below table. This segregation is performed to approximately simulate unit-commitment and economic dispatch while keeping the solving time of the model within reasonable time limits.

Table 2: Segregation of coal based generators

Category	Technology	Lower Bound VC (Rs/kWh)	Upper Bound VC (Rs/kWh)	Weighted Avg VC (Rs/kWh)
Sub1500	Subcritical	0.00	1.50	1.29
Sub3000	Subcritical	1.50	3.00	2.42
Sub4500	Subcritical	3.00	4.50	3.65
Sub5500	Subcritical	4.50	5.50	4.92
SC1500	Supercritical	0.00	1.50	1.30
SC3000	Supercritical	1.50	3.00	2.42
SC4500	Supercritical	3.00	4.50	3.63
SC5500	Supercritical	4.50	5.50	5.09

Data for all the thermal plants are either obtained from CEA reports or derived. The following table captures the data of all categories of the generators.

Table 3: Thermal generator data

		Technology								
		Subcritical				**Supercritical**				**Gas**
		Sub1500	**Sub3000**	**Sub4500**	**Sub5500**	**SC1500**	**SC3000**	**SC4500**	**SC5500**	**Gas**
Installed Capacity in 2024	GW	10.23	59.19	64.78	13.09	8.86	18.15	35.84	8.52	24.37
Variable Cost	Rs/kWh	1.29	2.42	3.65	4.92	1.30	2.42	3.63	5.09	-
Variable cost escalation	%/year	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%
Availability	%	85%	85%	85%	85%	85%	85%	85%	85%	85%
Technical minimum	%	40%	40%	40%	40%	40%	40%	40%	40%	20%
Ramp rates										
i. ***2024-2027***	%/min	1%	1%	1%	1%	1%	1%	1%	1%	5%
ii. ***2027-2032***	%/min	2%	2%	2%	2%	2%	2%	2%	2%	5%
iii. ***Beyond 2032***	%/min	3%	3%	3%	3%	3%	3%	3%	3%	5%
Minimum annual PLF	%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Emissions	Kg CO_2/kWh	1.05	1.05	1.05	1.05	0.89	0.89	0.89	0.89	0.338

5.1.3 Under-construction capacities and retirements of thermal capacities

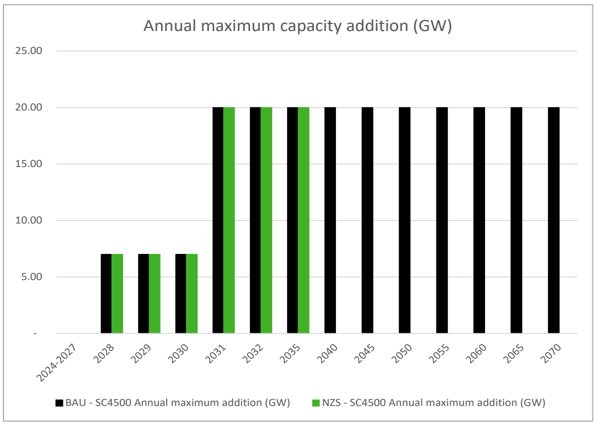
The commissioning years for the under-construction capacities are derived based on physical progress of the plant, as reported in CEA's thermal broad status report[47]. Based on available data, majority of the under-construction capacities should come online by 2029.

Gradual retirements of the existing capacities are considered as per the CEA's latest guidelines[48] and the age of the plants. This study has not considered any retirement of coal plants before 2032. From 2032 onwards, gradual retirement of older units (age > 50 years) has been considered. The retirement age for coal plants is further reduced gradually to 35 years by 2070 to decarbonize the electricity grid by 2070 in a Net Zero Scenario. For Business As Usual scenario, the retirement year has been considered as 45 years.

[46] Source: https://cea.nic.in/wp-content/uploads/pdm/2023/05/List_of_Power_Stations_31.03.2023.pdf
[47] Source: https://cea.nic.in/thermal-broad-status-reports/?lang=en
[48] Source: https://cea.nic.in/wp-content/uploads/notification/2024/02/Guidelines.pdf

5.1.4 Capacity expansion constraints for thermal generators

The supply side model is allowed to expand coal and gas capacities with certain practical constraints to limit the capacity addition. The current model has allowed capacity addition in "**SC4500"** (supercritical with VC between Rs. 3 – 4.50 per kWh) and **"Gas"** categories. Any new capacity addition other than the under-construction capacity is assumed to commence from 2028.



In the NZ scenario, coal capacity addition is allowed till 2035, whereas in the BAU scenario, the model has freedom to add coal capacity during the entire simulation horizon (till 2070) after 2028.

For both the scenarios the maximum gas capacity additions are assumed to be same. Any new capacity for gas is considered to be capable of blending green H_2.

5.1.5 Renewable generators – Retirement and CUF

The overall share of RE generation capacities has grown significantly over the past decade in India. The existing installed capacity data for different RE technologies is obtained from the latest reported data by CEA and MNRE. The under-construction capacity data for RE projects is obtained from the project monitoring portal of CEA[49]. Considering low gestation period of RE projects, majority of the under construction solar PV and onshore wind projects are expected to come online by 2028. Retirement year of RE capacities is considered as 25 years; for hydro and biomass-based generation capacities no retirement is considered.

With continuous evolution of Renewable technology, efficiency and Capacity Utilization Factor (CUF) of renewable projects are likely to improve. This study has considered gradual improvements in the CUF for solar PV and onshore wind technology. For onshore wind, the new capacity addition is further bifurcated based on the locational CUF as certain regions within India have better wind profiles as compared to other regions. The table illustrates the comparison of CUF of existing RE capacities and new RE capacities.

Category	Solar (existing)	Solar (New)	Onshore Wind (Existing)	Onshore Wind New (low CUF)	Onshore Wind New (high CUF)
CUF (%)	20%	25%	20%	28%	36%

5.1.6 Capacity expansion constraints for RE

The overall capacity additions constraints for different RE technologies are considered in the supply side model. For NZ scenario, higher annual capacity addition is considered as compared to the BAU scenario.

Table 4: Annual maximum capacity addition constraint data for non-fossil technologies (GW), NZS

NZS	2025-30	2030-35	2035-40	2040-45	2045-50	2050-55	2055-60	2060-65	2065-70	2070
Solar	18	30	40	50	84	120	128	136	160	200
Hydro	3	1	2	2	4	4	4	4	4	4
Onshore Wind - LCUF	7	8	15	27	33	40	50	60	70	80
Onshore Wind - HCUF	0	10	10	12	15	16	20	24	28	32
Offshore Wind	1	5	5	7	10	13	16	19	22	25
Rooftop	4	4	12	12	12	15	18	21	24	30

[49] Source: https://cea.nic.in/renewable-generation-report/?lang=en

Table 5: Annual maximum capacity addition constraint data for non-fossil technologies (GW), BAU

BAU	2025-30	2030-35	2035-40	2040-45	2045-50	2050-55	2055-60	2060-65	2065-70	2070
Solar	15	20	20	36	45	54	63	72	81	90
Hydro	3	1	2	2	4	4	4	4	4	4
Onshore Wind - LCUF	6	5	8	16	24	32	40	40	40	40
Onshore Wind - HCUF	0	5	6	10	10	10	10	10	10	10
Offshore Wind	1	5	5	7	10	13	16	19	22	25
Rooftop	4	4	8	12	12	14	16	20	24	28

Likewise, the model also considered constraints on minimum capacity addition of each technology.

In addition to minimum and maximum capacity addition, the supply side model also assumes constraints on maximum potential till 2070, as illustrated below:

Table 6: Capacity constraints for supply side

Technology	Capacity constraints for NZS
Coal	• No capacity addition after 2035 • No retirement till 2032; afterwards retirement year will be in between 35 – 40 years depending on system cost
Gas	• No addition of Gas
Hydro	• Maximum potential 140 GW by 2070
Solar	• Maximum potential 3600 GW by 2070
Wind Onshore	• High CUF (38% average): 200 GW by 2070 • Low CUF (30% average): 1100 GW by 2070
Wind Offshore	• Maximum potential 150 GW by 2070
Nuclear	• Maximum potential 150 GW by 2070
BESS	• No Limitation
PSP	• Maximum potential 100 GW

5.1.7 Energy storage assumptions

As the variable RE generation share increases within the generation mix of the grid, the requirement of flexible resources also increases for reliable operations. Short duration storage is expected to play an important role in successful integration of variable RE capacities. In this study, 6-hr Pumped Storage (PSP), and 4-hr and 6-hr BESS are considered as short-term storage technologies[50].

Daily operations of short-term storage would depend on several parameters, such as the storage duration, daily cycle limits, degradation etc. The following table summarizes key assumptions on energy storage for developing the supply side model.

Table 7: Short-term storage operational parameters

	Technology			
	BESS		PSP	
	4-hour	8-hour	6-hour	Comments
Storage duration (hours)	4	8	6	
Daily cycle limit (No.)	1.5	1	1	
Round-trip-efficiency (%)	85%	85%	75%	

[50] 2 hour BESS is not considered considering 4-hour will be economically viable from 2025 onwards

	Technology			
	BESS		PSP	
	4-hour	8-hour	6-hour	Comments
Degradation (%)	-	-	-	No degradation is considered for modelling purpose. It is assumed that the storage will be oversized by 20%. Appropriate capital cost escalation is considered.
Retirement age (years)	15	15	-	No retirement for PSP capacities is assumed.

The supply side model also accounted constraints pertaining to domestic manufacturing and import for short-term storage. Despite slow uptake of energy storage in the recent past, future RE capacity addition is expected to be accompanied with rapid adoption of storage for integration.

5.1.8 Long-term or seasonal energy storage

Short-term storage solutions capture the daily variations in renewable energy (RE) generation, while long-term or seasonal storage addresses the seasonal fluctuations in RE generation, particularly from wind. In India, wind-based RE generation shows notable weekly variations, with significant seasonal differences. Oversizing wind generation can lead to systemic issues like curtailment during periods of excess generation. During low-wind periods, there is a greater dependence on firm sources such as coal and gas. In a low-carbon scenario, deploying long-term or seasonal storage could be a potential solution to manage these variations. Such storage systems can capture excess energy generated during high-wind seasons and supply electricity to the grid during periods of low wind generation, with minimal energy loss.

Hydrogen storage is considered a leading option for seasonal storage. Hydrogen can be stored for extended periods in steel tanks (spherical or bullet storage) with minimal leakage, making it an ideal energy carrier for long durations. This study considers hydrogen-based long-term storage, which can be utilized in dedicated hydrogen turbines or retrofitted gas turbines capable of co-firing hydrogen with natural gas. Electrolysers, located near the hydrogen turbines, will generate the hydrogen.

The overall efficiency of long-term storage operations will depend on the efficiency of the electrolysers and the turbines used, whether dedicated hydrogen turbines or hydrogen-enabled natural gas turbines. The supply-side model assumes a 30% round-trip efficiency for seasonal storage. While the technical maturity of hydrogen-fired turbines is already established, dedicated hydrogen turbines and hydrogen-compatible gas turbines are assumed to become commercially viable after 2035 in both BAU and NZ scenarios.

5.1.9 Electricity demand response

The energy model has considered demand side response from agricultural electricity demand - the assumption is 80% of the non-solar agricultural demand would be shifted to solar hours. This would enable higher utilization solar PV capacities and reduce the demand during non-solar hours when expensive flexible resources are required to be dispatched. An illustration of the effective demand after shifting the agricultural load (for 2029) is shown in the figure below:

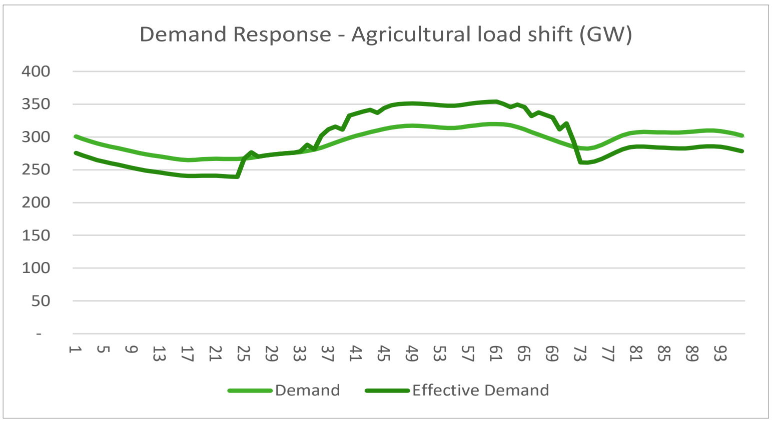


Figure 57: Illustration of demand response (Peak demand day in 2029)

5.1.10 Cost assumptions for new capacities

Reductions in overall capital requirements are also anticipated across various renewable energy technologies, much like the expected improvements in efficiency.

Table 8: Capital costs for new capacities (INR Cr/ MW)

	Technology										
	Coal	Gas	Solar	Onshore Wind	Offshore Wind	Hydro	Nuclear	Biomass	PSP	BESS (4-hr)	BESS (8-hr)
2024	10.00	4.50	4.40	7.50	17.00	10.00	23.00	9.00	6.00	6.48	9.72
2025	10.00	4.50	4.33	7.50	17.00	10.00	23.00	9.00	6.00	6.35	9.53
2030	10.00	4.50	4.12	6.78	13.15	10.00	23.00	9.00	6.00	5.74	8.61
2035	10.00	4.50	3.92	6.13	10.18	10.00	23.00	9.00	6.00	5.19	7.78
2040	10.00	4.50	3.90	6.13	8.74	10.00	23.00	9.00	6.00	4.69	7.04
2045	10.00	4.50	3.90	6.13	8.31	10.00	23.00	9.00	6.00	4.24	6.36
2050	10.00	4.50	3.90	6.13	8.31	10.00	23.00	9.00	6.00	3.83	5.75
2055	10.00	4.50	3.90	6.13	8.31	10.00	23.00	9.00	6.00	3.83	5.75
2060	10.00	4.50	3.90	6.13	8.31	10.00	23.00	9.00	6.00	3.83	5.75
2065	10.00	4.50	3.90	6.13	8.31	10.00	23.00	9.00	6.00	3.83	5.75
2070	10.00	4.50	3.90	6.13	8.31	10.00	23.00	9.00	6.00	3.83	5.75

Table 9: Operational costs assumption for capacity expansion

	Technology										
	Coal	Gas	Solar	Onshore Wind	Offshore Wind	Hydro	Nuclear	Biomass	PSP	BESS (4-hr)	BESS (8-hr)
Annual O&M cost (% of capex)	2.2%	1.2%	1.0%	1.5%	25.0%	2.0%	1.2%	2.0%	2.0%	1.25%	1.25%
Plant lifetime (years)	40	30	25	30	30	40	40	20	40	15	15

5.2 Outcome of supply side modelling – Net Zero Scenario

5.2.1 Electricity and peak demand growth

In a net zero scenario, electricity demand is expected to be higher than business-as-usual scenario due to increased electrification in all sectors – industry, transport, building and cooking and increased penetration of hydrogen in the hard-to-abate sectors. The utility generation demand is expected to grow at a CAGR of 3.5 – 4% between 2024 and 2070. However, growth rate in the initial years is expected to be higher (~5.5% between 2024-50).

Utility electricity demand is expected to grow to 9000 – 9500 BU by 2070 and RE demand for green hydrogen is likely to grow to 2700 – 3000 BU.

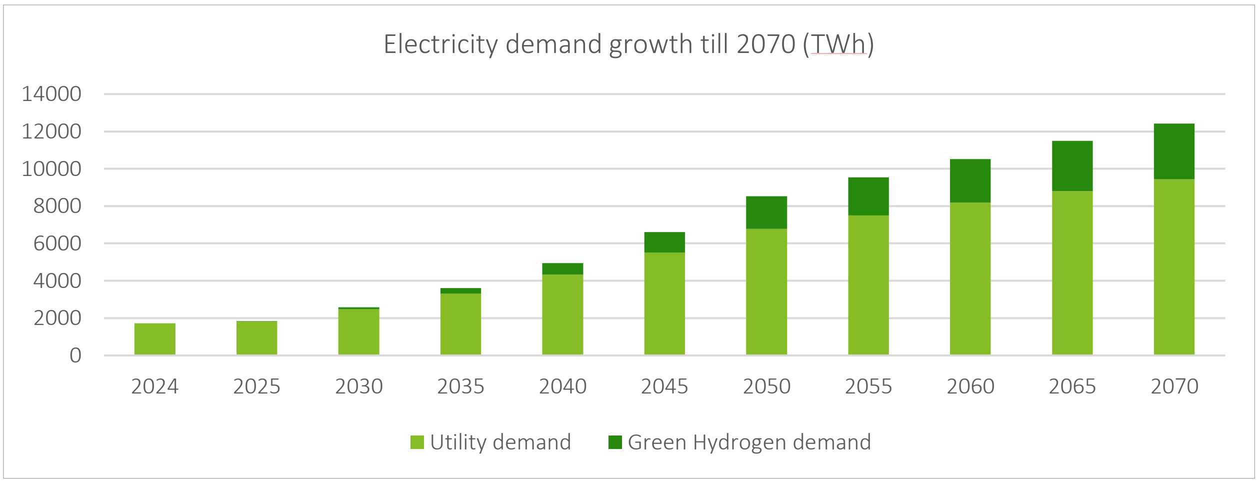


Figure 58: Electricity demand growth projection till 2070, NZS

During the same period, Peak demand is expected to increase at a CAGR of 3 – 3.5%, with 850 – 900 GW by 2050 and 1100 – 1200 GW by 2070. Growth in peak demand is expected to be lower than electricity demand due to flattening of load curve due to load shifting activities in industry and agriculture segment.

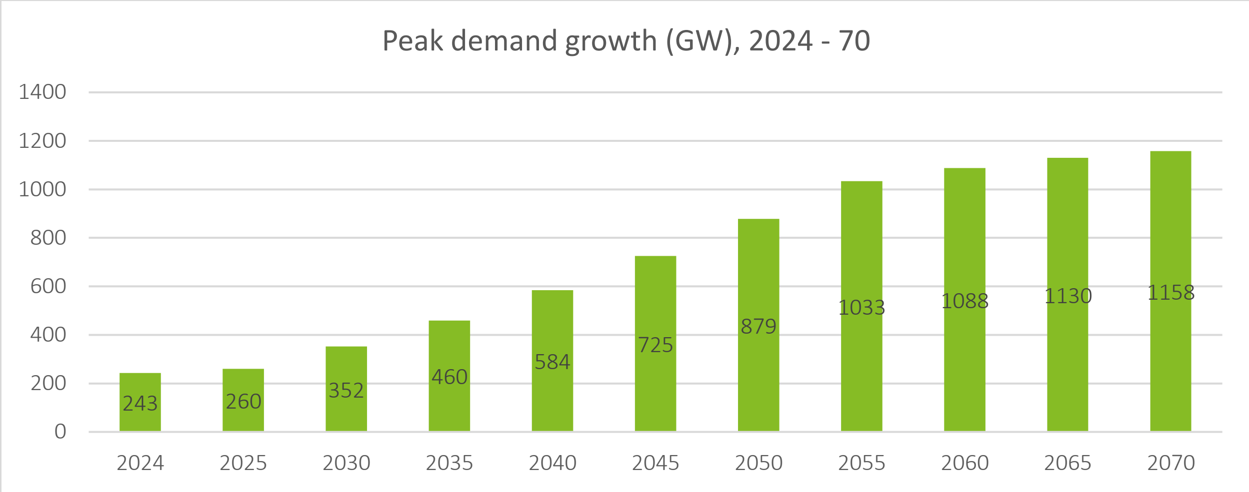


Figure 59: Peak demand growth projection till 2070, NZS

5.2.2 Capacity mix in Net Zero scenario

The electricity sector is the highest contributor to GHG emissions, and therefore decarbonisation of electricity would be key to achieving India's net zero ambition. This will require a substantial uptake of non-fossil energy sources – solar, wind, nuclear, hydro and others. The demand for electricity is expected to increase more rapidly than the overall energy demand due to electrification of everything – industry, transport, building and cooking. The share of electricity in the final energy consumption is expected to rise from 16 percent in 2022 to 55-60 percent by 2070. Most of this electricity will be supplied through non-fossil-fuel-based electricity sources. Integration of variable renewable energy will be supported by ensuring a robust transmission system and deployment of long duration (including seasonal energy storage) solutions.

Construction of new coal-based power plants is expected till 2035 to meet the overall electricity demand as well as peak demand. Post 2035, no new capacity addition of coal-based power plant is considered. Further, Green Hydrogen is expected to find applications in fertiliser, refineries, steel production, cement kiln, gas distribution network and transport sector.

Based on supply side assumptions and constraints, the Linear Programming (LP) model provides the capacity (GW) trajectory for a Net Zero scenario, as illustrated below:

Table 10: Capacity expansion projection till 2070, NZS

		2024	2030	2035	2040	2045	2050	2055	2060	2065	2070
Utility (GW)	Coal	219	264	287	267	254	234	163	101	66	0
	Gas	24	24	24	20	16	16	16	13	13	13
	Solar (Utility)	74	216	280	471	761	1095	1534	2014	2344	2599
	Solar (Rooftop)	13	25	90	150	210	270	350	390	450	540
	Wind	45	82	206	366	564	751	967	1186	1247	1360
	Wind Offshore	0	5	30	60	90	120	120	130	140	150
	Hydro	56	70	80	90	110	130	140	140	140	140
	Nuclear	7	18	34	45	60	80	100	120	140	150
	Biomass	11	14	16	18	20	22	24	26	28	28
	PSP	5	12	16	24	31	41	51	71	88	88
	BESS (4 hour)	0	27	56	159	282	553	800	1000	1200	1500
	BESS (8 hour)	0	0	20	70	150	200	250	300	350	400
	Seasonal storage (H2 based)	0	0	0	0	3	16	36	68	110	132
Capacity for GH2 (GW)	Solar	0	17	32	87	139	205	266	386	606	978
	Onshore	0	3	3	14	43	105	164	164	153	125
	Storage for GH2 (4 hours)	-	9	36	38	32	116	500	700	900	1500

Source: Modelling output

Note: The outputs presented above are based on mathematical modeling. However, actual capacity expansion may vary due to factors such as supply chain constraints, execution challenges, and other real-world limitations.

The expected generation mix in the net zero scenario, as derived through supply side modelling, is illustrated below:

Table 11: Generation mix projection till 2070, NZS, TWh

	2024	2030	2035	2040	2045	2050	2055	2060	2065	2070
Utility										
Coal	1224	1410	1525	1532	1416	1316	762	382	230	0
Gas	0	0	0	0	0	0	0	0	0	0
Solar (Utility)	133	451	596	1026	1692	2459	3446	4522	5264	5836
Solar (Rooftop)	17	34	122	203	285	366	475	528	610	732
Wind	74	170	506	959	1494	2003	2574	3148	3332	3686
Wind Offshore	0	22	129	258	388	517	517	560	603	646
Hydro	187	233	266	300	366	433	468	468	468	468
Nuclear	52	129	240	315	420	561	701	841	981	1051
Biomass	28	35	43	48	53	58	64	69	73	73
Net Imports	10	24	52	69	86	103	121	138	155	172
Storage loss										
PSP	-1	-3	-1	-4	-8	-9	-13	-28	-33	-36
BESS (4 hour)	0	-6	-12	-35	-69	-124	-204	-293	-368	-482
BESS (8 hour)	0	0	-5	-21	-50	-61	-86	-121	-145	-168
H2 turbines	0	0	-3	-69	-132	-226	-336	-427	-550	-581
Sold to GH2 Offgrid (GH2)	0	-4	-22	-51	-149	-272	-338	-413	-409	-272
Excess/Curtailed	0	0	0	35	74	155	-159	-657	-862	-1140
Green Hydrogen										
Solar for GH2	0	38	72	196	312	460	596	867	1361	2197
Onshore Wind for GH2	0	9	9	36	125	278	425	425	399	310
Purchase from Grid	0	4	22	51	149	272	338	413	409	272
Total Generation	**1725**	**2546**	**3539**	**4814**	**6378**	**8135**	**9509**	**11079**	**12379**	**13903**

Source: Modelling output

In an alternate scenario, if coal plants are not decommissioned after 2060, requirement of BESS and installed RE would decline. However, the impact will not be significant as coal-based power generation is likely to be very costly due escalation of coal price and logistics cost (coal price escalation is assumed as 3.5% y-o-y). In this scenario, nearly 50 - 100 GW of coal capacity is expected to operate as peaking power stations, reducing the overall BESS requirement by 1500 – 2000 GWh.

Key takeaways:

- Coal based installed capacity peaks in 2035 at 287 GW. Apart from under-construction capacity of ~26 GW as on March 2024, 35-40 GW new capacity is likely to be finalized and commissioned between 2024 – 2035. After 2035, no coal based capacity addition is envisaged.
- Rapid decommissioning of coal based plant (mainly driven by completion of economic life) may be required after 2050 to green the grid. The gap in base load arising out of coal based capacity decommissioning must be bridged through renewables integrated with storage system, nuclear and hydro capacity.
- Solar, Wind, Hydro are likely to hit the maximum potential of 3500 GW, 1500 GW (onshore), 150 GW (Offshore) and 140 GW respectively. Nearly 45–50 GW of annual RE capacity addition is required for grid decarbonization till 2050; this is likely to be multifold 150 – 180 GW per year from 2050 -70, similar to what China has achieved during 2023 - 24.
- In terms of generation, Solar is expected to contribute 60-65% of electricity demand by 2070, followed by Wind (26 – 28% Onshore), Nuclear (~7%), Offshore wind (~5%) and Hydro (~4%). Rooftop deployment would be critical to decarbonize the residential and commercial segments.
- **India would require 12 – 14 million Acres land till 2070 for RE resources in a low carbon scenario, which is 10 – 11% of India's wasteland (~140 million acre).** Solar alone would require 9 – 10 million acres while wind would require another 3 – 4 million acres by 2070.
- Wind power potential can be realized at 150m Hub height.

- To achieve net-zero by 2070, Energy Storage System (ESS) deployment is expected to grow multi-fold with new long-duration energy storage technology gaining maturity. Short-duration energy storage systems would be sufficient in the ongoing decade. Later years would require a significant amount of Long-duration Energy Storage (LDES) systems, such as eight hours of battery storage, and H2 storage (to be fired in the gas turbine). Therefore, energy storage systems for stationary grid applications must evolve beyond lithium-ion technologies, such as sodium ion technology, GH2-based storage solutions for seasonal storages, etc. The quantum increases multifold in later years due to gradual phasing out of coal based generation. Cumulative energy storage requirement may grow to 3500 – 4000 GWh by 2050 and 12000 – 15000 GWh by 2070.
- It is believed that trend of cost reductions for solar and wind as well as battery storage technologies over the past decade could continue, allowing India to build a sustainable and affordable power system through renewables.
- Hydro and nuclear power will also play a crucial role in grid decarbonisation. In the absence of coal based capacity, Nuclear is expected to provide baseload support.
- In addition to domestic capacity addition, hydro import from Nepal and Bhutan would be critical; import of 150 - 180 BU is expected by 2070.
- Green Hydrogen (GH2) is expected to play an important role in this energy transition, particularly in decarbonising the "hard-to-abate" sectors that cannot be electrified easily. In a net zero scenario, total green hydrogen demand is expected to be 55-60 million tons annually, driven by decarbonization of Steel, Fertilizer, Refinery and Freight transport sector. Renewable energy requirement for green hydrogen production is expected to reach 1600 – 1700 BU by 2050 and 2800-3000 BU by 2070.
- Green hydrogen will be powered through off-grid or captive renewable projects as well as grid as the emission intensity of grid declines gradually.
- No gas-based capacity addition has been considered due to shortage of domestic gas. Some of the existing gas stations are expected to be retrofitted for Hydrogen blending. New Hydrogen turbines are likely to be installed as seasonal storage. Seasonal storage (H2 turbine based) deployment is expected to kick-in in 2035, which is would gradually increase to 130 – 150 GW by 2070.

Developing a robust domestic manufacturing ecosystem is essential to mitigate risks associated with supply chain disruptions and geopolitical factors. At present, the manufacturing ecosystem is in its early stages and needs substantial enhancement to support India's ambition of achieving net-zero emissions.

Table 12: Inda's manufacturing demand for clean technologies

Category	Unit	Annual demand			Comments
		2024 - 30	2030 - 50	2050 - 70	
Solar upstream manufacturing	GW	30 - 40	50 - 60	100 - 120	Integrated manufacturing from polysilicon to module is the critical to achieve supply chain sustainability and cost leadership
Wind turbine	GW	5 – 8	25 - 35	35 - 45	Focus should be on high capacity WTG for onshore as well as offshore projects
BESS (Stationary storage)	GWh	5 - 8	100 - 150	250 - 350	Manufacturing capability should be developed at both cell and pack level
BESS (mobility)	GWh	10 – 20	100 - 200	150 - 250	
Electrolyser	GW	1- 2	8 - 10	10 - 20	Demand is expected to increase multifold post 2030 driven by industrial decarbonization and emergence of H2-turbine as seasonal storage

Source: Estimated

Note: Above figures are only to meet domestic demand. In case of export, additional capacity is required.

5.2.3 Future of coal based projects

With rapid greening of the grid, coal based plants are expected to lose share in the overall electricity mix. The share of coal is expected to decline from ~71% in 2024 to 35 - 37% in 2040, 18 – 20% in 2050 and 4-5% by 2060. Decommissioning of total fleet would by 2070 would be critical to achieve the net-zero target.

While the share of coal would decline, the operating plants are expected to maintain a healthy utilization factor (PLF) till 2050, mainly driven by rapid increase of demand due to higher level of electrification. The Net-Zero scenario also considers introduction of a carbon price in 2035 (USD 100/ton), which would accelerate the decommissioning of higher cost thermal plants.

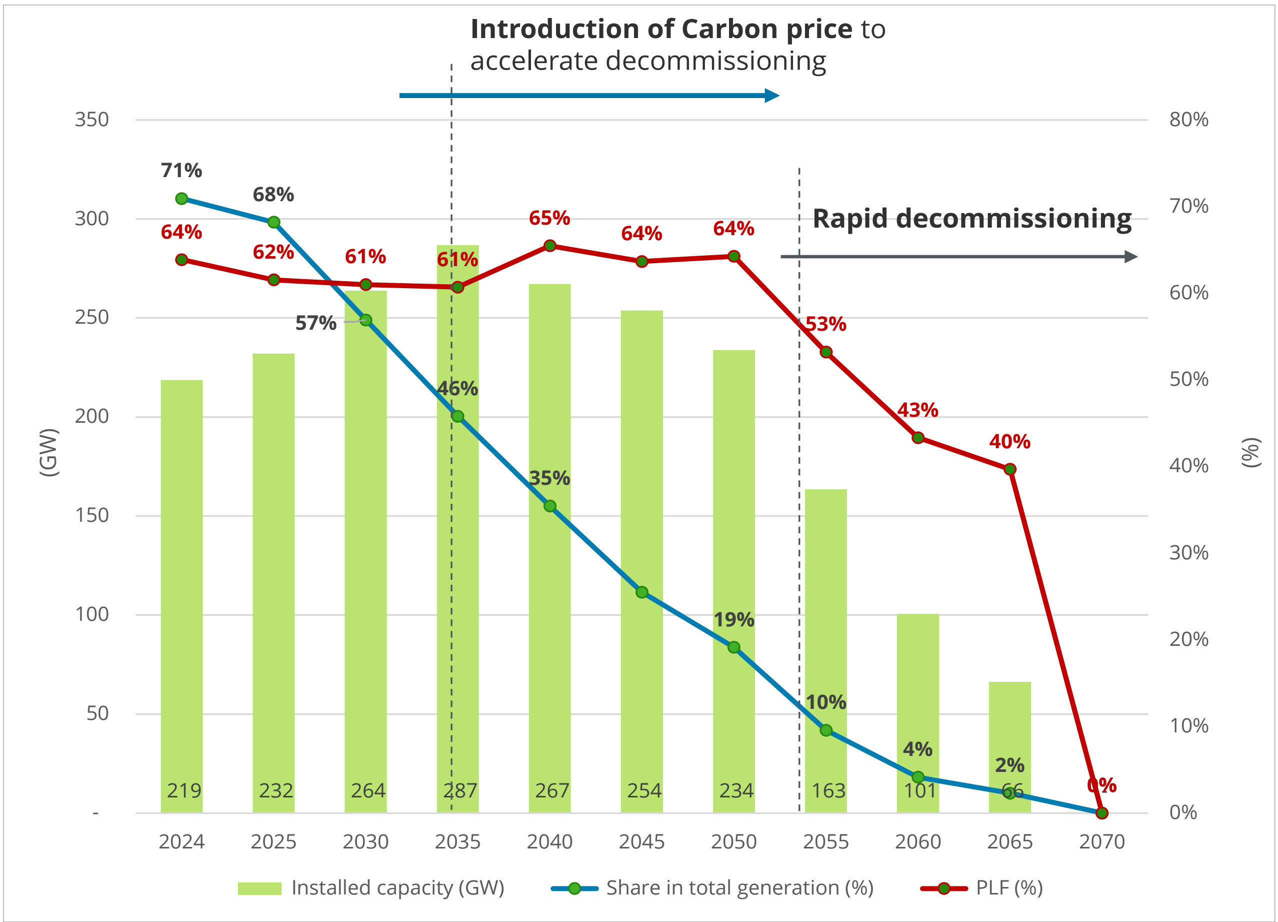


Figure 60: Future operating trajectory for coal based TPP, NZS

5.2.4 Trajectory of primary energy mix

In the NZS, India's primary energy in 2070 is expected to increase by 40 – 50% from the 2022 level. To meet the emission reduction targets, there will be substantial uptake of cleaner sources of energy, especially solar and wind in a net zero scenario.

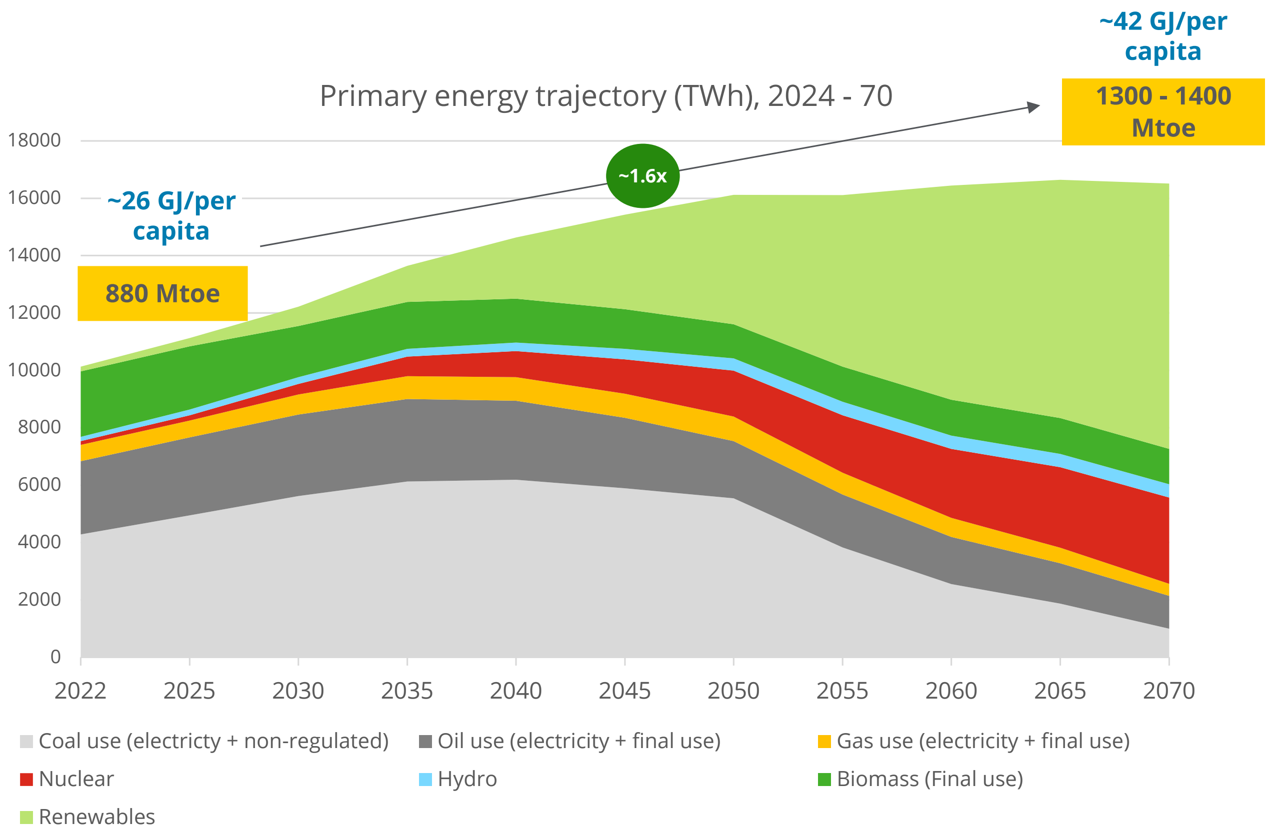


Figure 61: Projection of primary energy mix till 2070, NZS

India's per capita energy consumption is projected to rise from approximately **26 GJ in 2022 to 40–45 GJ by 2070**. However, this remains significantly lower than the per capita energy consumption in developed nations, which ranges from **65 to 85 GJ,** and in high-growth economies like China, where it exceeds 100 GJ. **It is important to note that India's per capita energy consumption is expected to be more efficient, driven by advancements in technology and improved utilization of infrastructure and assets.**

Key takeaways:

- **Renewable:** Renewable energy (Solar and Wind) is expected to meet 55 – 60% of primary energy by 2070. Contribution of renewables will be driven by decarbonization of grid and increased production of green hydrogen. However, challenges related to rapid uptake of renewables (e.g., land availability, supply chain, domestic ecosystem etc.) need to be addressed.
- **Coal:** Coal is expected to contribute 6 – 8% of primary energy by 2070, driven by use in the industry sectors, such as Cement and MSME sectors. Contribution of coal as a source of primary energy is expected to peak around 2035-40, driven by demand from electricity generation and industry sector consumption, such as steel, cement, petrochemical etc. A carbon tax is expected to be introduced around 2035, with the share of coal anticipated to begin declining shortly thereafter.
- **Oil**: The share of oil in the energy mix is projected to be around 6–8% by 2070, primarily due to freight transport. Oil's contribution to the primary energy mix is expected to peak around 2035–2040, driven by demand from the transportation sector. This share is anticipated to decline as the transition in transport sector gains momentum, including the adoption of Zero Emission Vehicles (ZEVs), aviation decarbonization, and a shift towards public transport.

- **Gas:** Gas is expected to be utilized in industries for heating and in cooking (PNG), contributing around 3–4% to the overall primary energy mix. However, the limited availability of domestic gas and the high cost of imported LNG are significant barriers to its wider use.
- **Nuclear and Hydro:** While increasing the penetration rate of renewables is a clear part of the solution to reaching carbon neutrality, Nuclear and Hydroelectric energy will remain as critical element for India's Net Zero ambition.
    - In addition to providing low carbon electricity, nuclear energy can facilitate the integration of high shares of renewables and support both long term energy security and climate resilience. Nuclear energy has also the potential to provide heat and hydrogen that can be used to decarbonize processes and activities that are less suited to electrification. Commercial scale adoption of Small Modular Reactor (SMR) has not been considered for India due to higher cost of technology and challenges associated with regulations and managing safety for small scale use.
    - Nuclear energy is projected to contribute about 14–15% to the overall primary energy mix by 2070, with an installed electricity generation capacity reaching 150 GW. Currently, India's nuclear power capacity stands at 6,780 MW, with plans to add 21 new atomic power units totaling 20,000 MW by 2032. However, challenges such as fuel import dependency and lengthy gestation periods must be addressed.
    - India has an estimated hydroelectric potential of around 140 GW, which should be fully utilized. Additionally, the country will need to import hydropower from neighboring countries like Nepal and Bhutan. By 2070, hydropower is expected to account for 2–3% of the overall primary energy mix.

5.2.5 Emission trajectory

India is the third largest global emitter of greenhouse gases (GHG), largely due to its coal-dominated primary energy mix, as elaborated in this report. However, its emissions per capita and carbon emission intensity per unit GDP (PPP) are lower than global average. India's GHG emissions are primarily driven by the coal-dominated energy mix, particularly in the power and industrial sectors, followed by oil and gas.

In the industrial sector, iron and steel, cement, aluminum, and pulp and paper account for about half of the total energy demand. A large proportion of the energy demand in these industries is met through either fossil fuels like coal and oil or electricity from captive thermal power plants (coal accounts for about ~80 percent of the total captive capacity of 75 GW). Heavy reliance on fossil-based energy makes the Industrial sector one of the largest contributors to emissions in India after electricity generation sector.

Transport sector contributed around 12-13 percent of the total emissions in 2022. Importantly, the transport sector accounts for more than 50 percent of the total oil demand in India. Oil demand for road freight transport in India has tripled since year 2000, highest after China with more than 45 percent of emissions from road transport in India coming from trucks.

CO_2 emissions under the NZS is expected peak around 2035 - 40 and gradually come down to 700 - 800 Mt CO2 by 2070. These residual emissions must be abated through mix of deployment of Carbon Capture and Storage (CCS) and through carbon sequestration through afforestation.

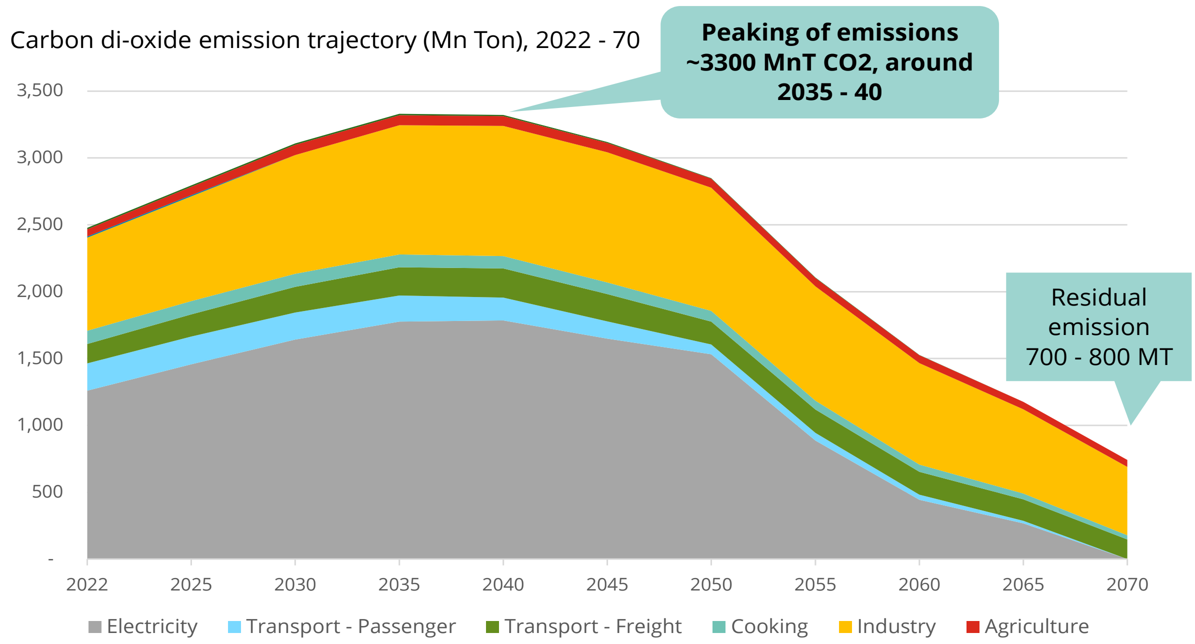


Figure 62: Emission trajectory till 2070, NZS

The residual emissions are most likely to be contributed by hard to abate sectors like Cement, Petrochemical and few MSME industries. The cement sector is considered the most viable sector for the adoption of CCS. In this sector, CO_2 is emitted as a result of the clinker production process – ~50 percent of total emissions from cement production are process emissions, and they can only be eliminated by adoption of suitable "Carbon Removal Methodologies", such as Carbon Capture and Storage (CCS). Globally, cement producers are relying heavily on CCS to achieve their net-zero target. India must explore suitable "Carbon Removal Methodologies" to abate the residual emissions from industries and other sub-sectors.

Carbon Di-oxide Removal (CDR) Methods – Options for India

As a developing nation with a growing economy, India faces significant challenges in managing its carbon emissions while maintaining its economic growth trajectory. Carbon Dioxide Removal (CDR) methods play a vital role in achieving climate goals. Various CDR methods should be explored for abating the residual emission:

Afforestation and Reforestation:

- Afforestation (planting trees in areas that were not previously forested) and reforestation (restoring forests in areas where they have been depleted) are among the most straightforward and cost-effective CDR strategies. Trees naturally absorb CO_2 from the atmosphere during photosynthesis, storing carbon in biomass and soil.
- India has a strong tradition of forestry and a wide range of ecosystems that can support tree planting. The country's existing programs, such as the Green India Mission and the National Afforestation Programme, can be scaled up to sequester more CO_2. However, issues like land availability, water scarcity, and maintaining biodiversity need careful consideration.
- As per ISFR2021, the total forest cover of the country is 7,13,789 km2 which is 21.71% of the geographical area of the country[51]. India has committed to increasing its forest cover from to more than 30% by 2030, which could create a carbon sink of **2.5–3 billion tonnes of CO2-equivalent**. Achieving this ambitious target requires a well-planned strategy taking into consideration all possible interventions within the forests and all other available lands. Some of the initiatives may include afforestation in wastelands, restoration of impaired forest, green corridor along highway, plantation along railways etc.

Soil Carbon Sequestration

- This is another nature-based solution which holds potential. This method involves increasing the carbon content of soils through practices like no-till farming, cover cropping, agroforestry, and the use of biochar.
- With its vast agricultural sector, India has significant potential to enhance soil carbon sequestration. Sustainable agricultural practices are being promoted under initiatives such as the National Mission for Sustainable Agriculture.
- Farmers may require incentives and support to adopt new practices. The impact on carbon sequestration can vary widely depending on local conditions, such as soil type and climate

Carbon Capture, Utilization and Storage (CCUS)

- CCUS is a technology-based solution. It involves using chemical processes to capture CO_2 directly from the air. The captured CO_2 can then be stored underground or utilized in industrial applications. CC(U)S is the only way to abate emission in the industrial sub-sectors where electrification or use of green fuel can't be scaled-up beyond a certain limit.
- CCUS is well-suited to the cement sector since 50% of total emissions are process emissions and cannot be eliminated through fuel-switch alone. Use of high-concentration emissions stream also reduces the cost of CCUS compared to Direct Air Capture (DAC) from the atmosphere.
- As of 2025, CC(U)S is currently cost prohibitive as well as potential geological storage sites have not been identified in India. However, in an NZS, 400 – 500 Million Ton CC(U)S capacity is envisaged to abate the residual emission (while the rest can be abated through other CDR methods). Significant focus on site identification and investment in research, development, and infrastructure are needed to make this technology viable in India.
- Some of the newer supercritical thermal power plants which have higher energy efficiency and have end of life expected near 2070, may be considered for retrofitting with CCUS from the point of view of grid stability and energy security. Many of India's renewable energy resources are located near the land borders and are reliant on critical imported minerals.

[51] https://pib.gov.in/PressReleasePage.aspx?PRID=1849867

5.3 Outcome of supply side modelling – Business As Usual Scenario

5.3.1 Electricity and peak demand growth

In the BAU scenario, electricity demand is projected to be lower than in the NZS scenario due to less aggressive electrification in the industry, transport, and building sectors, as well as a slower adoption of green hydrogen in industrial sub-sectors. Utility generation demand is expected to grow at a CAGR of 3–3.5% from 2024 to 2070, with a higher growth rate of around 5% anticipated in the initial years (2024–2050).

By 2070, utility electricity demand is expected to reach 8,000–8,500 BU, while renewable energy demand for green hydrogen is projected to grow to 1,100–1,200 BU, which is about 50% lower than in the NZS scenario.

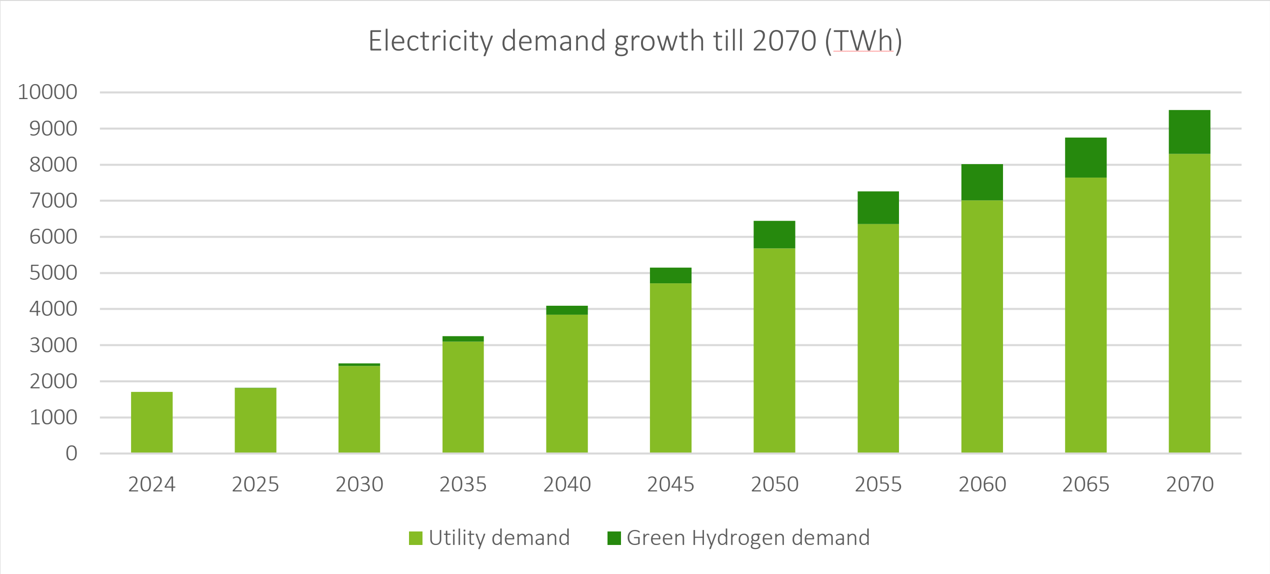


Figure 63: Electricity demand growth till 2070, BAU

During the same period, Peak demand is expected to increase at a CAGR of ~3%. Peak demand is expected to grow to 700 – 750 GW by 2050 and 900 – 1000 GW by 2070.

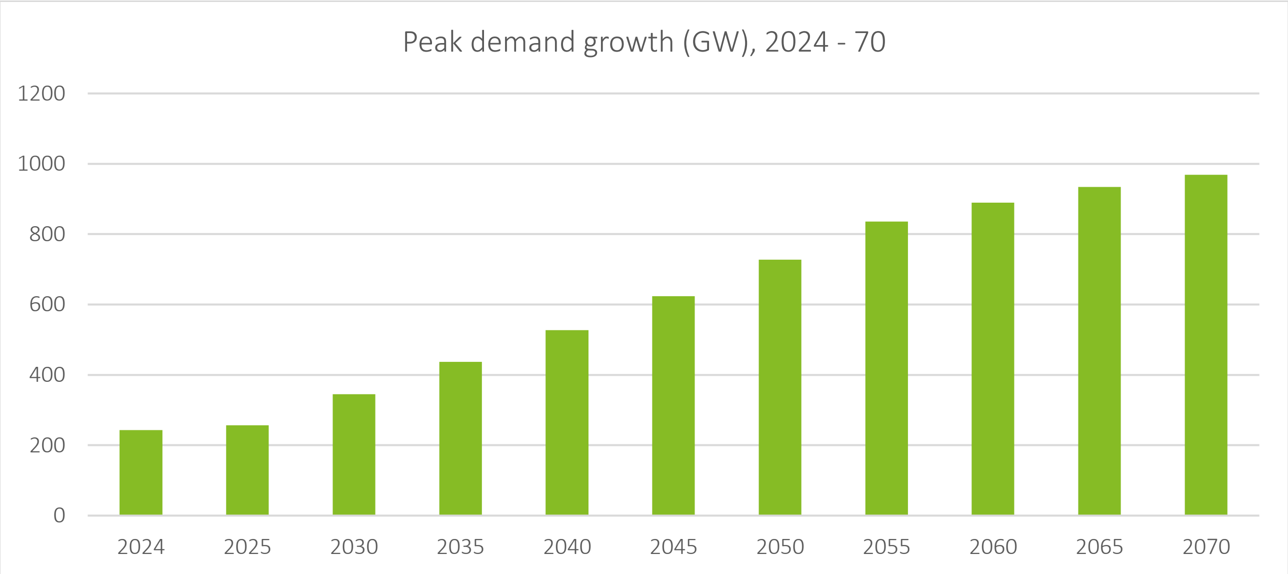


Figure 64: Peak demand growth till 2070, BAU

Growth in peak demand is expected to be lower than electricity demand due to flattening of load curve due to load shifting activities in industry and agriculture segment.

5.3.2 Capacity mix in BAU scenario

In the BAU scenario, the share of electricity in final energy consumption is projected to increase from 16% in 2022 to 40–45% by 2070, which is significantly lower than the electrification levels anticipated in the NZS scenario. Electricity will be supplied through a combination of fossil and non-fossil fuel-based sources. Nevertheless, there will be substantial additions to renewable energy capacity, supported by the deployment of long-duration and seasonal energy storage solutions for better integration.

Coal-based thermal power plants are expected to remain in operation until 2070, although their share in the overall energy mix will decline. The adoption of green hydrogen is also expected to be much lower compared to the NZS scenario.

Based on supply-side assumptions and constraints, the LP model provides the capacity (GW) trajectory for the BAU scenario, as shown below:

Table 13: Capacity expansion projection till 2070, BAU

		2024	2035	2040	2045	2050	2055	2060	2065	2070
Utility (GW)	Coal	219	287	287	294	294	243	201	186	197
	Gas	24	25	24	24	24	17	15	16	16
	Solar (Utility)	74	287	435	616	760	993	1223	1448	1645
	Solar (Rooftop)	13	89	149	209	264	324	370	430	510
	Wind	45	171	277	433	630	839	988	1104	1184
	Wind Offshore	0	30	60	90	120	120	130	140	150
	Hydro	56	80	90	110	130	140	140	140	140
	Nuclear	7	27	40	45	50	60	70	85	100
	Biomass	11	16	18	20	22	24	26	28	28
	PSP	5	16	24	31	31	31	51	71	88
	BESS (4 hour)	0	39	142	171	339	619	596	799	1099
	BESS (8 hour)	0	20	70	150	200	250	300	350	400
	Seasonal storage (H2 based)	0	0	0	40	80	92	92	110	135
Capacity for GH2 (GW)	Solar	0	47	75	88	160	152	127	127	155
	Onshore	0	2	2	2	2	11	22	26	26
	Offshore	Included in Utility capacity								
	Storage for GH2 (4 hours)	0	20	53	40	73	110	110	74	154

The expected generation mix in the net zero scenario, as derived through supply side modelling, is illustrated below:

Table 14: Generation mix projection 2070, BAU

	2024	2032	2035	2040	2045	2050	2055	2060	2065	2070
Utility										
Coal	1201	1509	1330	1149	1115	1247	1084	913	831	819
Gas	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
Solar (Utility)	133	416	611	945	1366	1707	2230	2746	3252	3694
Solar (Rooftop)	17	66	120	202	283	358	439	501	583	691
Wind	74	223	416	732	1163	1688	2230	2604	2890	3088
Wind Offshore	0	22	129	259	388	517	517	560	603	646
Hydro	187	233	266	300	366	433	468	468	468	468
Nuclear	52	156	191	280	315	350	420	491	596	701
Biomass	28	40	43	48	53	58	64	69	73	73
Net Imports	10	35	52	69	86	103	121	138	155	172
Storage loss										
PSP	-1	-3	-7	-7	-11	-7	-6	-15	-19	-22
BESS (4 hour)	0	-5	-10	-36	-47	-84	-149	-161	-211	-286
BESS (8 hour)	0	0	-8	-26	-60	-68	-75	-104	-119	-126
H2 turbines	0	0	-6	-21	-68	-228	-377	-434	-540	-561

	2024	2032	2035	2040	2045	2050	2055	2060	2065	2070
Utility generation	1703	2669	3057	3822	4749	5747	6635	7404	8145	8899
Sold to GH2 Offgrid	0	13	42	28	1	-15	-110	-124	-194	-214
Excess/Curtailed	0	0	-4	-4	-40	-54	-180	-280	-328	-398
Green Hydrogen										
Solar for GH2	0	76	106	169	197	359	342	286	285	348
Onshore for GH2	0	6	6	6	6	6	33	62	74	74
Offshore for GH2	*Included in Utility generation*									
Purchase from Grid	0	-13	-42	-28	-1	15	110	124	194	214
Total Generation	**1703**	**2773**	**3240**	**4068**	**5152**	**6441**	**7339**	**8124**	**8919**	**9779**

Key takeaways:

- Coal based installed capacity peaks in 2050 at 294 GW. There will not be any force retirement of coal based thermal plants, and 180 – 200 GW capacity will continue to operate through 2070.
- Solar, Wind, Hydro and Nuclear capacity addition will be much lower than NZS. However, despite moderate growth rate of RE, nearly 45–50 GW of annual RE capacity addition is anticipated to meet the BAU targets.
- Solar is expected to contribute 40 - 45% of electricity demand by 2070, followed by Wind (28 – 30% Onshore), Coal (~8%), Nuclear (~7%), Offshore wind (~5%) and Hydro (~4%) and import (~2%). Rooftop deployment would be critical to decarbonize the residential and commercial segments.
- In BAU also, the country would require a significant amount of Long-duration Energy Storage (LDES) systems, such as eight hours of battery storage, and H2 storage (to be fired in the gas turbine) to integrate renewables. Total energy storage requirement may grow to 3000 – 3500 GWh by 2050 and more than 8000 GWh by 2070.
- Hydro and nuclear power are expected to play a crucial role in supporting the grid stability, even in BAU scenario.
- Adoption of green hydrogen will be lower than NZS. In BAU, demand of green hydrogen is expected to be 23 – 25 million ton by 2070. Renewable energy requirement for green hydrogen production is expected to reach 1200-1300 BU by 2070. Green hydrogen will be powered through off-grid or captive renewable projects as well as grid as the emission intensity of grid is expected to decline gradually.
- No gas-based capacity addition has been considered due to shortage of domestic gas. Some of the existing gas stations are expected to be retrofitted for Hydrogen blending. New Hydrogen turbines are likely to be installed to be deployed as seasonal storage. Seasonal storage (H2 turbine based) is likely to be kicked in from 2045 onwards (delayed from NZS), which is expected to increase gradually to 120 – 130 GW by 2070.
- In addition to domestic capacity addition, hydro import from Nepal and Bhutan would be critical; import of 150 - 180 BU is expected by 2070.

5.3.3 Future of coal based projects

Even in BAU scenario, coal based plants are expected to lose share in the overall electricity mix. The share of coal is expected to decline from ~71% in 2024 to 28 - 30% in 2040, 18 – 20% in 2050 and 10 - 11% by 2060 and 8 -10% by 2070.

While the share of coal would decline, the operating plants are expected to maintain a moderate utilization factor (PLF) till 2070. The BAU scenario doesn't considers introduction of any carbon price. However, it is important to note that utilization of coal based plant may become higher in NZS due to higher electricity demand.

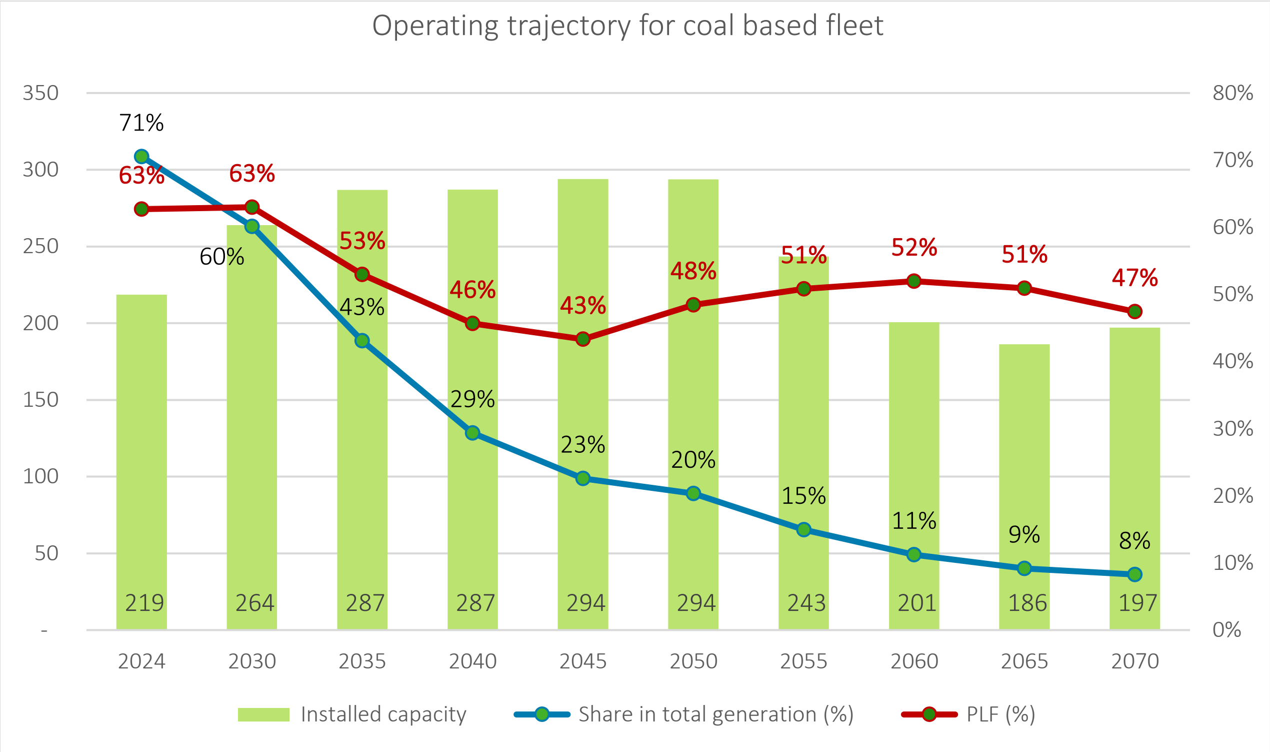


Figure 65: Future operating trajectory for coal based plants, BAU

5.3.4 Trajectory of primary energy mix

In the BAU scenario, India's primary energy in 2070 is expected to increase by ~100% from the 2022 level. In this scenario also, substantial uptake of cleaner sources of energy, especially solar and wind is expected. However, other fossil based primary energy sources, such and coal, oil and gas will also be significant. Continuing operation of coal based plants, ICE vehicles and limited focus on industrial decarbonization are likely to impact the primary energy mix in the BAU scenario.

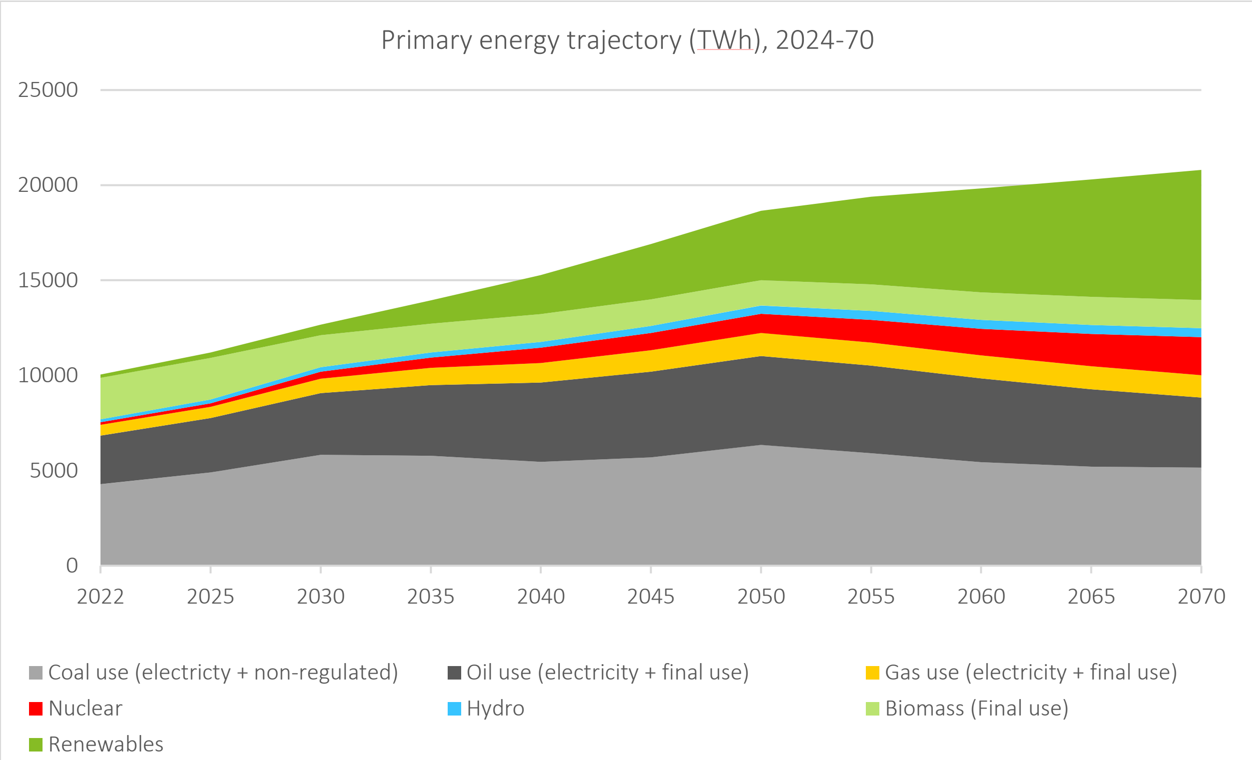


Figure 66: Projection of primary energy mix

Key takeaways:

- **Renewable:** Renewable energy (Solar and Wind) is expected to meet 30 - 35% of primary energy by 2070 vis-à-vis 55-60% in the NZS.
- .
- **Coal:** Coal is expected to contribute 22 – 25% of primary energy (vis-à-vis 6 – 8% in the NZS) by 2070, driven by use in the power generation and industry sectors, such as Steel, Cement and MSME sectors.
- **Oil**: The share of oil in the energy mix is projected to be around 16 – 18% (vis-à-vis 6 – 8% in the NZS) by 2070, primarily driven by transport sector. Oil's contribution to the primary energy mix is expected to peak around 2045–2050, followed by a declining trend, driven by better commercial viability of ZEVs.
- **Gas:** Gas is expected to be utilized in industries for heating and in cooking (PNG), contributing around 3–4% to the overall primary energy mix. However, the limited availability of domestic gas and the high cost of imported LNG are significant barriers to its wider use.
- **Nuclear and Hydro:** While increasing the penetration rate of renewables is a clear mandate from Government of India, Nuclear and Hydroelectric energy will have a critical role in the energy system
    - In addition to providing low carbon electricity, nuclear energy can facilitate the integration of sizeable shares of renewables and support long term energy security. Commercial scale adoption of Small Modular Reactor (SMR) has not been considered for India due to higher cost of technology and challenges associated with regulations and managing safety for small scale use.

- Nuclear energy is projected to contribute about 8 -10% to the overall primary energy mix by 2070, with an installed electricity generation capacity reaching 100 GW. Currently, India's nuclear power capacity stands at 6,780 MW, with plans to add 21 new atomic power units totaling 20,000 MW by 2032. However, challenges such as fuel import dependency and lengthy gestation periods must be addressed.
- India has an estimated hydroelectric potential of around 140 GW, which should be fully utilized. Additionally, the country will need to import hydropower from neighboring countries like Nepal and Bhutan. By 2070, hydropower is expected to account for 2–3% of the overall primary energy mix.

5.3.5 Emission trajectory

Emissions under the BAU scenario is expected peak around 2050 at ~3900 Mt CO2 and gradually come down to 3000 - 3200 Mt CO2 by 2070. Some of these residual emissions could be abated through mix of deployment of Carbon Capture and Storage (CCS) and carbon sequestration through afforestation. However, abatement of the entire emission would not be possible in BAU scenario.

The residual emissions are most likely to be contributed by electricity sector, hard to abate sectors like Steel, Cement, Petrochemical and few MSME industries and Transport sector.

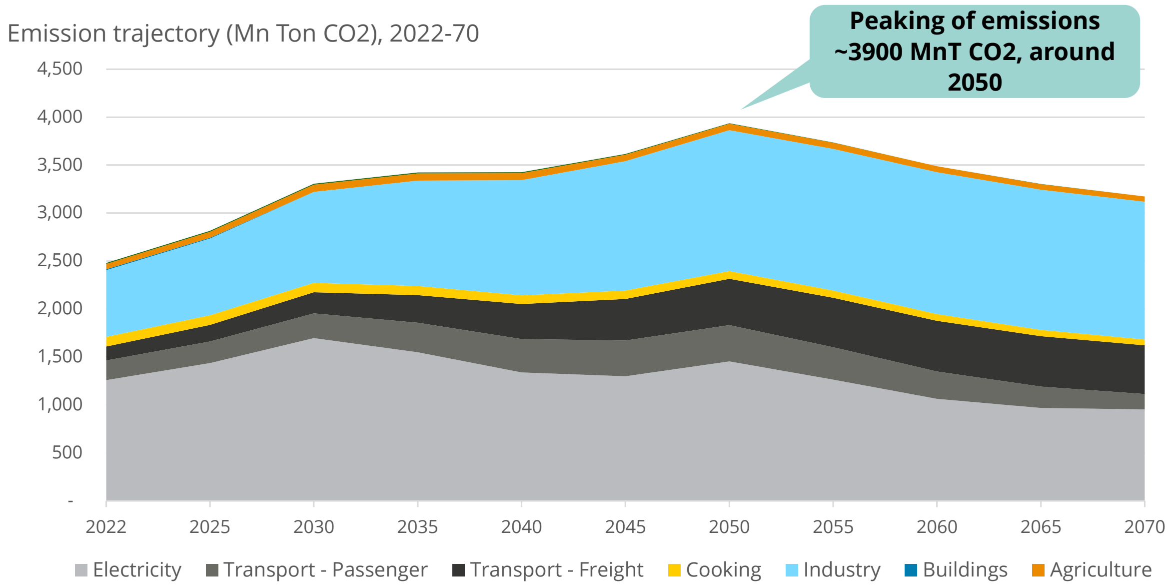


Figure 67: Emission trajectory (Mt CO2) in BAU scenario

In BAU scenario, significance of afforestation and CCUS will be more due to higher residual emission. Along with industry sectors, power generation may also require deploying carbon capture and storage infrastructure.

5.4 Energy balance for 2070

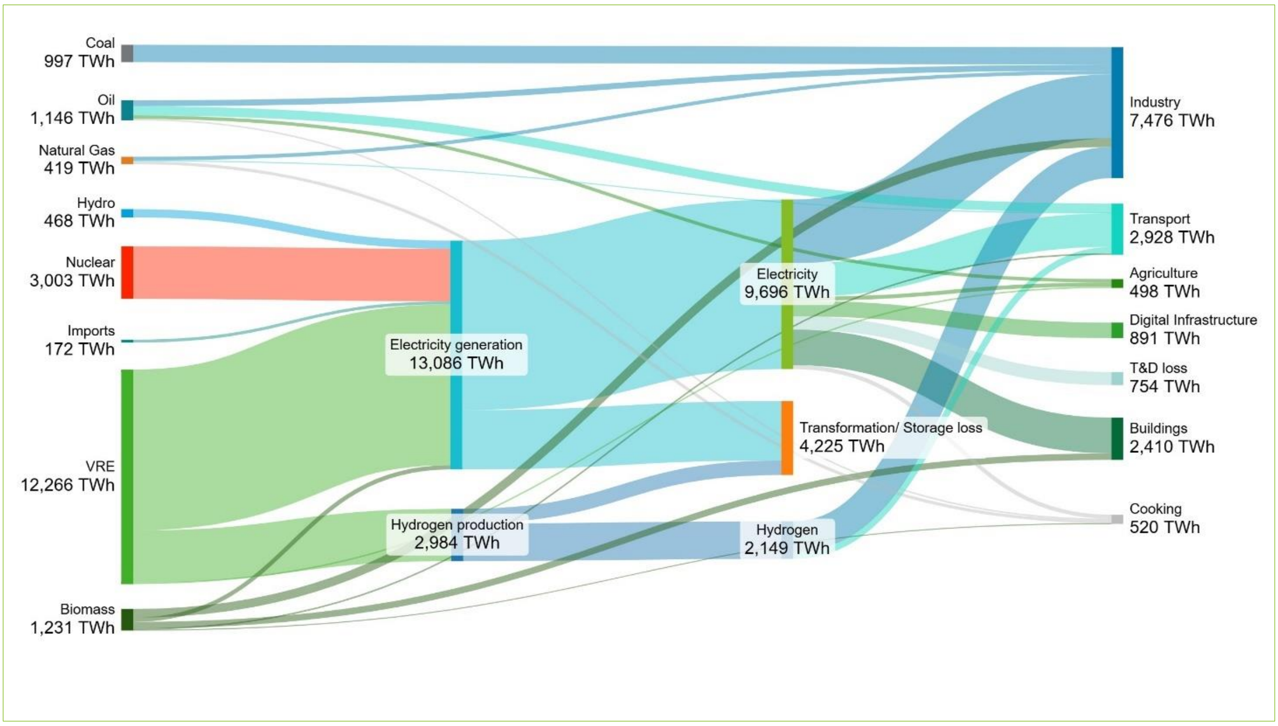


Figure 68: Energy balance diagram, NZS, 2070

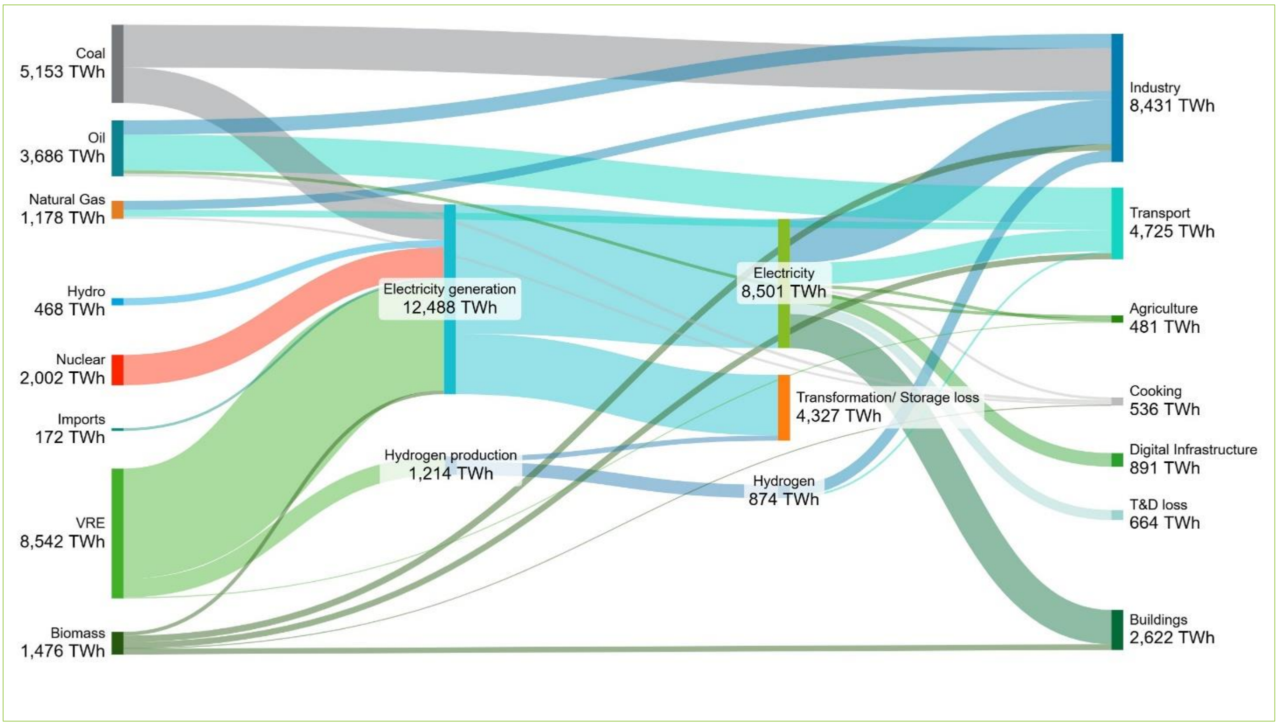


Figure 69: Energy balance diagram, BAU, 2070

6 Investment requirements

6.1 Net Zero Scenario

India's energy transition will be expensive. Total cost towards energy transition to achieve net zero by 2070 is expected to be **USD 14 – 15 trillion between 2024 – 70**.

This is a meaningful cost to the economy – at 1-2% of annual GDP over 50 years. However, there could be reasonable front-loading of these investments, with the 2030-2050 decades seeing substantially higher investment intensity.

Investment areas	Investment amount (USD Billion)	Investment share (%)	Assumptions and Rationale
Coal based capacity addition	80 – 100	0 -1%	40 – 50 GW new Coal based capacity (in addition to under-construction) is expected to be commissioned by 2035 to meet the increasing energy demand.
Renewable energy	3800 - 4200	28 – 30%	Capital expenditure towards Solar, Wind, Hydro, Nuclear
Energy storage	1500 - 1700	10 - 12%	Capital expenditure towards Pump Storage, Battery Storage and H2 turbine based seasonal storage
Transmission & Distribution	900 - 1200	8 – 9%	Capital expenditure towards augmentation and modernization of T&D infrastructure for integration of RE
Transport – ZEV and Infrastructure	4500 - 5000	28 – 32%	Capital expenditure towards EV battery, FCEV, Charging infrastructure and Hydrogen refuelling system
GH2 infra and associated RE	1500 - 1700	11 – 13%	Capital expenditure towards deployment of electrolyser, associated RE and energy storage, hydrogen storage.
Green Steel Infrastructure	500 - 600	4 – 5%	Additional expenditure towards green steel infrastructure
CCUS	150 - 180	1 – 1.5%	Cost of CCUS deployment in cement industry for 400 - 500 Million Tons. This includes capex towards carbon capture, pipeline and storage infrastructure.
RE equipment manufacturing and recycling facilities	40 – 50	0.5%	Capital expenditure towards indigenization of renewable equipment and systems manufacturing, such as Solar upstream value chain, battery storage manufacturing, electrolyser manufacturing etc.
Just transition	70 - 100	0.4 – 0.6%	Cost towards decommissioning of power plant, social cost towards job loss in power plant and coal mines
Others – Energy efficiency, Buildings, Cooking etc.	500 - 1000	4 – 7%	Cost towards industrial energy efficiency, energy efficient building, appliances, PNG pipeline etc.
Total	**13500 - 15000**		

Source: Estimated

Note:

- For estimation of investment in power generation, transmission and transportation, absolute aggregated investment has been considered.
- For buildings, cooking and industrial energy efficiency, incremental investment has been considered over BAU scenario.

In an alternate scenario, if coal plants are not decommissioned after 2060, overall investment may reduce by USD 300 – 400 billion due to lower requirement of BESS and installed RE. However, the impact will not be significant as coal-based power generation is likely to be very costly due escalation of coal price and logistics cost (coal price escalation is assumed as 3.5% y-o-y). Nearly 100 GW of coal capacity is expected to operate as peaking power stations, reducing the overall BESS requirement by 1500 – 2000 GWh.

6.2 Business As Usual Scenario

Many of the above initiatives will be undertaken in Business-as-Usual scenario also as per intended policies. However, the investment requirement will be 20 – 25% lower than the Net Zero scenario.

Investment areas	Investment amount (USD Billion)	Investment share (%)	Assumptions and Rationale
Coal based capacity addition	100 – 120	1-2%	80 – 100 GW new Coal based capacity (in addition to under-construction) is expected to be commissioned by 2045 to meet the increasing energy demand. Nearly 200 GW of coal-based plants will still be operational in 2070.
Renewable energy	3000 - 3400	28 – 30%	Capital expenditure towards Solar, Wind, Hydro, Nuclear
Energy storage	1000 - 1200	8-10%	Lower requirement of energy storage
Transmission & Distribution	700 - 1000	6-8%	Lower requirement of T&D infrastructure for integration of RE
Transport – ZEV and Infrastructure	4500 - 5000	35-40%	Some savings due to lower costs of hydrogen infrastructure, however higher road transport modal share will result in increased infrastructure costs compared to rail infrastructure
GH2 infra and associated RE	600 - 800	6-8%	Green steel provides majority of requirement for GH2, this will be lower in the BAU scenario
Green Steel Infrastructure	200 - 300	2-3%	Delayed adoption of green steel and on lower scale
CCUS	Minimal	-	Minimal deployment of CCUS
RE equipment manufacturing and recycling facilities	40 - 50	0.5%	Capital expenditure towards indigenization of renewable equipment and systems manufacturing, such as Solar upstream value chain, battery storage manufacturing, electrolyser manufacturing etc.
Just transition	–Minimal	-	Not applicable, since there will be no early shutdown of coal power plants and significant coal-based capacity will remain operational until 2070
Others – Energy efficiency, Buildings, Cooking etc.	500 - 1000	6-8%	Incremental cost towards industrial energy efficiency, energy efficient building, appliances, PNG pipeline etc.
Total	**11000 - 12000**		

In Business-As-Usual scenario also, significant investment is expected to be incurred towards clean energy and emission reduction measures, guided by various policy measures and regulations. However, in a Net Zero scenario, investment will be incrementally higher (by USD 2 – 4 trillion through 2024-70) and front-loaded.

7 Key challenges of Net Zero Scenario

Despite significant progress in reducing energy deficit and boosting the share of clean energy in its economy, India's ambitions to achieve net zero will demand extraordinary efforts to overcome challenges and meet its targets for the coming decades. India will require scaling up of clean technologies multifold; it is estimated that total capital expenditure required between 2024 – 70 is USD 14 – 15 trillion, with significant front loading between 2024 – 35 to achieve its energy transition goals.

Moreover, challenges such as supply chain constraints, resource availability, a shortage of necessary skillsets, and technological uncertainties will impact India's energy transition aspirations.

Table 15: Key challenges of Net Zero scenario

Areas	Challenges
RE capacity addition and supply chain	• Rapid scale of capacity addition: Solar 40 – 80 GW/year, Wind 20 – 50 GW/year, BESS 10 – 30 GW/year between 2024 - 70 • Non-availability of domestic supply chain, leading to significant import dependency and exposure to geo-political risk • Global availability of critical minerals required for clean technologies, such as Nickel, Cobalt, Platinum, Iridium, Lithium etc.
Land availability for RE project development	• India would require 10- 12% of total wasteland to develop 3500 GW solar and 3 – 5% land for 1400 GW wind; timely identification and acquisition of land could pose significant threat
Transmission constraint	• Integration of 3500 GW solar and 1500 GW Wind would require extensive planning and infrastructure capex, which may reach ~USD 1.0 trillion between 2024 - 70
Technological Uncertainties	• Timely evolution and scaling up of new technologies, such as Long duration energy storage, Hydrogen turbine, H2-DRI, Electric Freight Truck, Electric Boiler, CCUS etc., could be a challenge. Any delay in scaling up could derail the Net Zero ambition.
Capacity ramp up of Hydro and Nuclear	• Historically, gestation period for these technologies is a challenge; annual capacity addition of 3 – 10 GW of hydro and nuclear could pose significant challenge.
Capital Expenditure	• Net Zero transition would require overall capital expenditure in between USD 14 – 15 trillion between 2024 – 70, which translates to 2-3% contribution of India's annual GDP. • Availability of low cost financing to scale up frontier technologies and support deployment of associated infrastructure would be critical to achieve net-zero ambitions.
Industry acceptance of new technologies	• New technologies, such as GH2, CCUS, new RE technology could be cost prohibitive (GH2 – USD 5 – 7 per kg, CCUS – USD 50 – 80 per ton of CO2 capture, Offshore tariff – INR 8 – 12 per kWh)
Recycling and disposal	• Recycling of batteries and solar panel would be critical once they reach end-of-life (EOL). By 2070, India would generate 800 – 1000 GW solar waste and more than 8000 GWh battery waste which need to be recycled and disposed.

8 Key Charts and Imperatives

8.1.1 System marginal cost duration curves

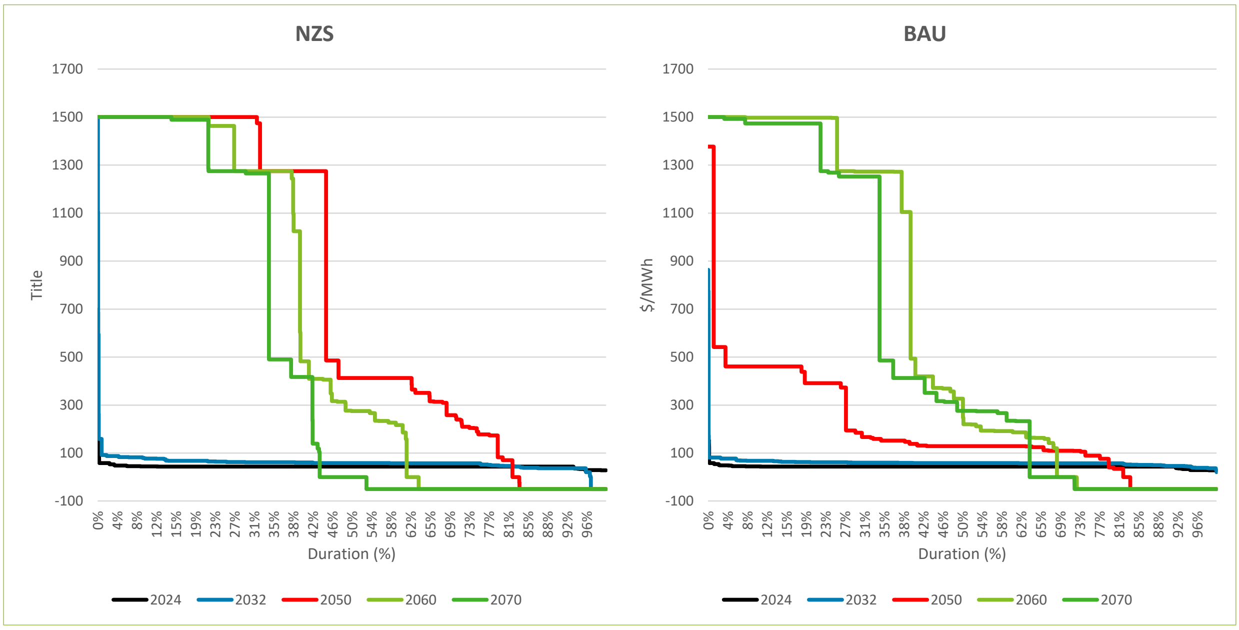


Figure 70: System Marginal Cost duration curve ($/MWh) - NZS and BAU

The marginal generation cost of a system is defined as the cost of generating one additional MW of power. This information is derived from the duals of the demand balance equation. In the NZ scenario the marginal cost of generation peaks around 2050, whereas in the BAU scenario the marginal cost of generation peaks around 2060-65 due to operation of high cost coal based plants and slightly reduces by 2070. Marginal cost of generation also becomes negative in several time slots due to excess generation (mainly in high solar hours).

8.1.2 Average system marginal cost of electricity

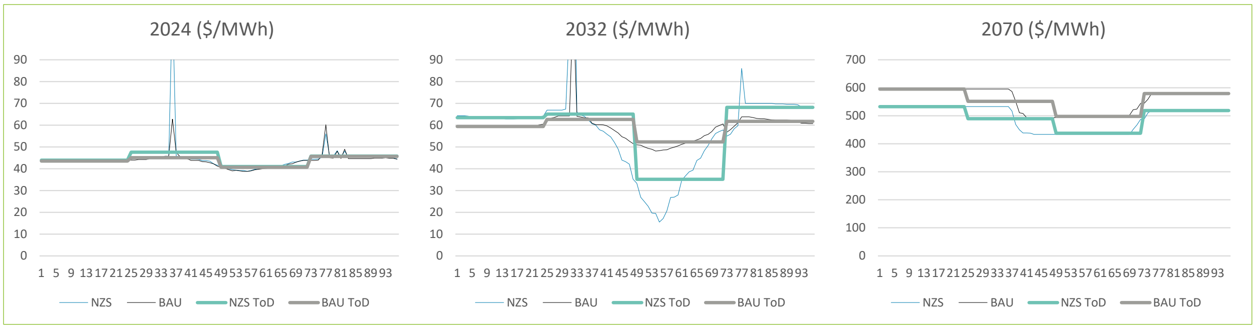


Figure 71: Average system marginal cost of electricity ($/MWh)

System marginal cost of generation increases from 2024 to 2070 in the BAU scenario, as coal prices are escalated at 3.5% per year. However, the average system marginal cost of electricity does not increase at the same rate to increasing share of RE providing cheaper electricity in both NZ and BAU scenario. As solar and wind capacities increase to significant levels by 2070, the system marginal cost reduces during solar hours and evening hours (when wind generation is typically higher) in both the scenarios. The average system marginal cost of electricity in NZ scenario, is much lower as compared to BAU scenario due to higher share of RE based generation.

8.1.3 Ramp limits for thermal generators

The following plot illustrates the percentage of time (15 mins time block) coal based fleet are required to hit 1% ramp limit.

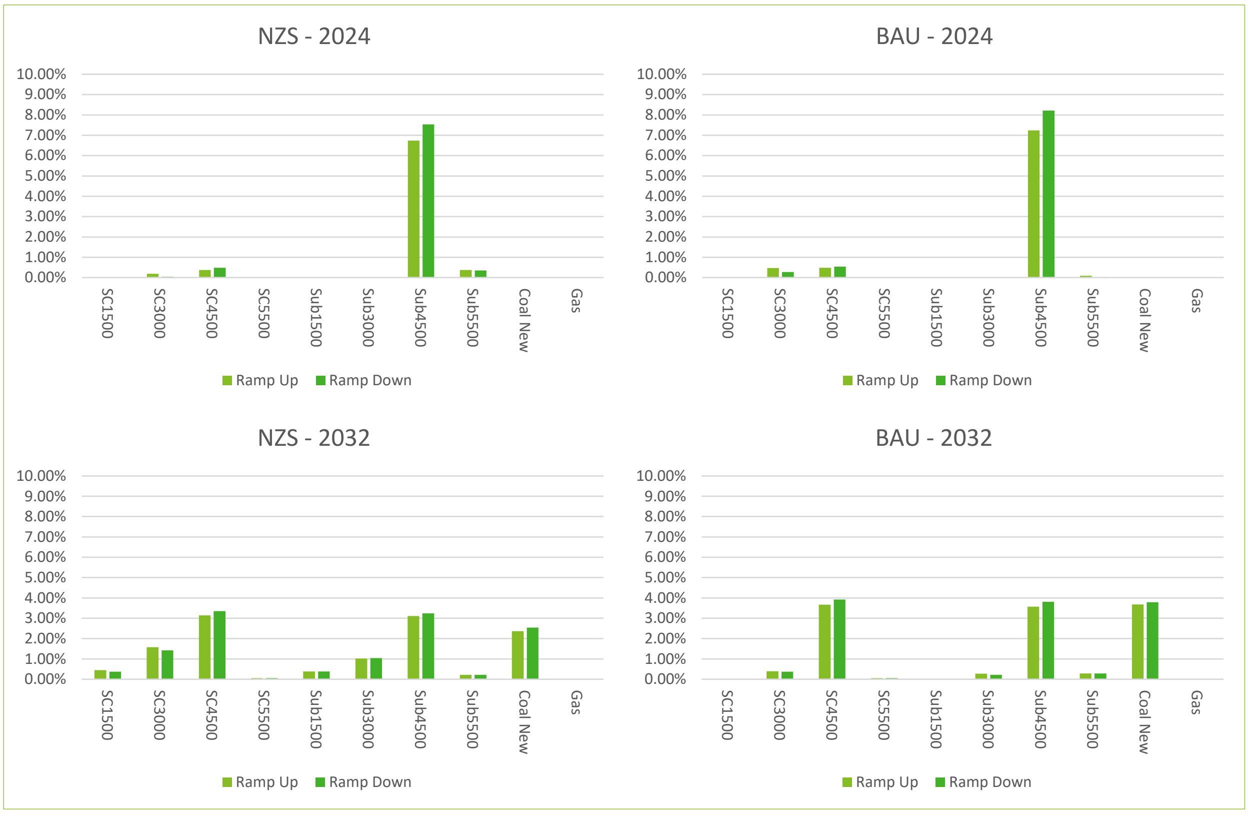


Figure 72: Ramp limit (1%/min) of thermal generators (in percentage of time) in 2024 and 2032

Note: Description of plant categories are provided in the earlier sections

Plants with variable cost (VC) > Rs. 4.0/kWh are likely to hit the ramping limits the most (1%/min). In 2024, these plants hit the ramping limits almost **6-8%** of the time across both the scenarios. This behavior is expected as the plants in the variable cost of more than Rs. 4/kWh tend to be the marginal generators within the system. As the RE mix increases, the marginal generators also change, and lower VC plants also may breach ramping limit. However, this increase is not anticipated to be significant. **Therefore, plants with VC >Rs. 4.0/kWh are more likely to be ramped up and down frequently, and they (including State Gencos) should be retrofitted for 1%/min ramp limit.**

8.1.4 Average system marginal cost of green hydrogen

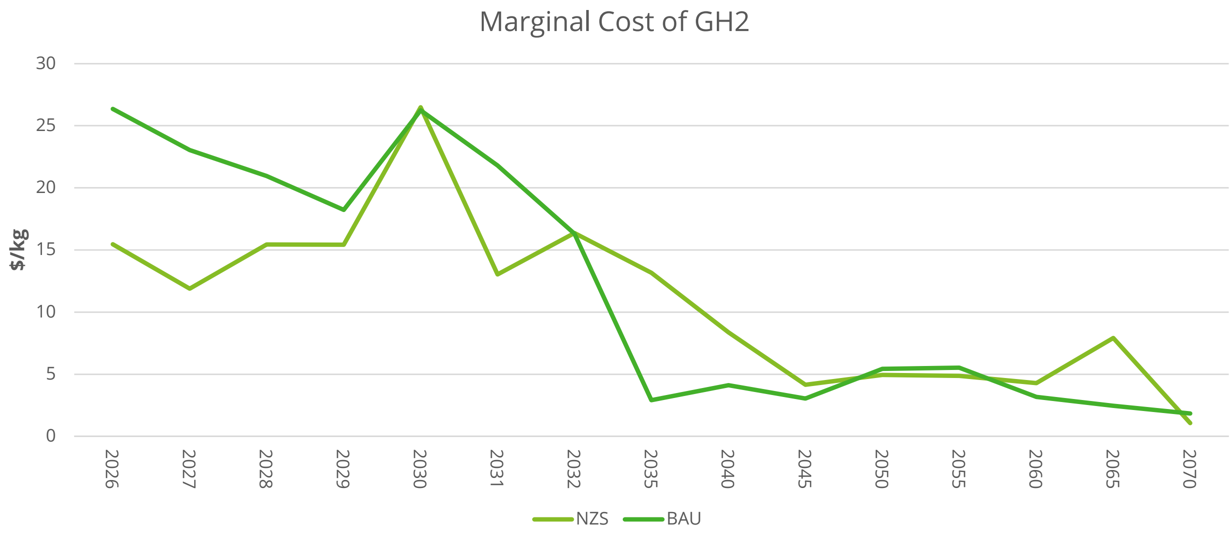
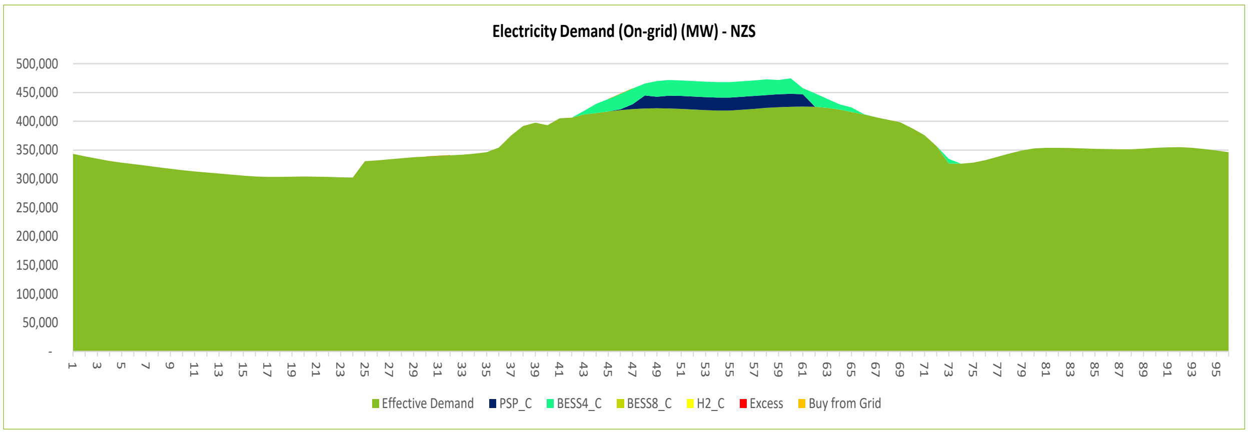


Figure 73: Average system marginal cost for Green Hydrogen, NZS and BAU

In the BAU scenario, the average marginal cost of green hydrogen (GH2) remains around $2-6/kg from 2035 to 2070. In contrast, the NZ scenario shows a higher average marginal cost for GH2 due to increased demand, though it eventually drops to $0.25/kg by 2070. As rapid capacity expansion of renewable energy occurs by 2070, the cost of GH2 in the NZ scenario becomes lower than in the BAU scenario. However, the system marginal cost of GH2 generation is higher in the NZ scenario due to the overall higher demand for both electricity and GH2, leading to significant unmet demand caused by capacity addition constraints.

8.2 Electricity generation and demand for a representative day (peak demand day) in 2035

8.2.1 Electricity demand and supply (on-grid/ utility electricity):



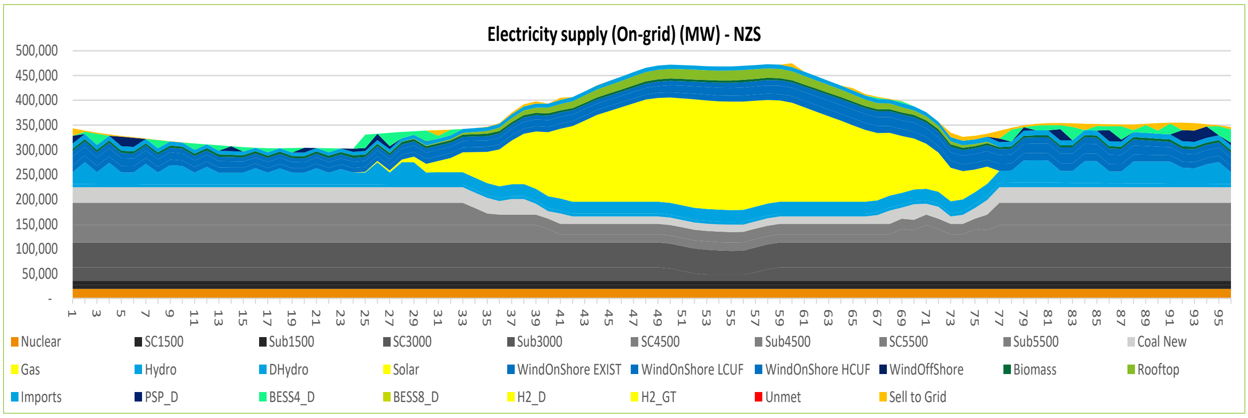
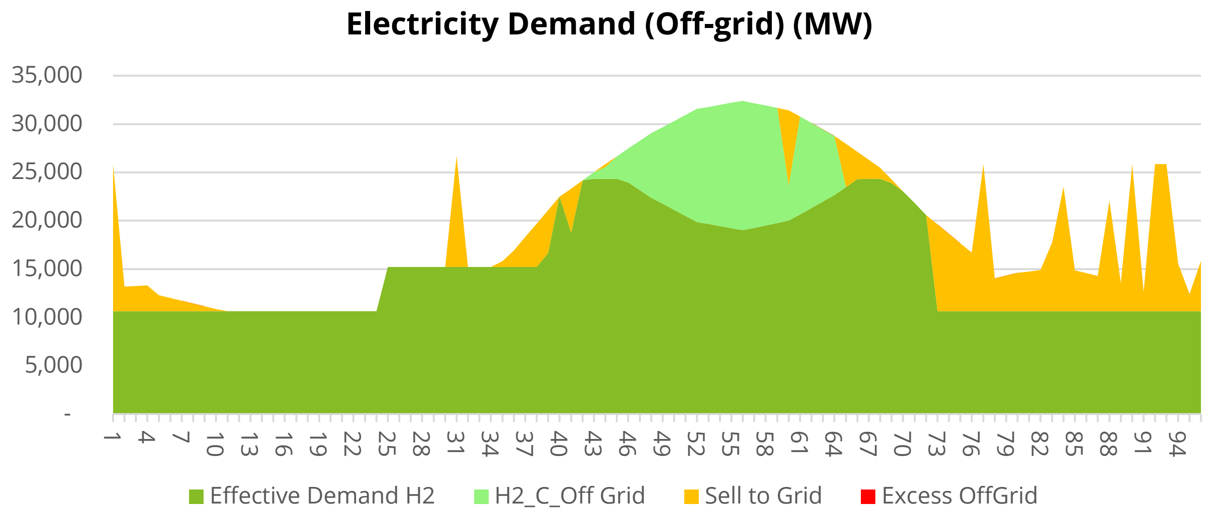


Figure 74: Electricity demand-supply in a peak demand day - 2035

The on-grid electricity demand profile is significantly affected by the shifting of agricultural loads, with 80% of agricultural demand moving from non-solar to solar hours. Additionally, most of the charging for short-duration energy storage occurs during solar hours, causing thermal generators to operate at their technical minimum during this period. As solar generation declines rapidly in the early morning and evening hours, the need for ramping resources increases. Flexible resources like thermal generators (coal and gas), short-duration energy storage (BESS and PSP), and long-duration storage are crucial for providing ramping support to the grid. Some of the electricity demand can also be fulfilled by purchasing electricity from off-grid operations, as illustrated in the graphs above.

8.2.2 Electricity demand and supply (off-grid/ green hydrogen):



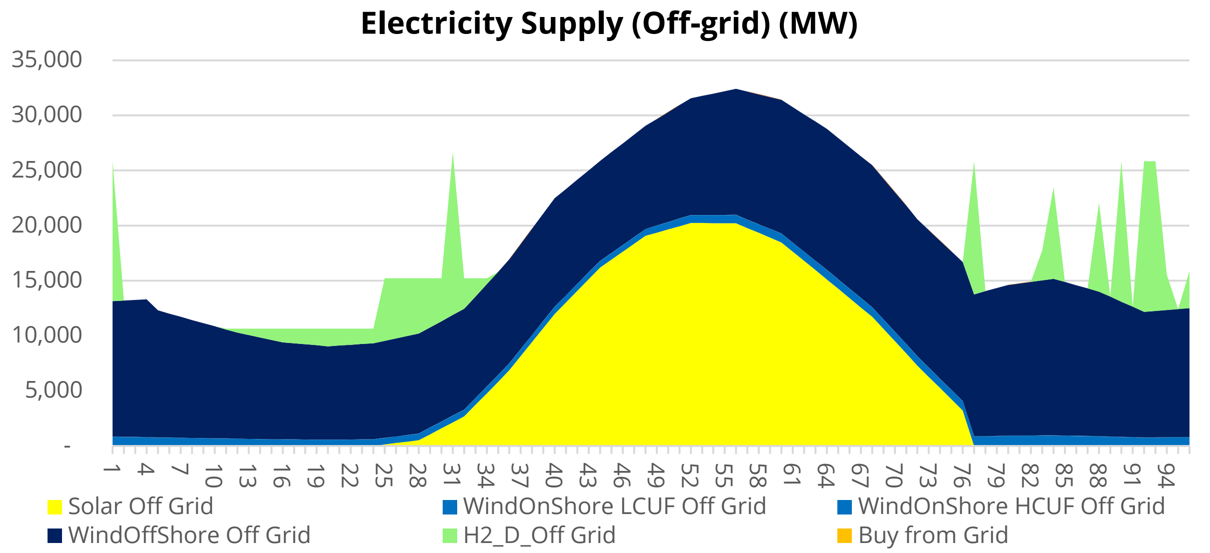


Figure 75: Electricity demand and supply for off-grid requirement (GH2 production)

The analysis above includes demand response strategies, such as shifting agricultural loads and leveraging the flexibility of green hydrogen electrolysers. This allows a portion of the grid's electricity generated during daylight hours to be utilized for green hydrogen production.

9 Policy levers and Enablers

The NZS aims to accelerate decarbonisation by leveraging advanced decarbonisation technologies backed by a green electricity grid, leading to India achieving the net zero target by 2070. India needs to work backward to achieve this target and develop decisive plans and implementation roadmaps for India's energy transition. Along with the development of an enabling environment and formulation of plans, it is important to ensure timely implementation. Policy and regulatory enablers are critical in opening and developing new markets and the adoption of novel technologies, such as battery storage, green hydrogen, etc. Without a definitive and favorable policy environment, it may be difficult to bring attractive investment in markets, which are in the nascent stages of development but critical to India's successful energy transition.

The following set of policy levers and enablers are critical for achieving India's net zero targets.

9.1 Critical policy levers and targeted interventions for Net Zero transition

The Government and public sector play critical roles by providing a conducive and predictable enabling environment (through policy framework) to drive long-term private sector investment decisions. Conducive policies and regulations will incentivise and facilitate private sector investors and developers' decisions in developing, financing and building the volume of projects needed for the energy transition.

Short term: 2024 – 28 Medium term: 2028 – 35 Long term: beyond 2035

Table 16: Critical policy levers for Net Zero transition

Policy areas	Recommendations	Action points	Timeline
Strengthening supply chain	• Support indigenous manufacturing of Solar PV, Wind turbine, BESS and Electrolysers; Policy measures should be targeted to reduce import dependency and exposure to geo-political risk by focusing on indigenization of manufacturing and supply chain. • Supply chain should be established to ensure rapid scale of capacity addition: Solar 40 – 80 GW/year, Wind 20 – 50 GW/year, BESS 10 – 30 GW/year, Electrolyser 10 -15 GW/year between 2024 – 70	**Supply chain indigenization**: Gradually increasing domestic manufacturing through implementation of incentive scheme and encouraging R&D and technology transfer. Timely implementation of support measures (e.g., PLI scheme) is critical for emerging technologies. • Polysilicon to Module: 80 – 100 GW per year • Wind Turbine: 50 – 60 GW per year • BESS (Cell and Pack): 300 – 400 GWh per year • Electrolyser: 15 – 20 GW per year • Ancillary and BOS systems	*Short to Medium*
		G2G trade agreements for critical minerals: Forge G2G agreement and negotiate Free Trade Agreement (FTA) to establish supply of critical minerals required for clean technologies, such as Nickel, Cobalt, Platinum, Iridium, Lithium etc.	*Short*
Resource re-evaluation and site identification	• Achievement of net zero targets would require huge capacity addition of renewable energy sources, which would cross the current announced potential in the country. Therefore, re-evaluation of solar and wind potential is the need of the hour; India would cross current solar potential of 750 GW by 2040-45 • Identification of resource rich sites for both solar and wind would be crucial. The Minstry should earmarked the resource rich sites on priority to enable rapid scale up of capacity addition.	**Re-evaluation of potentials**: Re-evaluate the potential of Solar in the country and earmarked sites across pan-India based on resource potential.	*Short*

Policy areas	Recommendations	Action points	Timeline
Technological Interventions	**Coal fleet operation:** • Ramping capability for certain critical thermal plant categories should be increased by 2050. All state and private sector plants under this category should undergo plant modification to achieve the ramp requirement. • Technical minimum for all plants should be lowered to 40%, as suggested by CEA also **Wind re-powering** • ~40 GW existing wind generators should be replaced with high-capacity turbines as they already occupy high wind generation potential regions. They could unlock additional 80 – 150 GW potential at 150 m height	**Preparing coal fleets for flexible operation:** Form a task force to identify plants with higher variable cost (VC> INR 4.0/kWh) that should be retrofitted for 1-2%/min ramp rate, and retrofit those in a time-bound manner. Ensure all private and public sector coal-based plants be suitable for operation at a "Technical Minimum" of 40% by 2035. A task force may be formed to monitor the progress in a time-bound manner.	*Medium*
		WTG repowering: Form a task-force to identify old WTGs located in the high wind potential regions with focus on plants that are reaching end of the PPA tenure. A plan should be created for re-powering those WTGs	*Medium*
Thermal capacity addition	In the short to medium term, additional thermal capacity would be required to meet the increasing energy demand. The action items for the policy makers should be aligned to expedite the capacity addition.	**Revival of stalled projects**: Reviving at least 50% of the stalled capacity (10-12 GW) to optimize the investment requirement	*Short*
		Expediting capacity addition plan: Additional 30-40 GW will be required to meet the demand by 2035. Therefore, planning of this additional capacity should be undertaken by CEA/MoP on priority	*Short*
		Development of BTG and BOP vendors: Identifying and developing vendors for BTG and BOP of thermal plants	*Short*
Prioritization of Hydro and Nuclear capacity	Hydro and Nuclear projects are critical to ensure energy security and provide dispatchable power in a high RE scenario	**Expediting hydro and nuclear capacity addition plan**: Hydro and Nuclear projects should be cleared and awarded on priority; develop a plan for annual capacity addition of 3 – 5 GW post 2030	*Short*

Policy areas	Recommendations	Action points	Timeline
		Development of Thorium based nuclear reactor: Develop domestic nuclear fuel based technology to reduce import dependence of Uranium based fuel	*Medium*
Strengthening transmission grid and regional grid interconnections, off-grid operations for green hydrogen	Significant investment and planning are required for strengthening transmission infrastructure for integrating large-scale variable renewable, including new infrastructure and modernization of existing grid. Additionally, regional interconnection is required for import of Hydro power from Nepal and Bhutan	**Transmission planning**: Undertake a transmission planning exercise to integrated 3000+ GW solar and 1400+ GW wind along with capex planning. **Resource Adequacy planning:** State and central level Resource Adequacy plans should consider transmission constraints for developing capacity expansion plan	*Continuous*
		Regional transmission interconnection plan: Develop an execution plan for regional transmission interconnection with Nepal and Bhutan for import of Hydro Power (nearly 150 BU annual import is anticipated by 2050)	*Medium*
		Regulatory interventions for off-grid green hydrogen operations: Identify regulatory interventions required for introduction of flexible off-grid green hydrogen operations; with greening of Grid, Hydrogen electrolyser can offtake 20 – 30% power from Grid by 2070	*Long*
Transport decarbonization	Policies should be aligned towards planning and channelizing investment (USD 4 – 5 trillion) for transition to Zero Emission Vehicles and efficient urban planning.	**Efficient urban planning**: Efficient urban planning should be carried out at the city level that has the potential to reduce the distance travelled and reduce motorised travel demand. This includes meticulous planning of public transport infrastructure, such as metro, Rapid Transit System etc.	*Medium*

Policy areas	Recommendations	Action points	Timeline
		Deployment of low-carbon transport: Undertake aggressive targets for phasing out ICE vehicle and adoption of zero-emission vehicles (BEVs, H2-ICE, FCEV etc.). The country level targets should be translated into state level target	*Short to Medium*
Demand response	Aggressive demand response policy and regulations should be introduced to flatten the load curve	**Demand response mandates**: Bring mandates for industrial and agricultural load shifting from non-solar hours to solar hours (for example, up to 80% of non-solar agricultural load could be distributed in solar hours)	*Medium*
Industrial decarbonization	Policies and regulations must be targeted to expedite the pace of industrial decarbonization. The major focus areas should be on: • Green Steel • Green Fertilizer • CCUS • Carbon price • Circularity	**Decarbonization task-force**: Dedicated task force should be formed to drive sectoral decarbonization, with focus on Steel, Cement, Fertilizer, Aluminium, Refinery and petrochemicals	*Short*
		CCUS potential assessment: Study the CCUS potential and identify potential storage. Cement industry alone would require 600 - 800 Million tons of CCUS for capturing the process emission. The Government may collaborate with academic institutes to initiate study for source-sink mapping, pore space mapping, geological characterisation of the most promising CO_2 storage regions and basins, and developing the CO_2 storage infrastructure	*Short*
		CCUS demonstration projects: Ensure funding early-stage CCUS demonstration projects in cement sector to provide the initial thrust and select the best available technologies.	*Short*
		Develop a scale-up plan for deployment of CCUS in cement sector in collaboration with Cement manufacturers.	*Long*
		Introduction of Carbon pricing: Introduce carbon pricing to accelerate decarbonization initiatives; Carbon price can be introduced around 2035, with gradual increase till 2070.	*Medium*

Policy areas	Recommendations	Action points	Timeline
		Introduction of Carbon price could faster decarbonization by 5-10 years	
		Public procurement of green steel: The Government may explore use of public procurement to drive volumes of decarbonised steel to market. Government procurement may mandate purchase of green steel, providing greater demand certainty.	*Medium*
		Steel circularity: Develop a mandate to increase market demand for recycled steel, which would incentivise investment in steel recycling. The Government may consider setting up recycled content targets for key off-taking sectors, such as automotive, industrial manufacturing etc.	*Short*
Incentives and subsidies	Availability of low cost finance is critical to fund the capex for energy transition (USD 14 – 15 trillion for 2024 – 70). The government should implement policies focused on incentivizing clean technologies and associated infrastructure development (e.g., urban planning) through tax breaks, production-linked incentives (PLI) schemes, capital grants, green bonds etc.	**Incentivize new technologies:** Incentivize sunrise sectors such as green hydrogen, CCUS, battery storage, offshore wind or any other clean tech technologies that are emerging and in the early stage of commercial maturity. Additionally, suitable incentive schemes should also be designed to support ancillary and Balance of System (BOS) manufacturing.	*Continuous*

9.2 Enablers for Net Zero transitions

9.2.1 Availability of low-cost capital and innovative financing instruments

To align India's energy system with its net-zero target, an investment of USD 14–15 trillion will be required between 2024 and 2070 for clean technologies and related infrastructure. The nature of these investments will vary by sector: the electricity generation sector will need funding for solar, wind, hydro, and nuclear projects; the transport sector will focus on zero-emission vehicles (ZEVs) and related infrastructure; the industry sector will invest in decarbonization technologies and retrofitting existing processes; and the building sector will require investments in energy efficiency, among others.

Ensuring the availability of low-cost capital in sufficient quantities is crucial for India's energy transition. For this, the public sector alone cannot suffice; partnerships between the public, private, and development sectors are essential. Both the private and public sectors play critical roles in advancing the energy transition agenda, while the development sector can offer concessional contributions to help de-risk energy transition projects. Close collaboration and partnerships among these entities are necessary.

Investments in new and emerging technologies may present significantly different risk profiles compared to traditional infrastructure projects. Factors such as technological complexity, supply chain availability, the expertise of EPC contractors, and commercial viability will determine the risk profile of these investments. Therefore, introducing suitable financial instruments is vital to de-risk these investments, particularly in the initial years. For instance, in a blended finance structure, public or development institutions provide concessional capital to mitigate certain risks that the private sector cannot absorb or would require a high premium to cover.

To accelerate the deployment of energy transition technologies and associated infrastructure, following innovative financial instruments should be explored to create a supportive business environment.

- Concessional financing
- Risk Guarantee/ Partial Risk Guarantee
- Contract for Differences/ Carbon Contract for Differences
- Payment security mechanism
- Insurance

9.2.2 Continuous innovation

Innovation is crucial for scaling up emerging and essential energy transition technologies. As markets expand, innovation—alongside economies of scale—is a key driver for reducing technology costs and accelerating market adoption. Effective innovation frameworks are needed at every stage of the technology deployment process, from research and development to market entry, commercial deployment, and subsequent scaling. For instance, ongoing innovation in electrolyser technology can reduce material usage and costs, enhance system performance, and lower overall project expenses. A notable example of innovation-led cost reduction and technological advancement is the shift from multi-crystalline solar cell technology to PERC and other high-efficiency cell technologies; the cost of solar cells has dropped from $1 per watt in 2010 to $0.15 per watt in 2023.

Financial support to industry, academic institutes and innovators is essential to drive innovation in energy transition technologies, as it accelerates their deployment and commercialization. For example, the EU has launched one of the world's largest funding programs for deploying net-zero and innovative technologies, which could provide around €40 billion from 2020 to 2030[52].

9.2.3 Cross sector collaboration

Net-zero is a shared goal among corporations, investors, and governments, requiring strong partnerships to develop the necessary technologies, markets, and business models. Achieving this transition demands collaboration from all sectors—industry leaders, policymakers, innovators, and the younger generation—to evaluate the industry's landscape and share ideas, experiences, and expertise across the entire value chain. Such collaboration would facilitate the pooling of resources, knowledge, and networks, accelerating the development of clean technologies and ensuring that sufficient commercial capital and mechanisms are in place to advance solutions at the required pace and scale.

[52] https://climate.ec.europa.eu/eu-action/eu-funding-climate-action/innovation-fund/what-innovation-fund_en

9.2.4 Re-skilling and upskilling of workforce

As India strives to build a sustainable and resilient energy system, investing in human capital development through targeted training, education, and capacity-building programs will be essential. The energy transition will often require the creation of new educational, certification, and vocational training programs, as well as specific upskilling and reskilling initiatives for the existing workforce. Identifying the new skills needed for the future is critical. By prioritizing reskilling and upskilling, India can facilitate a smooth, inclusive, and accelerated transition to a low-carbon future, driving economic growth, job creation, and social equity. This transition has the potential to create millions of well-paying, sustainable jobs, from innovations in battery technology transforming the auto industry to the impact of hydrogen in industry and transport.

Recognizing this need, the Government of India established the Skill Council for Green Jobs (SCGJ) in October 2015 under the Ministry of Skill Development and Entrepreneurship to address the demand for skilled manpower for emerging climate technologies and to meet India's commitments under the UNFCCC. The program is supported by the Ministry of New and Renewable Energy and the Confederation of Indian Industry. However, it is important to map the existing skill sets in the energy sector, identify new skills required in emerging clean technology segments, and develop a comprehensive plan for reskilling and upskilling.

New areas of skilling are:

- Solar and Wind operation, including offshore wind
- Green hydrogen – engineering, operations, transport, storage and handling
- Carbon Capture, utilization and storage
- Industrial decarbonization including advanced energy efficiency, integration of clean technologies, such as green hydrogen
- Energy modelling, use of AI in data analysis etc.
- Any other frontier technology

10 Conclusion

India’s transition to a diversified and low-carbon energy system is already underway, driven by national targets and supportive government policies. The central and state governments, businesses and industries, and research centres and innovators now can accelerate the deployment of established decarbonisation technologies and development of others. In order to achieve net zero, India needs to work backward, and develop decisive plans and implementation roadmaps for its energy transition. Policy and regulatory enablers are critical in opening and developing new markets and adopting novel technologies, such as advanced energy efficient technologies, battery storage, GH2 and CCUS. Key policy focus areas include building a domestic supply chain, providing viability gap funding for emerging technologies, deploying low-emission vehicles and supporting infrastructure, urban planning, and demonstration projects for new technologies. Introducing a carbon pricing mechanism in a timely manner is also essential. Without a strong and favorable policy framework, attracting significant investment in nascent but vital markets for India's energy transition will be challenging.

Moreover, comprehensive transmission planning is essential to integrate large-scale renewables into the Indian grid. By 2070, in the Net Zero Scenario (NZS), renewable capacity is expected to exceed 6,000 GW, with peak load surpassing 1,100 GW. This scenario will require a robust and flexible transmission system to manage the growing demands efficiently.

Timely development of new technologies and planning for required infrastructure is critical. Faster and more cost-efficient adoption of sustainable technologies is possible through fostering innovation, investment in research and development, acquisition of technical know-how from technically advanced markets, and strengthening supply chain. In addition, awareness and capacity building of concerned public and private sector stakeholders will be necessary for smooth and fast adoption of new technologies.

Lastly, the energy transition will be expensive – the journey to net zero would require trillion dollars of investment, with an estimated requirement of an average annual spend of ~US$ 300 - 500 billion between 2022 and 2070. Given the large magnitude of investment required, government and concessional funding would not be sufficient. Innovative financing models including introduction of carbon tax should be adopted to accelerate the transition.

11 Annexure

Output and Specific Energy Consumption (SEC) – Industry sector

Parameters	Unit	2022	2050		2070	
		As-is	BAU	NZS	BAU	NZS
GDP at constant dollar	$ Trillion	3.0	25	25	64	64
Cement						
Production	Million Tons	350	1336	1336	1477	1477
Specific Energy Consumption	TWh/Million ton	0.67	0.59	0.59	0.59	0.59
Fertilizer						
Production	Million Tons	64	84	84	84	84
Specific Energy Consumption	TWh/Million ton	6.90	6.63	6.40	6.63	6.40
Steel						
Production	Million Tons	105	607	607	738	738
BF-BOF	*Million Tons*	*50*	*204*	*73*	*186*	*0*
DRI-EAF	*Million Tons*	*25*	*91*	*58*	*84*	*0*
DRI – IF	*Million Tons*	*23*	*84*	*53*	*78*	*0*
Scrap - IF	*Million Tons*	*7*	*98*	*103*	*141*	*166*
H2 DRI - EAF	*Million Tons*	*0*	*130*	*320*	*249*	*572*
SEC – BF-BOF	TWh/Million ton	6.97	4.65	4.65	4.65	4.65
SEC – Coal DRI-EAF	TWh/Million ton	5.30	4.76	4.76	4.76	4.76
SEC – Coal DRI – IF	TWh/Million ton	5.30	4.76	4.76	4.76	4.76
SEC – Scrap - IF	TWh/Million ton	1.22	1.22	1.22	1.22	1.22
SEC – H2 DRI - EAF	TWh/Million ton	3.37	3.27	3.27	3.27	3.27
Aluminium						
Demand	Million Tons	5.8	24	24	35	35
Specific Energy Consumption - Primary	TWh/Million ton	19.60	19.20	18.90	19.20	18.90
Specific Energy Consumption - Secondary	TWh/Million ton	2.0	2.0	2.0	2.0	2.0
Pulp & Paper						
Production	Million Tons	24	53	53	76	76
Specific Energy Consumption	TWh/Million ton	6.50	5.60	5.60	5.00	5.00
Textile						

Parameters	Unit	2022	2050		2070	
		As-is	BAU	NZS	BAU	NZS
Production	Million Tons	16	36	36	48	48
Specific Energy Consumption	TWh/Million ton	10	8.55	7.65	7.70	7.00
Other industry						
Output	INR Trillion	25	65	65	87	87
Specific Energy consumption	TWh/INR Trillion	33	30	28	30	28

Energy Mix in NZS – Industry sector

Cement sector

Energy mix	2022	2050	2070
Electricity (delivered to end user)	25.0%	11.3%	11.3%
Solid hydrocarbons	15.0%	63.2%	62.2%
Liquid hydrocarbons	48.0%	1.5%	1.5%
Gaseous hydrocarbons	10.0%	0.0%	0.0%
H2 (non-fossil)	0.0%	4.0%	5.0%
Biomass	2.0%	20.0%	20.0%

Fertlizer sector

Energy mix	2022	2050	2070
Electricity (delivered to end user)	2.0%	2.0%	2.0%
Solid hydrocarbons	4.0%	4.0%	4.0%
Liquid hydrocarbons	0.0%	0.0%	0.0%
Gaseous hydrocarbons	94.0%	54.0%	14.0%
H2 (non-fossil)	0.0%	40.0%	80.0%
Biomass	0.0%	0.0%	0.0%

Aluminium sector

Energy mix	2022	2050	2070
Electricity (delivered to end user)	10.0%	88.0%	88.0%
Solid hydrocarbons	87.0%	10.0%	10.0%
Liquid hydrocarbons	3.0%	2.0%	2.0%

Energy mix	2022	2050	2070
Gaseous hydrocarbons	0.0%	0.0%	0.0%
H2 (non-fossil)	0.0%	0.0%	0.0%
Biomass	0.0%	0.0%	0.0%

Steel sector *(aggregated at sector level)*

Energy mix	2022	2050	2070
Electricity (delivered to end user)	14.6%	39.4%	51.3%
Solid hydrocarbons	83.5%	27.3%	2.2%
Liquid hydrocarbons	43.3%	0.4%	0.0%
Gaseous hydrocarbons	0.0%	0.0%	0.0%
H2 (non-fossil)	0.0%	31.6%	46.5%
Biomass	0.0%	1.2%	0.0%

Note: Energy mix is weighted average energy mix of all routes of steel production – BF-BOF, DRI-EAF, DRI-IF, Scrap-IF and H2-DRI

Pulp & Paper sector

Energy mix	2022	2050	2070
Electricity (delivered to end user)	15.0%	20.0%	20.0%
Solid hydrocarbons	79.0%	58.0%	58.0%
Liquid hydrocarbons	2.0%	2.0%	2.0%
Gaseous hydrocarbons	0.0%	0.0%	0.0%
H2 (non-fossil)	0.0%	0.0%	0.0%
Biomass	0.0%	20.0%	20.0%

Textile sector

Energy mix	2022	2050	2070
Electricity (delivered to end user)	25.4%	60.0%	80.0%
Solid hydrocarbons	70.5%	36.0%	16.0%
Liquid hydrocarbons	1.0%	1.0%	1.0%
Gaseous hydrocarbons	3.0%	3.0%	3.0%
H2 (non-fossil)	0.0%	0.0%	0.0%
Biomass	0.0%	0.0%	0.0%

Other sector

Energy mix	2022	2050	2070
Electricity (delivered to end user)	25.0%	50.0%	70.0%
Solid hydrocarbons	15.0%	10.0%	5.0%
Liquid hydrocarbons	48.0%	20.0%	5.0%
Gaseous hydrocarbons	10.0%	8.0%	5.0%
H2 (non-fossil)	0.0%	2.0%	5.0%
Biomass	2.0%	10.0%	10.0%

Note: Other sector includes all other industry sub-sectors, such as petrochemical, glass, sugar, other MSMEs etc.

Transportation assumptions for NZS

Passenger Transport

Description	2022	2050	2070
Passenger transport demand elasticity with GDP	0.9	0.3	0.0
Modal share of passenger transport			
Road	85.3%	79.0%	79.0%
Rail	12.9%	18.0%	18.0%
Air	1.8%	3.0%	3.0%
Share of Passenger-km in road transport			
BUS	27.7%	30.0%	30.0%
MINI BUS	4.7%	4.0%	4.5%
CAR	24.8%	33.0%	38%
2W	31.0%	23%	20%
3W	6.5%	4%	3%
TAXI	5.2%	6%	5%
Modal share by technology			
Bus			
DIESEL	94%	14%	0%
CNG	5%	1%	0%
ELECTRIC	1%	80%	80%
FCV	0%	5%	20%
Mini Bus			
DIESEL	98%	19%	0%
CNG	1%	1%	0%
ELECTRIC	1%	80%	100%
FCV	0%	0%	0%
Car			

Description	2022	2050	2070
PETROL	57%	19%	0%
DIESEL	43%	4%	0%
CNG	0%	1%	0%
LPG	0%	0%	0%
ELECTRIC	0%	74%	98%
FCV	0%	2%	2%
Two - Wheeler			
PETROL	99%	0%	0%
ELECTRIC	1%	100%	100%
Three Wheeler			
CNG	9%	0%	0%
LPG	8%	0%	0%
PETROL	29%	0%	0%
DIESEL	29%	0%	0%
ELECTRIC	25%	100%	100%
Taxi			
CNG	3%	0%	0%
LPG	2%	0%	0%
DIESEL	92%	0%	0%
ELECTRIC	3%	100%	100%
Rail			
DIESEL	29%	0%	0%
ELECTRIC	71%	100%	100%

Freight Transport

Description	2022	2050	2070
Freight transport demand elasticity with GDP	1.4	0.35	0.10
Modal share of freight transport demand			
Road	71.6%	43.0%	40.0%
Rail	22.4%	45.0%	45.0%
Shipping	6.0%	12.0%	15.0%
Air	0.0%	0.0%	0.0%
Share of freight transport demand by technology			
Heavy Duty Commercial Vehicle (HCV)			
DIESEL	44%	25%	20%
LNG	1%	10%	0%

Description	2022	2050	2070
FCV	0%	10%	10%
ELECTRIC	0%	5%	20%
Low Duty Commercial Vehicle (LCV)			
DIESEL	52%	10%	10%
CNG	3%	5%	5%
ELECTRIC	0%	35%	35%
RAIL			
DIESEL	24%	0%	0%
ELECTRIC	76%	100%	100%
Shipping			
DIESEL	100%	18%	0%
LNG	0%	52%	0%
GH2-based fuels	0%	30%	100%

In addition, suitable assumptions were taken on fuel efficiency improvement, bio-fuel blending, average freight tonnage etc. to arrive at the final energy requirement for transportation sector.

Assumptions for Cooking

Parameter	Unit	2022	2050	2070
Cooking energy required – Urban per capita per month	MJ	68	68	68
Cooking energy required – Rural per capita per month	MJ	66	66	66
Penetration of cooking technologies				
Urban				
LPG	%	86.00%	40.00%	20.00%
Electricity	%	0.10%	20.00%	40.00%
PNG	%	8.00%	40.00%	40.00%
Hydrogen	%	-	-	-
Coal	%	0.3%	0.0%	0.0%
Kerosene	%	0.3%	0.0%	0.0%
Biogas	%	0.1%	0.0%	0.0%
Biomass	%	5.2%	0.0%	0.0%
Rural				
LPG	%	56.9%	50.0%	5.0%
Electricity	%	0.2%	20.0%	71.0%

Parameter	Unit	2022	2050	2070
PNG	%	0.00%	20.00%	9.00%
Hydrogen	%	-	-	-
Coal	%	0.2%	0.0%	0.0%
Kerosene	%	0.2%	0.0%	0.0%
Biogas	%	0.5%	5.0%	5.0%
Biomass	%	42.0%	5.0%	10.0%
Fuel efficiency of cooking fuels				
LPG	%	61%	64%	65%
Electricity	%	80%	85%	85%
PNG	%	60%	65%	65%
Hydrogen	%	60%	65%	65%
Coal	%	21%	25%	25%
Kerosene	%	35%	38%	38%
Biogas	%	60%	65%	65%
Biomass - Improved	%	50%	50%	50%
Biomass - Traditional	%	13%	13%	13%