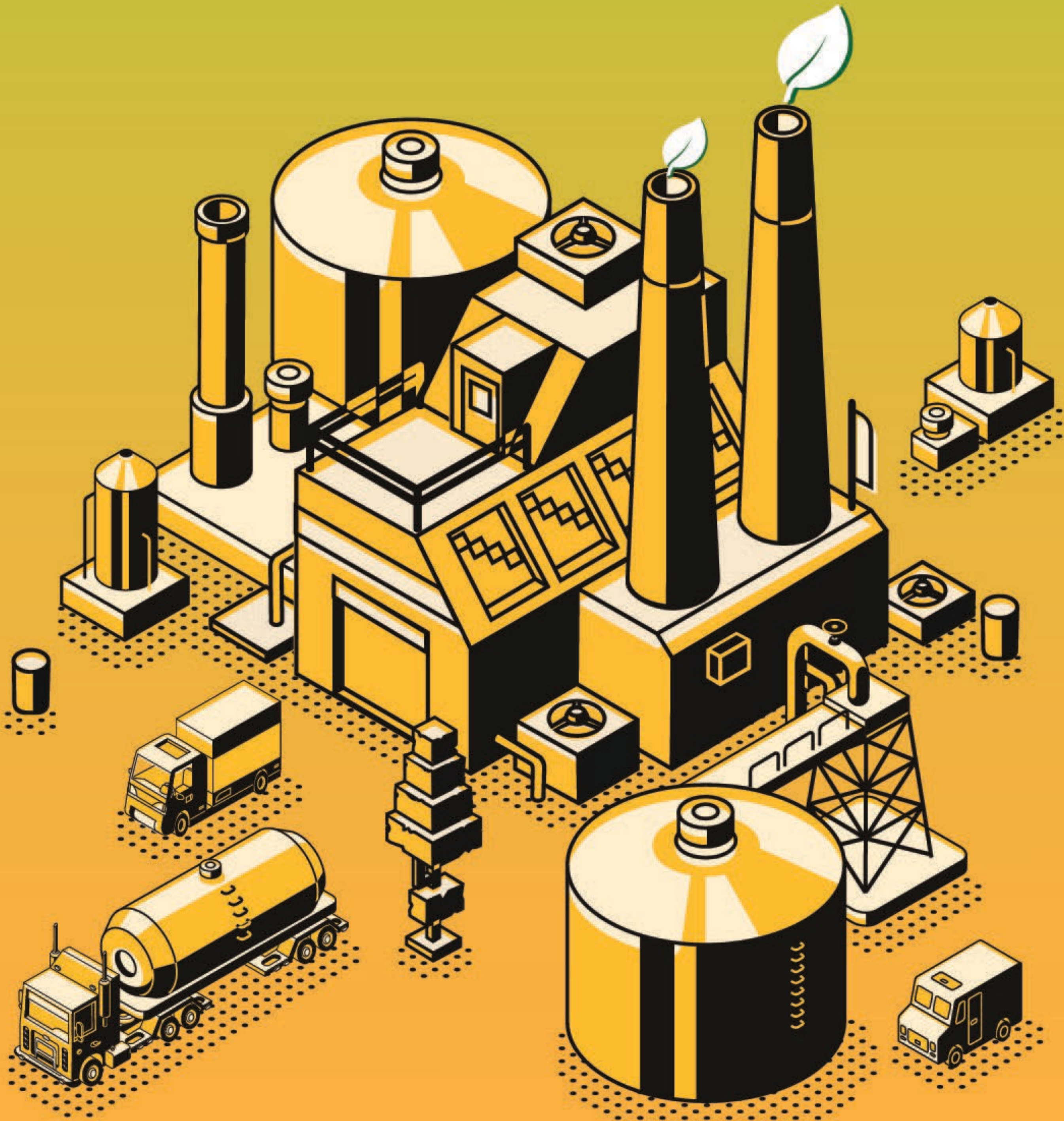
LOW-CARBON TRANSITION OF
PETROCHEMICAL INDUSTRIES
IN INDIA



Low-Carbon Transition of Petrochemical Industries in India

Center for Study of Science, Technology and Policy
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Designed and Edited by CSTEP

Disclaimer

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(The author list provided assumes no particular order as every individual contributed to the successful execution of the project)

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Executive Summary

The growth of the Indian petrochemical industry can be made sustainable only by mitigating the emissions from it. This study examines the decarbonisation potential of India's petrochemical sector until 2050 through low- or zero-emission technologies. It also underlines measures for decarbonising this hard-to-abate sector, with the aim to provide inputs for devising suitable strategies and guide policy formulation.

Considering the diversity and complexity of the petrochemical industry, the study is focussed on ethylene—the basic chemical building block for daily-use products like plastics and textiles—and adopts a modelling approach to estimate the emissions arising from domestic ethylene production. The model is based on the concept of system dynamics and is used to examine various plausible scenarios, such as energy efficiency improvements, circular economy strategies, carbon capture and storage (CCS), and decarbonisation through changes to the source of energy (electrification, green hydrogen). The total emissions arising from ethylene production are estimated on the basis of specific energy consumption (SEC) numbers and the share of various feedstocks (naphtha, natural gas, ethane, dual feed).

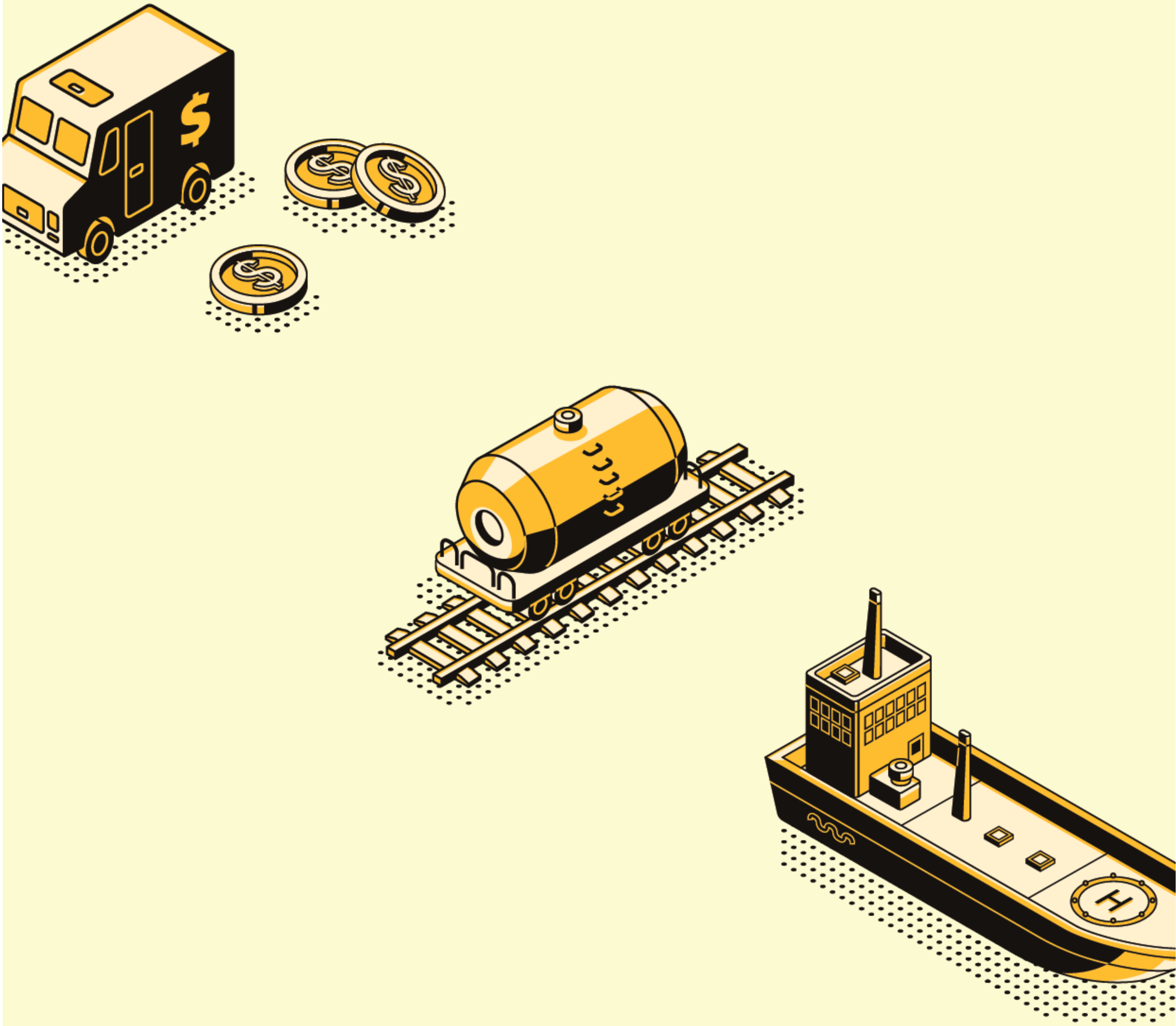
The study shows that demand reduction and technology interventions are necessary for deep decarbonisation. The scenario analysis highlights that process electrification becomes effective for emissions mitigation only when the electricity is sourced from renewables. Moreover, all emission mitigation technologies involve significant capital costs, which will raise the production costs of downstream products.

The study identifies high technology costs as a key barrier that could inhibit the large-scale adoption of decarbonisation technologies by the petrochemical industry. The requirement of uninterrupted electricity powered by renewables for process electrification and for producing green hydrogen is seen as another key challenge.

To help overcome the above barriers and facilitate the market adoption of these breakthrough technologies, the study recommends policy interventions. These include the provision of subsidies and soft loans to ease the adoption of high capital-intensive decarbonisation technologies, and policy support for providing uninterrupted supply of renewables-based electricity at subsidised rates for the petrochemical plants.

Additionally, the study presents a combination of actions that can together constitute a low-carbon roadmap for the petrochemical industry, going forward. These are:

- Considering emissions reduction by means of SEC improvement as the immediate and low-hanging strategy.
- Focussing on the existing units that depend on fossil-fuel-based electricity, with a view to replacing them with renewables-based electricity.
- Electrifying high-temperature units (such as the steam cracker) and powering them through renewables-based electricity.
- Adopting emerging technologies (such as green hydrogen and CCS) for deep decarbonisation, keeping in view their capital costs, policy support, and technology readiness.



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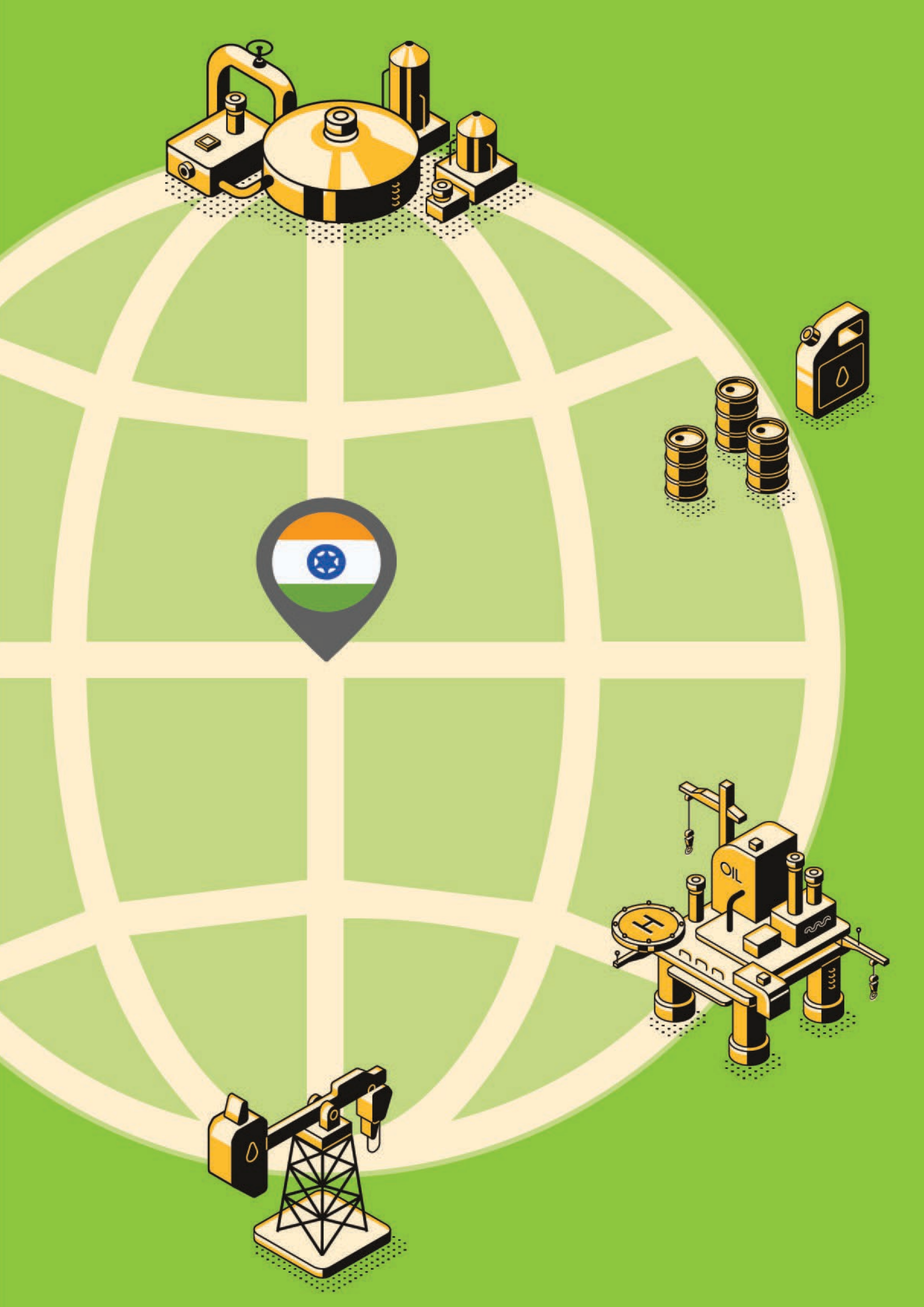
Abbreviations

BAU	Business as usual
BEE	Bureau of Energy Efficiency
CCS	Carbon capture and storage
CEPCI	Chemical Engineering Plant Cost Index
CO_2	Carbon dioxide
EDC	Ethylene dichloride
GDP	Gross domestic product
GHG	Greenhouse gas
HDPE	High-density polyethylene
IEA	International Energy Agency
LDPE	Low-density polyethylene
LLDPE	Linear low-density polyethylene
MEA	Mono ethanol amine
MNRE	Ministry of New and Renewable Energy
MOCF	Ministry of Chemicals and Fertilisers
MoEFCC	Ministry of Environment, Forest and Climate Change
MTPA	Metric tonnes per annum
PAT	Perform, Achieve and Trade
PET	Polyethylene terephthalate
PVC	Polyvinyl chloride
RE	Renewable energy
SAFARI	Sustainable Alternative Futures for India
SEC	Specific energy consumption
USD	United States dollar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1. Introduction

1.1 Context

Within the manufacturing sector, the petrochemical and allied industries constitute one of the largest energy consumers globally. The basic petrochemical production processes for producing ethylene, propylene, and aromatics are the most energy intensive. It is estimated that the demand for ethylene and propylene will grow two- to three-fold in the next 20–25 years.

The overall growth of the Indian petrochemical industry has typically remained higher than the gross domestic product (GDP) growth rate and the trend is expected to continue in the near future. The recent initiatives of the Government of India (GoI) such as the 'Make in India' scheme and the *AatmaNirbhar Bharat* campaign are expected to further boost the demand for petrochemicals.

However, petrochemicals are energy-intensive and contribute significantly to environmental pollution and greenhouse gas (GHG) emissions. Ethylene and propylene production have the most emissions-intensive processes after those of ammonia production (Mynko et al., 2022). Considering the rate at which India's petrochemical industry is growing, and the country's commitment to achieve net zero by 2070, it is imperative that a decarbonisation strategy for the petrochemical sector is put in place.

In this context, the Center for Study of Science, Technology and Policy (CSTEP) undertook a study to assess the decarbonisation potential of India's petrochemical sector until 2050 and suggest low- or zero-emission technologies and strategies for the sector. The study underlines measures to decarbonise this hard-to-abate sector, with the aim of providing inputs and guidance to policymakers, academia, and industry stakeholders for devising suitable policy instruments.

1.2 Petrochemicals and the world

Petrochemicals came into existence globally during the 19th century when synthetic rubber, plastics, and petrochemical solvents were invented. They are required in the agriculture, infrastructure, healthcare, packaging, textiles and clothing, automobiles, information technology (IT), and power sectors.

The petrochemical industry primarily comprises synthetic fibre or yarn, polymers, synthetic rubber or elastomers, synthetic detergent intermediates, and processed plastics (Mott MacDonald & FICCI, 2019). The overall global structure of the industry is illustrated in Figure 1.

Figure 1 Overall structure of the petrochemical industry (MoCF, 2021)

Naphtha and natural gas are important feedstocks for manufacturing petrochemicals. Many important petrochemicals like low-density polyethylene (LDPE), linear low-density polyethylene (LLDPE), high-density polyethylene (HDPE), ethylene dichloride (EDC), polyvinyl chloride (PVC), and polypropylene can be manufactured from the olefin fraction of naphtha.

Globally, the petrochemical sector has a significant carbon footprint, accounting for about 17 percent of industrial carbon-dioxide emissions (Cullen et al., 2022). While these emissions come from chemical reactions, high temperature heat generation, energy conversion processes, and end-of-life treatments, additional emissions are produced during the use phase and from the upstream oil and gas operations as well. Besides, the petrochemical industry is responsible for other kinds of environmental damages like those due to fertiliser runoffs, bioaccumulation of toxic chemicals in creatures, and dumping of plastic waste in the oceans and seas (Cullen et al., 2022).

1.3 The growth of petrochemicals in India

In India, hydrocarbon derivatives entered the industrial scene during the 1970s, and have registered a steady growth since then (Figure 2). The petrochemical sector has witnessed exponential growth over the years, and chemicals and petrochemicals (excluding pharmaceutical products and fertilisers) exports have increased (Figure 3) from approximately US$ 18.75 billion in 2012-13 to nearly US$ 34 billion in 2019-20. The percentage share of the exports of chemicals and petrochemicals (excluding pharmaceutical products and fertilisers) in the total national exports increased from 9.2% to 12.4% during the same period.

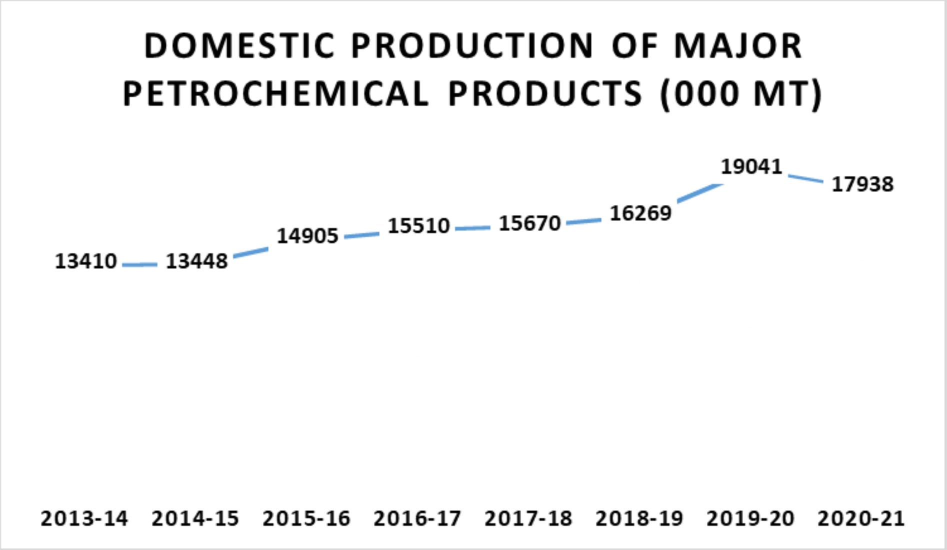

Figure 2 Domestic production of major petrochemical products (MoCF, 2021)

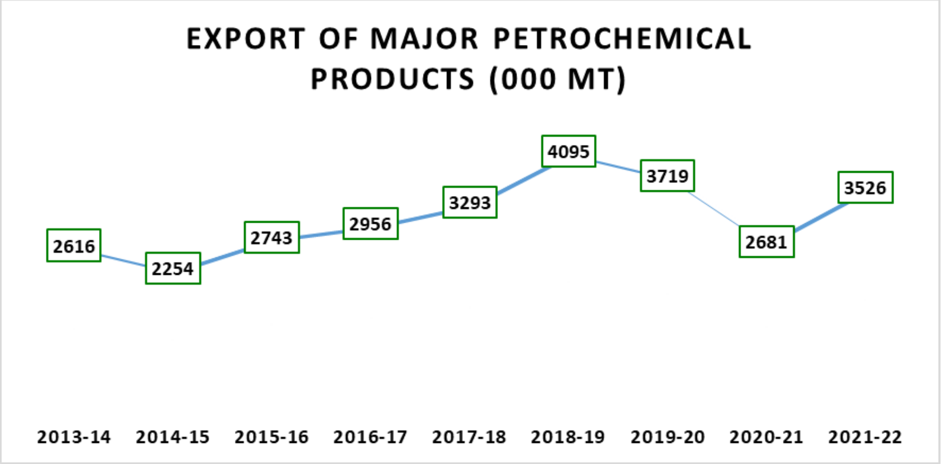

Figure 3 Export of major petrochemical products in India (MoCF, 2021)

It is estimated that India will contribute more than 10% to the global growth in petrochemicals demand over the next decade. Many oil and petrochemical companies in the country are planning to expand their petrochemical production as the demand is expected to shift away from refined crude oil products such as diesel and petrol. The sector is also witnessing an increase in both international and domestic investments.

The estimated demand for plastics is expected to reach 35 million tonnes by 2027-28 (MoCF, 2021). The current production of basic petrochemicals—ethylene and propylene—is approximately 7 million tonnes and 5 million tonnes, respectively. To meet the growing demand of petrochemicals, India needs five cracker units by 2025 and 14 cracker units by 2040 (Mott MacDonald & FICCI, 2019).

1.4 Key focus and objectives of the study

Considering the diversity and complexity of the petrochemical industry, this study is focussed on ethylene, which is the basic chemical building block for daily-use products, including plastics and textiles (Woodall et al., 2022). Ethylene is produced conventionally through the steam-cracking process from a range of hydrocarbon feedstocks like naphtha, ethane, and natural gas (Ren et al., 2006; Zhao et al., 2018). Steam cracking is a highly endothermic process in which large molecules are broken down into smaller ones. The demand for ethylene in India is expected to rise from 7 million metric tonnes per annum (MTPA) in 2019 to 25.5 million MTPA by 2040 (Mott MacDonald & FICCI, 2019). Therefore, decarbonisation of this industry is critical for meeting India's net-zero goals.

The overarching objective of the study is to examine the decarbonisation and demethanisation potential of India's petrochemical industry through low- or zero-emission technologies. The specific objectives are:

- Map the decarbonisation technologies/actions under adoption by the Indian petrochemical industry.
- Develop scenarios to assess the decarbonisation potential of the Indian petrochemical industry till 2050.
- Estimate the system-level costs for decarbonisation.
- Assess the feasibility and barriers for key emerging technologies and identify strategies to facilitate commercialisation.

> *As an educator and a researcher, I feel that this project should be considered as an important opportunity to build the case for 'Atmanirbhar Bharat' (self-sufficient India) in skill development for the petrochemical industry. Promoting innovation through leveraging the 'Panchtatva' (five elements) of renewable energy and sustainability, digitalisation, circular economy, energy efficiency, and process technology, is one of the key pathways by which India can become a 'Vishwaguru' (global leader) in the area of low-carbon transition."*
>
> - Dr Asad H Sahir, Assistant Professor,
> Department of Chemical Engineering, IIT Ropar


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2. Methodology

This study involved multiple methods like reviews and surveys, modelling, and scenario analysis. The study methodology is summarised in Figure 4:

Study of Technology and Policy Landscape	• Literature review • Identify the technology and policy landscape • Identify promising decarbonisation technologies
Stakeholder Consultations	• Interaction with petrochemical industry experts • Identify relevant technologies for India
Scenario Analysis	• Estimate potential for deep decarbonisation under various scenarios
Technology Cost Analysis	• Literature review and stakeholder consultation • Estimate technology cost for various decarbonisation strategies
Exploring Futuristic Technologies	• Literature survey and industry perspectives • Identification of barriers and gaps

Figure 4 Methodology adopted for the study

First, research on the existing manufacturing processes for basic petrochemical production in India was conducted to identify the various industry players, production processes, feedstocks, product share, current specific energy consumption, and electricity requirement. Next, a literature review was conducted to identify the promising decarbonisation technologies. These technologies were then evaluated through a set of parameters, such as current scale of implementation (global), future scalability, carbon-dioxide mitigation potential, and cost and technology requirements (qualitative). Additionally, the policy landscape of the Indian petrochemical sector was also studied.

2.1. Study of technology and policy landscape

The following are some of the prominent strategies being considered for decarbonising the petrochemical industry at the global level.

2.1.1. Energy efficiency improvements

The key decarbonisation measure pursued in the petrochemical industry is improving energy efficiency to minimise the process heat demand. Energy efficiency improvement is measured in terms of specific energy consumption (SEC), which is defined as the total energy consumed per unit of ethylene for steam cracking process in gigajoule/tonne (Ren et al., 2006). SEC is the sum of the thermodynamic minimum energy required for the process and the associated energy loss. Traditional measures for SEC improvement include improving insulation of steam distribution systems, heat/cold exchanger optimisation (using pinch analysis), waste heat recovery, and improving energy efficiency of pumps and compressors (Boulamanti & Moya, 2017).

In the Indian context, the SEC improvement in industries has been primarily happening as part of the Perform, Achieve and Trade (PAT) scheme. For the petrochemical industry, this has been mandated as part of the PAT IV notification (BEE, 2018).

2.1.2. Circular economy strategies

This includes demand reduction strategies that focus on reducing, reusing, and recycling petrochemical products (Saygin & Gielen, 2021). For instance, increased collection, reuse, and recycling of plastics can minimise the production of virgin plastics and thereby reduce the resulting overall emissions (Ellen MacArthur Foundation, 2017).

2.1.3. Decarbonisation through changes to source of energy

Electrification is a major decarbonisation strategy for the transportation and building sectors. It can be considered as an option for decarbonisation of the petrochemical industry also (Gu et al., 2022). A conventional steam cracker is heated by burning fossil fuels to reach high temperatures, which results in significant carbon dioxide emissions. It has been reported that every tonne of ethylene production emits approximately 1.8 to 2 tonnes of carbon dioxide, owing to the use of fossil-fuels-based thermal energy, which is needed for the cracking process (Boulamanti & Moya, 2017). An electrified cracker powered by low-carbon electricity can solve the problem of carbon emissions that result from ethylene production. In this regard, some global companies like BASF, LINDE, and SABIC have commenced the construction of the world's first demonstration plant (in Germany) for large-scale electrified steam crackers (Duckett, 2022). A key advantage of this strategy is that no changes happen in the process chemistry when a conventional steam cracker is replaced with an electrified steam cracker (Cullen et al., 2022).

Another decarbonisation strategy under this category is the use of low-carbon hydrogen (Woodall et al., 2022). Hydrogen is conventionally produced from natural gas by the steam methane reforming (SMR) process. However, the SMR process is associated with a high carbon footprint. It has been reported that every kilogram of SMR-based hydrogen production emits around 8.7 kilograms of carbon dioxide (Consonni et al., 2021). Here, the use of green hydrogen (produced through water electrolysis using renewable electricity) as a source of energy for the ethylene cracker can be an emissions-mitigation strategy. A key benefit of using hydrogen is that a part of the existing equipment which is fit for natural gas may be retrofitted without major additional capital investment (Woodall et al., 2022).

2.1.4. Carbon capture and storage

Carbon capture and storage (CCS) is a promising emissions-reduction strategy for the petrochemical industry, where the emitted carbon dioxide from ethylene production plants can be captured and stored deep underground. Also being researched is the post-combustion CCS strategy using different technologies, such as solvent-based absorption, membrane separation, and carbon-dioxide mineralisation (Shaw & Mukherjee, 2022).

2.2. Modelling and scenario planning

With the rising population and the improving standards of living in India, it is expected that the demand for downstream petrochemical products would increase in the future. Therefore, the downstream products of ethylene (such as HDPE, LDPE, LLDPE, ethylene oxide, ethylene dichloride, and mono ethylene glycol) have been considered as the key drivers for the future growth of the sector in this study. Further, the GDP is considered as the driving factor for the demand of downstream products (Cordier et al., 2021; Richardson, 2022). A regression analysis of GDP and the demand for downstream products for the historical period (2003-04 to 2020-21) has been performed. This correlation has been used to forecast the demand for downstream products up to 2050, with the base year being 2017, as shown in Figure 5. All the necessary data have been taken from the annual chemicals and petrochemicals statistics published by the Ministry of Chemicals and Fertilisers, Government of India (2021). The simulation horizon considered for the study is 2017 to 2050.

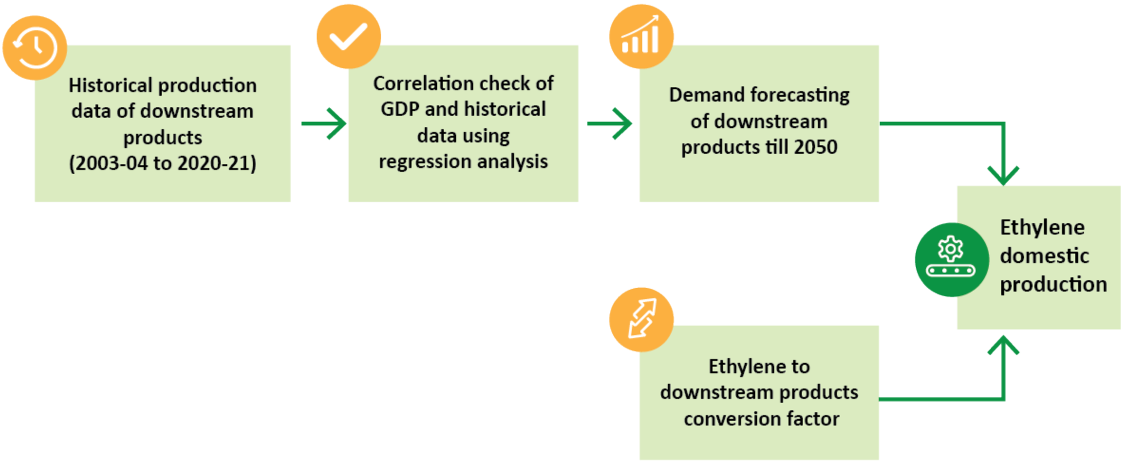


Figure 5 Schematic diagram depicting the proposed methodology for ethylene production

This study adopts a modelling approach to estimate the emissions arising from domestic ethylene production. The model is based on the concept of system dynamics and is used to examine the various plausible scenarios. System dynamics is a widely used systems-thinking tool for examining the behaviour of complex systems over time (Sterman, 2002). According to systems thinking, a system cannot be split into individual entities to analyse its behaviour. Systems thinking thus takes a holistic approach wherein the interaction between the different entities is used to understand the system behaviour (McAvoy et al., 2021).

The total emissions arising from ethylene production have been estimated on the basis of SEC numbers and the share of various feedstocks (naphtha, natural gas, ethane, dual feed), as shown in Figure 6. The rate of SEC improvement is assumed to be the same for all steam crackers for ethylene production, irrespective of their feedstocks.

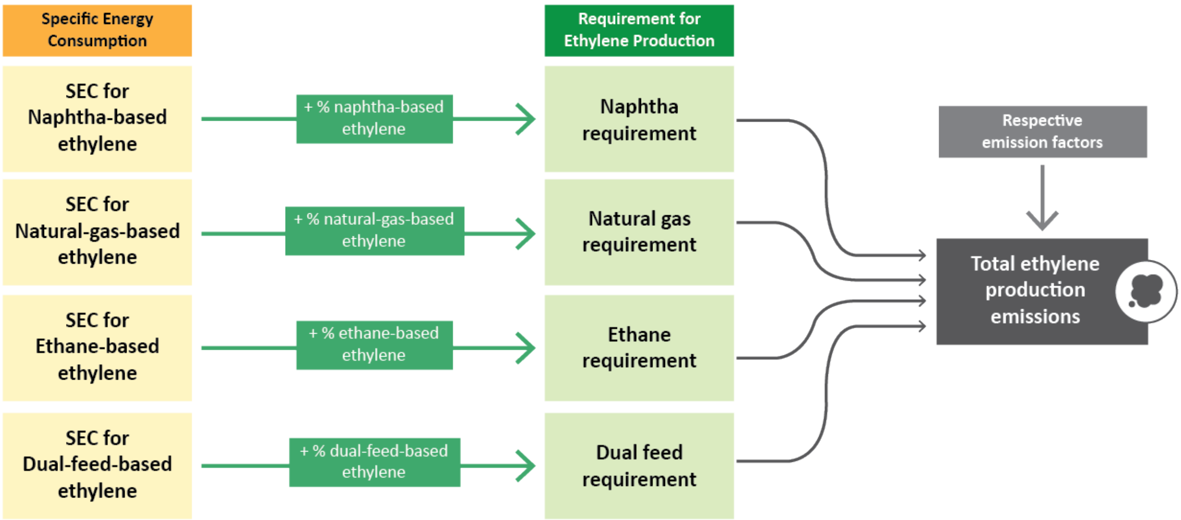


Figure 6 Schematic diagram depicting estimation of emissions

A description of the scenarios examined, which account for possible future developments in the Indian petrochemical industry, is presented in Table 1.

Table 1 Decarbonisation scenarios and assumptions

Scenarios	**Description**	**Specific energy consumption targets**	**Virgin plastic demand reduction target for 2050**
Business-as-usual (BAU) scenario	No specific emission mitigation actions.	SEC trend to continue as usual. The SEC numbers are sourced from literature (Boulamanti & Moya, 2017; Ren et al., 2006), as follows: • Naphtha steam cracker: 26 GJ/ tonne of ethylene • Ethane and natural gas steam cracker: 17 GJ/ tonne of ethylene • Dual-feed steam cracker: 21.5 GJ/ tonne of ethylene (assuming an average SEC of naphtha and natural gas)	• Polyethylene terephthalate (PET) for plastic packaging: 15%, • PET for other applications: 6% All other plastics:6% (Ellen MacArthur Foundation, 2017)
Low-action scenario	Emission mitigation based on energy efficiency improvements and plastic recycling.	SEC improvement at reasonable targets (using the PAT target as baseline) SEC targets: • 1.2% for first 10 years • 1% for the next 10 years • 0.8% for the next 10 years (BEE, 2018)	Considering the National Resource Efficiency Policy as baseline: • PET for plastic packaging: 40%, • PET for other applications: 10% • All other plastics: 10% (MoEFCC, 2019)
Reasonable-action scenario (electricity sourced from grid)	Adoption and implementation of cracker electrification technology for 50% of the ethylene production by 2050.	The above SEC targets have been considered.	The above plastic recycling targets have been considered.
Reasonable-action scenario (electricity sourced from renewable energy)			
High-action scenario (electricity sourced from grid)	Adoption and implementation of cracker electrification technology for 100% of the ethylene production by 2050.		• PET for plastic packaging: 50%, • PET for other applications: 20% • All other plastics: 20% (Ellen MacArthur Foundation, 2017)
High-action scenario (electricity sourced from renewable energy)			
CCS scenario	Post-combustion carbon capture with 95% efficiency 2030 onwards.		The above plastic recycling targets have been considered.
Green hydrogen scenario	Fueling 25% of ethylene crackers with green hydrogen 2040 onwards.		

2.2.1 Business-as-usual (BAU) scenario

Emission mitigation is assumed to be resulting from only SEC improvements, owing to normative annual maintenance and plastic demand reduction strategies. The plastic recycling (mechanical recycling) target and the resulting demand reduction for virgin plastic is assumed to continue in line with the current trends, as mentioned in Table 1.

2.2.2 Low-action scenario

SEC improvements are assumed at reasonable targets, considering the PAT target as baseline. The assumed SEC trajectory is shown in Figure 7. In addition, the plastic recycling targets as per the National Resource Efficiency Policy (MoEFCC, 2019) have been considered.

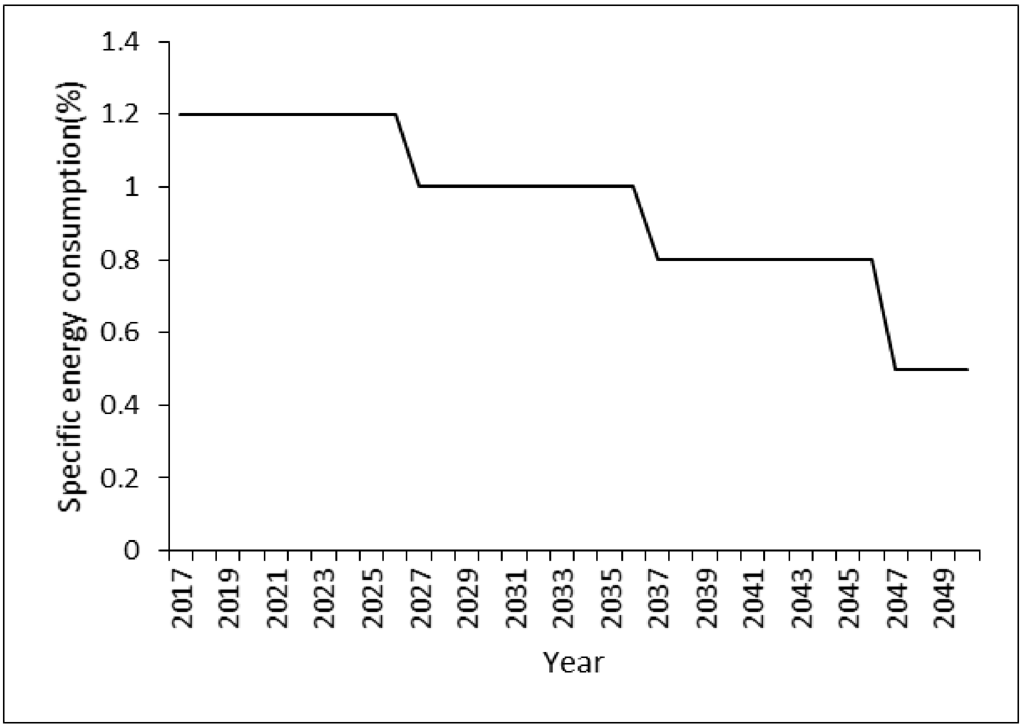


Figure 7 SEC improvement trajectory

2.2.3 Reasonable-action scenario

In this scenario, process electrification is considered as the emission-mitigation strategy. It is assumed that process electrification would commence in 2030 and 50% of the thermal energy needs would be met through electricity by 2050. This is based on the assumption that the electrified steam cracker technology would be commercially available in India by 2030 for new plants and that all the existing plants would be retrofitted. Two sub-scenarios that, respectively, consider electricity sourced from renewable energy (RE) and from the grid are analysed separately. In case of RE, it is assumed that the electricity would be sourced from captive generation plants. The emission factors for grid are sourced from CSTEP's Sustainable Alternative Futures for India (SAFARI) model (CSTEP 2020) and are provided in the Appendix. The SEC improvement and plastic recycling targets are considered to be the same as those under the low-action scenario.

2.2.4 High-action scenario

In the high-action scenario, process electrification is considered as the emission mitigation strategy. It is assumed that process electrification would commence in 2030 and 100% of the thermal energy requirements would be met through electricity by 2050. Like the reasonable-action scenario, two sub-scenarios are analysed that consider electricity sourced from the grid and from renewables, respectively. The SEC improvement target is considered to be the same as that under the low-action scenario. However, a higher plastic recycling target is assumed for the high-action scenario.

2.2.5 CCS scenario

In this scenario, post-combustion carbon capture based on amine absorption technology (using monoethanol amine [MEA]) with 95% efficiency is considered. It is assumed that the first CCS plant would be installed in 2030, followed by another two plants in 2032, another five plants by 2035, and all the remaining plants after 2035. The SEC improvement targets and the plastic recycling targets are considered to be the same as those under the high-action scenario.

2.2.6 Green-hydrogen scenario

In this scenario, fuelling 25% of the ethylene crackers —using low-carbon hydrogen (specifically green hydrogen) as a source of energy—is examined. It is assumed that green hydrogen technology would be commercially available in India by 2030 (MNRE, 2023). Once available, it is assumed that green hydrogen would be initially prioritised for the fertiliser sector, and that it would be made available for the petrochemical sector only after 2040. In addition, the SEC improvement targets and the plastic recycling targets considered are the same as those under the high-action scenario.

2.3. Technology-cost analysis

Economics plays a key role in choosing a decarbonisation strategy out of the different ones available. Under the study, a cost analysis framework has been developed to compare the different decarbonisation technologies for the petrochemical industry. A standard annualised cost is calculated for 1 million tonne of ethylene production, using natural gas and naphtha as feedstock. Annualised cost is the annual cost of owning and maintaining an asset, calculated over its lifetime. It is the sum of annual capital expenditure, fixed costs, and variable costs. The framework for cost analysis is presented in Figure 8.

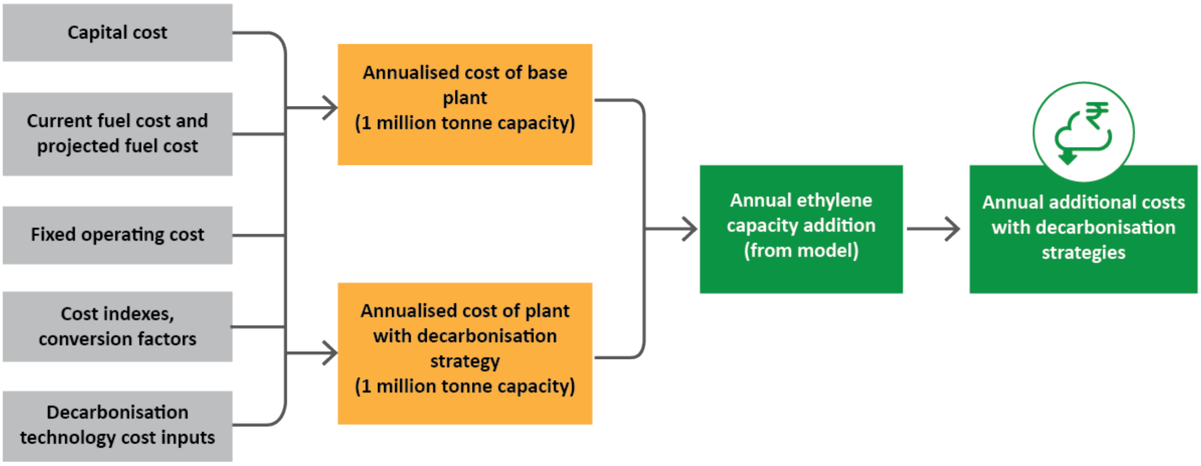


Figure 8 Framework for technology-cost analysis

The chemical engineering plant cost index (CEPCI) has been used to account for the effects of change in capacity and inflation, as shown in the equation below:

$$Cost_{Capacity_2} = Cost_{Capacity_1}\left(\frac{Capacity_2}{Capacity_1}\right)^{size\ factor}\left(\frac{CEPCI_2}{CEPCI_1}\right)$$

Here, $Capacity_2$ refers to the new plant capacity and $Capacity_1$ refers to the reference plant capacity. The size factor is considered to be 0.6 (Peters et al., 2003).

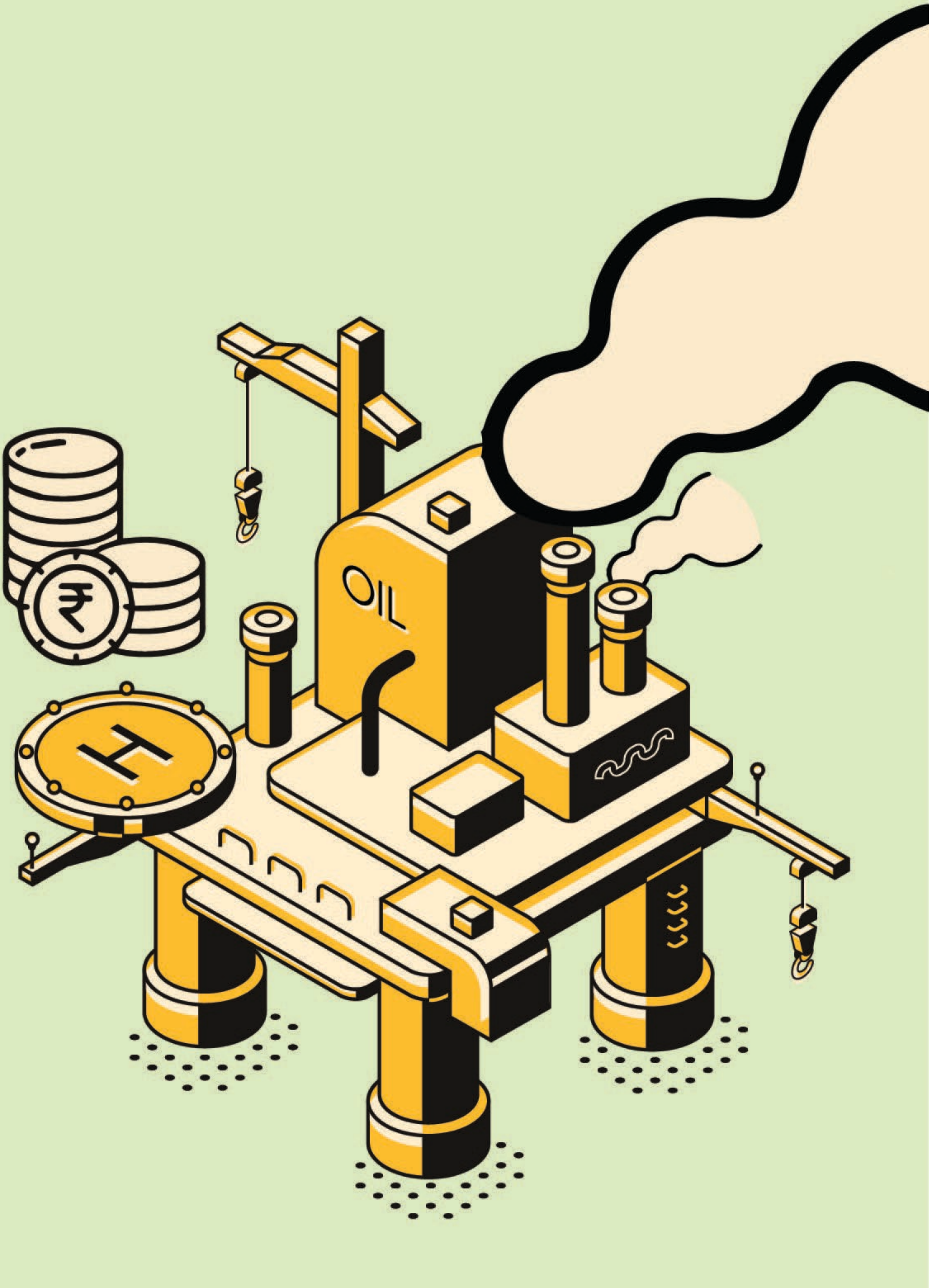
The following assumptions have been made for the cost analysis:

1. A plant life of 25 years is assumed.
2. A discount rate of 4.75% is considered (Gu et al., 2022; IEA, 2018).
3. The electricity cost is considered to be static throughout the plant life.
4. Retrofitting of the existing conventional steam crackers in the case of electrified steam cracker in 2030 is assumed (Gu et al., 2022).
5. As the historical prices of naphtha and natural gas have undergone huge fluctuations, different feedstock prices (low, median, and high) are considered.

2.4. Voice of the industry

In addition to model-based analysis and scenario planning, stakeholder consultations with experts were held to understand industry perspectives, and the various planned decarbonisation strategies and their implementation challenges in India. A questionnaire-based survey was also conducted among experts from the petrochemical industry. In addition, continuous stakeholder engagements were undertaken (through video conferencing) to identify a pool of low-carbon technologies.

> “*India is at a very nascent stage when it comes to decarbonisation of petrochemicals. The decarbonisation of downstream industry and old petrochemical complexes need special focus.”*
>
> –Mr Uday Chand, Secretary General,
> Chemicals and Petrochemicals Manufacturers’ Association



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3. Findings and Analysis

This chapter presents the forecasted ethylene production, the forecasted GHG emissions, and the cost analysis for different decarbonisation strategies. The model and the scenarios discussed in the previous chapter were simulated in STELLA, a software that allows a systems-based approach. The model results were used as inputs for cost analysis, which was done using a spreadsheet.

3.1. Scenario analysis

In the BAU scenario, the projected demand for ethylene increases rapidly to 41 million tonnes by 2050, indicating a five-fold growth in production (Figure 9). This is driven by the GDP growth, which is marginally offset by the assumed plastic recycling targets. The GHG emissions continue to rise as the ethylene production increases in the future.

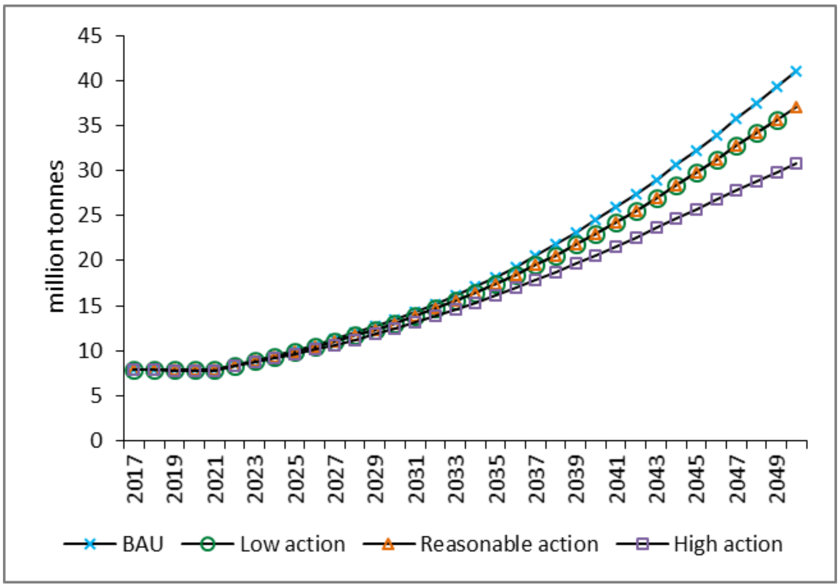

Figure 9 Forecasted ethylene production under different scenarios

Under the low-action scenario, the forecasted ethylene production is 9% lower than that in the BAU scenario in 2050. This is due to the higher plastic recycling rates and the resulting demand reduction for virgin plastics. It can be observed from Figure 10 that the SEC improvement based on PAT targets and plastic recycling targets can only marginally mitigate the emissions, in comparison to the BAU scenario. The scenario highlights the need for technological interventions to significantly lower GHG emissions.

In the reasonable-action scenario, ethylene production is the same as that under the low-action scenario, as is evident from Figure 9. This is because the plastic recycling rates are assumed to be the same for both the scenarios. The reasonable-action scenario shows that process electrification that is powered by renewables has the potential to mitigate emissions to almost half by 2050. However, grid-powered process electrification is not an effective strategy for decarbonisation.

In the high-action scenario, ethylene production is further reduced, as compared to the reasonable-action scenario, owing to the assumption of higher plastic recycling rates. The production gets reduced by 25% in comparison to that in the BAU scenario in 2050. The results show that emissions under the high-action scenario get mitigated significantly (to almost zero) by 2050 if the electricity needs are met by renewables. However, the emissions increase (in comparison to the BAU scenario) if electricity is sourced from the grid, as shown in Figure 10.

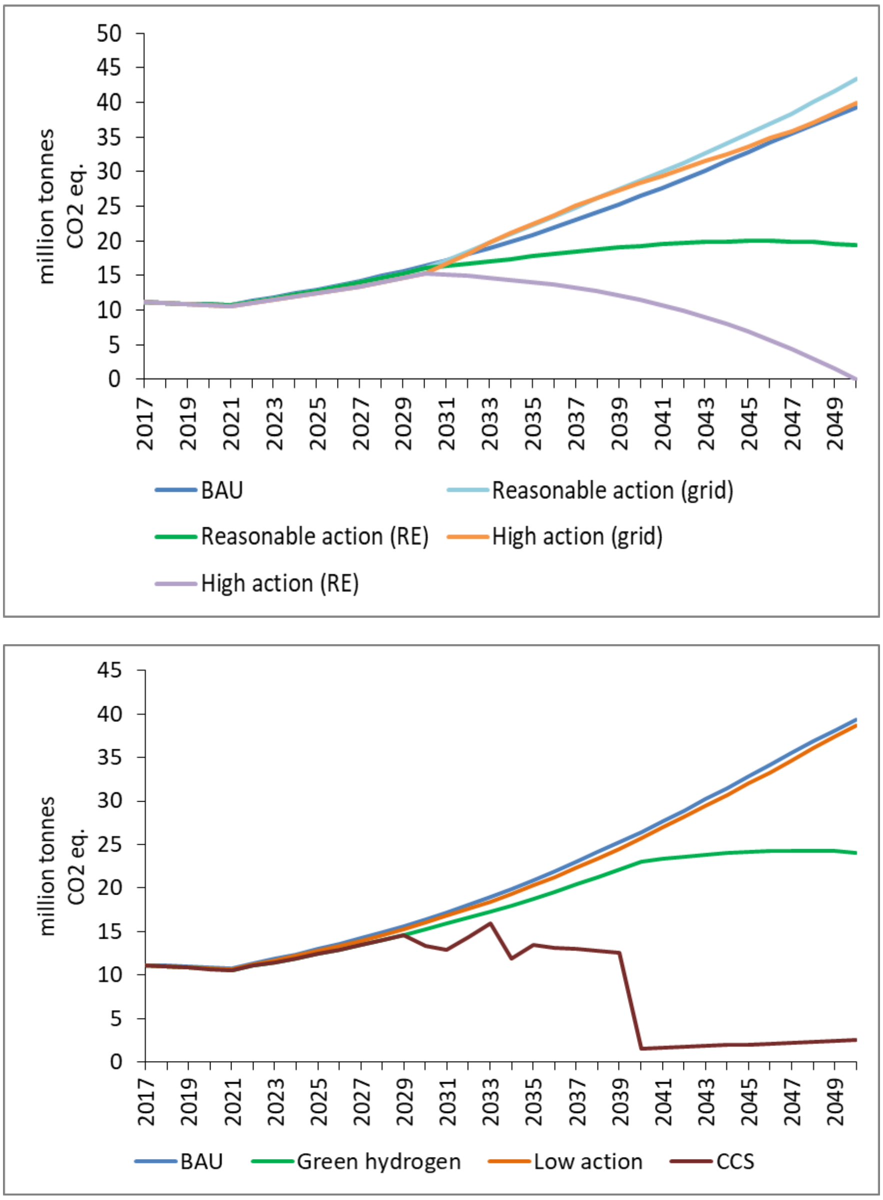

Figure 10 Forecasted emissions for the different decarbonisation scenarios

In the CCS scenario, ethylene production is the same as that under the high-action scenario due to the same plastic recycling assumptions. It can be observed that once the first CCS plant becomes operational in 2030, the emissions get mitigated in a step-by-step manner. The emissions get mitigated significantly by 2040 due to the assumption that all the existing and future ethylene production facilities have CCS plants. It is to be noted that beyond 2040 the emissions continue to increase gradually, owing to the increase in ethylene production.

Under the green-hydrogen scenario, ethylene production again is the same as that in the high-action scenario, due to the same plastic recycling targets. The petrochemical industry commences the adoption of green hydrogen as a source of energy in 2040. The results show that green hydrogen can mitigate some emissions from ethylene, as is evident from Figure 10. However, at the assumed utilisation level of green hydrogen, the potential to mitigate emissions by 2050 is not as significant as that of other strategies (such as CCS or process electrification powered by renewables).

The potential for emissions abatement under different scenarios has been estimated for 2050 as shown in Table 2. It is evident that either CCS or RE-powered process electrification is necessary to significantly mitigate emissions in the petrochemical industry.

Table 2 Emission abatement potential for different scenarios

Scenario	**Emissions abatement potential compared to BAU scenario in 2050**
Low action	1.6%
Reasonable action (grid)	0%
Reasonable action (RE)	50.8%
High action (grid)	0%
High action (RE)	100%
CCS	93%
Green hydrogen	38.8%

3.2. Results of cost analysis

The estimated annualised costs for various decarbonisation technologies are presented in this section. The capital costs and variable costs for the base plant and electrified cracker plant are given in Table 3. The capital costs for naphtha-based plants are significantly higher than that for natural-gas-based plants, leading to a higher fixed operating cost and annualised capital cost. Fuel costs make up the variable costs, as shown in Table 3.

Table 3 Techno-economic parameters considered for base plant and electrified plant

Parameter	**Base plant**	**Base plant**	**Electrified cracker plant**	**Electrified cracker plant**	**Unit**	**Source**
Feedstock considered	Naphtha	Natural gas	Naphtha	Natural gas		
Lifetime	25	25	25	25	Years	(IEA, 2018)
Capital costs	1445	1183	1797	1535	USD million	(Gu et al., 2022)
Variable costs (fuel costs)	Low: 180 Median: 671 High: 1180	Low: 89 Median: 305 High: 517	671	305	USD/ tonne	(Ray et al., 2014; Trading Economics, 2023)
Fixed operating costs	3.75% of capital cost				USD million	(IEA, 2018)

In the case of CCS, cost analysis is done separately for onshore storage and offshore storage, as shown in Table 4.

Table 4 Techno-economic parameters considered for CCS

Parameter	**Onshore storage**	**Offshore storage**	**Unit**	**Source**
Levelised cost of carbon capture	25	37.5	USD/tonne of CO_2	(IEA, 2021; Schmelz et al., 2020)
Levelised cost of pipeline transportation	2	14	USD/tonne of CO_2	
Levelised cost of storage	6	18	USD/tonne of CO_2	

Due to the assumption that the same process plant configurations are considered for different feedstock prices (low, median, and high), the annualised capital costs remain the same. The varying fuel prices are reflected in the increasing annualised variable costs (due to the higher feedstock price), as evident from Table 5 and Table 6.

Table 5 Estimated costs for naphtha-based base plant

Cost	**Low naphtha price (USD million)**	**Median naphtha price (USD million)**	**High naphtha price (USD million)**
Annualised capital cost	58	58	58
Annualised fixed cost and variable cost	967	3409	5940
Total annualised cost	1025	3467	5998

Table 6 Estimated costs for natural-gas-based base plant

Cost	**Low gas price (USD million)**	**Median gas price (USD million)**	**High gas price (USD million)**
Annualised capital cost	47	47	47
Annualised fixed cost and variable cost	251	722	1182
Total annualised cost	298	769	1229

The total annualised costs of electrified steam cracker plant were estimated by considering median fuel prices (naphtha and natural gas). It can be seen that the total annualised cost of electrified steam cracker plant is significantly higher than that of conventional plant (base plant), as evident from Table 7.

Table 7 Estimated costs for electrified steam cracker plant

Cost	Naphtha as feedstock (USD Million)	Natural gas as feedstock (USD Million)
Annualised capital cost	72	61
Annualised fixed cost and variable cost	4923	2199
Total annualised cost	4995	2260

In the case of CCS, the levelised costs are estimated by assuming an emission factor of 1.13 tonnes of CO_2 per tonne of ethylene (Boulamanti & Moya, 2017) . It can be seen from Table 8 that the levelised cost for offshore storage is significantly higher than that for onshore storage, owing to the higher transportation and storage expenses.

Table 8 Estimated costs for CCS

Parameter	Onshore storage	Offshore storage	Unit
Levelised cost for CCS	37.29	64.41	USD/tonne of CO_2

The key take-away points from the above analysis are summarised below:

- SEC improvement is the 'low-hanging fruit' for emissions mitigation.
- Demand reduction and technology interventions are necessary for hard decarbonisation.
- Reasonable-action scenario (RE) can mitigate the emissions to almost half by 2050.
- Process electrification becomes effective for emissions mitigation only when electricity is sourced from renewables.
- For emissions mitigation, green hydrogen at the assumed usage level (25% of the total heat required for cracking) is not as effective as CCS and RE-powered process electrification. However, it is obvious that a complete shift to green hydrogen for providing the required energy to the crackers will mitigate the CO_2 generated from the crackers to near-zero levels.
- All emission mitigation technologies involve significant capital costs, which will raise the production costs of downstream products.

3.3. Barrier and gap analysis

In the Indian petrochemical sector, decarbonisation-related discussions are happening mostly around SEC improvements. The analysis shows that adopting emissions-abatement or low-carbon technologies for deep decarbonisation will become essential for the petrochemical industry, as it moves forward. Following are the key barriers that inhibit the large-scale adoption of decarbonisation technologies in the petrochemical industry:

- **High technology costs:** High capital investment is required for novel decarbonisation technologies, such as electrified steam cracker and recycling technologies.
- **Early-stage technologies:** Most technologies (such as green hydrogen) are still at an early stage in India and considerable efforts will be needed to make them commercially available.

- **Limited availability of resources:** Supply of uninterrupted RE-powered electricity for process electrification and for producing green hydrogen is also a key barrier.
- **Other barriers:** There seems to be no streamlined market in India for utilising the carbon captured. Similarly, there seems to be a lack of market for recycled plastic products. The fact that recycled plastic products are more expensive than virgin plastic products can also form a barrier.

Table 9 Overview of key barriers for different decarbonisation strategies

Technology	Barriers
Process electrification	• Requires high temperature for crackers. • Uninterrupted power supply from renewables, which cannot be made available for certain ethylene plant locations. • Significant battery storage for RE. • High capital costs for electrified steam crackers. • Most of the existing plants utilise waste heat for energy needs, which might not be possible if they switch to electric cracker (Woodall et al., 2022).
Carbon capture	• High infrastructure cost. • Energy required for capture: 1420 to 2340 kJ/tonne CO_2 for MEA-based carbon capture (Cullen et al., 2022).
Green hydrogen	• High technology costs for green hydrogen production. • Higher electricity requirement for green hydrogen production than that for direct process electrification (Mallapragada et al., 2023).
Circular economy (recycling)	• Logistic difficulties in collecting plastics. • High upfront costs for setting up effective recycling units in India (Satapathy, 2017). • Low technology maturity for recycling. • Lack of public awareness on the benefits of recycling.

> *Every petrochemical industry should work on making the entire supply chain green and sustainable. Apart from carbon, methane is a major source of GHG emissions in the petrochemical industry and needs to be curbed using leak-proof valves and fittings.”*
>
> -Mr Vivek Sethi, Chief Manager (Petrochemical Maintenance),
> Gas Authority of India Ltd. (GAIL)

4. Conclusions and Way Forward

The Indian petrochemical industry is growing. This growth can be made sustainable only by mitigating emissions from this sector via policy and technological interventions, market shifts, and government-industry collaborations. This study has reviewed the potential decarbonisation strategies for the Indian petrochemical industry. It highlights that demand reduction strategies as well as technology interventions are necessary for emissions mitigation.

The following are the main themes that need to be focussed on to decarbonise the petrochemical industry:

a) Process and energy optimisation.
b) Renewable energy supply.
c) Carbon-dioxide reduction through breakthrough technologies.
d) Adoption and implementation of plastic repurposing and recycling technologies to reduce the overall need for petrochemical production.

It has also been discussed that the sector has several barriers and overcoming them would be essential for the effective implementation of decarbonisation strategies. Appropriate policy interventions can help overcome the barriers and facilitate the market adoption of these breakthrough technologies. Some such policy interventions are:

- Subsidies and soft loans to ease the adoption of capital-intensive decarbonisation technologies.
- Government grants to research laboratories and academic institutions towards developing demonstration/pilot plants for early-stage technologies, such as electrified steam cracker and electrolysers for green hydrogen production.
- Policy support for providing uninterrupted supply of renewables-based electricity at subsidised rates for the petrochemical plants.
- Incentives for plastic recycling ventures to boost collection, segregation, and recycling of plastics.

In addition to policy interventions, partnerships, engagements, and collaborations are needed. These include:

- Establishment of industry-academic consortia (e.g., Dutch Polymer Institute) with clearly laid-out targets and objectives.
- Government interactions with industry stakeholders and academic experts on a regular basis through symposiums and conferences.
- Industry-academia partnerships for R&D programmes and pilot plant demonstrations to improve the technology readiness of early-stage technologies.
- International collaborations in the form of academic exchange programmes and collaborative research to enhance the technology readiness levels.

4.1. Limitations of the study

The study has some inherent limitations, primarily owing to the scope of the study, as discussed below.

- Impact of price dynamics on feedstock is not considered in the study.
    - The share of various feedstocks for ethylene production, such as naphtha, natural gas, and ethane, is kept constant throughout the analysis timeframe.
- Import and export of various petrochemical products is not considered.

- Technology adoption of various decarbonisation strategies is assumed to be based on only the commercial availability of technology.
- Infrastructure limitations for making available large-scale uninterrupted supply of RE and green hydrogen (required for emission mitigation) are not considered.
- GHG generation during conversion of ethylene to the next set of products, and the environmental impacts of disposal of the final products are not considered in the study.

Decarbonisation of the petrochemical sector is uniquely challenging to achieve, and one of the key proposed strategies is electrification through grid electricity and through RE-captive power plants. However, in the case of grid, the use of large-scale, uninterrupted, low-carbon electricity may jeopardise the electricity supply for other sectors, including residential and commercial users. Moreover, process electrification as a decarbonisation strategy may simply shift the emissions mitigation burden from the petrochemical to the power sector.

4.2. Way forward

Moving forward, a low-carbon roadmap for the petrochemical industry would entail a combination of actions that include the following:

1) Firstly, emissions reduction by means of SEC improvement should be the immediate and low-hanging strategy.
2) Secondly, the focus should be on existing units (such as compressors and distillation columns) that depend on fossil-fuel-based electricity. This needs to be replaced with renewables-based electricity. In the long run, the industry should aim to become self-sustainable in terms of meeting its renewable energy needs by means of captive power plants.
3) Thirdly, high-temperature units (such as the steam cracker) need to be electrified and powered using renewables-based electricity.
4) Finally, other emerging technologies such as green hydrogen and CCS need to be adopted for deep decarbonisation, keeping in view their capital costs, policy support, and technology readiness.

As part of the future work, the potential of alternative feedstocks (including biomass and carbon dioxide) can be examined for ethylene production. Such feedstocks have significant potential to mitigate emissions from the sector. In addition, life cycle assessment (LCA) studies are necessary to understand and compare the environmental impacts of various decarbonisation strategies from a lifecycle perspective.

> *At present, there is no concrete policy or comprehensive plan for decarbonising the petrochemical sector in India. Some discussions are happening, but they are mainly around energy efficiency improvements.”*
>
> \- Mr Shyam Gupta, Chief Manager (Strategy and Analytics),
> Bharat Petroleum Corporation Ltd. (BPCL)

5. References

Boulamanti, A. & Moya, J. A. (2017). *Energy efficiency and GHG emissions: Prospective scenarios for the chemical and petrochemical industry.* Publications Office of the European Union. https://data.europa.eu/doi/10.2760/20486

Bureau of Energy Efficiency. (2018). *Notification of petrochemical sector under PAT scheme*. https://beeindia.gov.in/sites/default/files/184472.pdf

Consonni, S., Mastropasqua, L., Spinelli, M., Barckholtz, T. A., & Campanari, S. (2021). Low-carbon hydrogen via integration of steam methane reforming with molten carbonate fuel cells at low fuel utilization. *Advances in Applied Energy*, *2*. https://doi.org/10.1016/j.adapen.2021.100010

Cordier, M., Uehara, T., Baztan, J., Jorgensen, B., & Yan, H. (2021). Plastic pollution and economic growth: The influence of corruption and lack of education. *Ecological Economics*, *182*. https://doi.org/10.1016/j.ecolecon.2020.106930

Center for Study of Science, Technology and Policy. (2021). *Energy and emissions implications for a desired quality of life in India via SAFARI*. https://cstep.in/drupal/sites/default/files/2021-07/CSTEP_SAFARI_Final_Report_July2021.pdf

Cullen, J. M., Meng, F., Allen, D., & Christopher, P. (2022). *Carbon clarity in the global petrochemical supply chain: A critical review.* https://www.c-thru.org/first-year-report/

Duckett, A. (2022, September 16). *Electrification of steam cracking: BASF demo set to operate in 2023. The Chemical Engineer*. https://www.thechemicalengineer.com/news/electrification-of-steam-cracking-basf-demo-set-to-operate-in-2023/

Ellen MacArthur Foundation. (2017). *The new plastics economy: Rethinking the future of plastics & catalysing action*. https://ellenmacarthurfoundation.org/the-new-plastics-economy-rethinking-the-future-of-plastics-and-catalysing

Gu, J., Kim, H., & Lim, H. (2022). Electrified steam cracking for a carbon neutral ethylene production process: Techno-economic analysis, life cycle assessment, and analytic hierarchy process. *Energy Conversion and Management*, *270*. https://doi.org/10.1016/j.enconman.2022.116256

International Energy Agency. (2018). *The future of petrochemicals: Towards a more sustainable chemical industry*. https://www.iea.org/reports/the-future-of-petrochemicals

International Energy Agency. (2021). *Is carbon capture too expensive?* https://www.iea.org/commentaries/is-carbon-capture-too-expensive

Mallapragada, D. S., Dvorkin, Y., Modestino, M. A., Esposito, D. V., Smith, W. A., Hodge, B.-M., Harold, M. P., Donnelly, V. M., Nuz, A., Bloomquist, C., Baker, K., Grabow, L. C., Yan, Y., Rajput, N. N., Hartman, R. L., Biddinger, E. J., Aydil, E. S., & Taylor, A. D. (2023). Decarbonization of the chemical industry through electrification: Barriers and opportunities. *Joule*, *7*(1), 23–41. https://doi.org/10.1016/j.joule.2022.12.008

McAvoy, S., Grant, T., Smith, C., & Bontinck, P. (2021). Combining life cycle assessment and system dynamics to improve impact assessment: A systematic review. *Journal of Cleaner Production*, *315*. https://doi.org/10.1016/j.jclepro.2021.128060

Ministry of Chemicals and Fertilisers. (2021). *Demand and availability of petrochemicals including imports and exports.* Government of India. https://loksabhadocs.nic.in/lsscommittee/Chemicals%20&%20Fertilizers/17_Chemicals_And_Fertilizers_16.pdf

Ministry of Environment, Forest and Climate Change. (2019). *National Resource Efficiency Policy*. Government of India. https://moef.gov.in/wp-content/uploads/2019/07/Draft-National-Resourc.pdf

Ministry of New and Renewable Energy. (2023). National green hydrogen mission. Government of India. https://mnre.gov.in/img/documents/uploads/file_f-1673581748609.pdf

Mott MacDonald & Federation of Indian Chambers of Commerce and Industry. (2019). *PCPIR Rejuvenation Study*. https://ficci.in/spdocument/23135/PCPIR_Rejuvenation_Study_Report%202019.pdf

Mynko, O., Amghizar, I., Brown, D. J., Chen, L., Marin, G. B., de Alvarenga, R. F., Uslu, D. C., Dewulf, J., & Van Geem, K. M. (2022). Reducing CO2 emissions of existing ethylene plants: Evaluation of different revamp strategies to reduce global CO2 emission by 100 million tonnes. *Journal of Cleaner Production*, *362*. https://doi.org/10.1016/j.jclepro.2022.132127

Peters, M., Timmerhaus, K., & West, R. (2003). *Plant design and economics for chemical engineers* (5th ed.). McGraw-Hill Education.

Ray, S., Goldar, A., & Saluja, S. (2014). *Feedstock for the petrochemical industry* [Working Paper]. Indian Council for Research on International Economic Relations. https://www.econstor.eu/bitstream/10419/176289/1/icrier-wp-271.pdf

Ren, T., Patel, M., & Blok, K. (2006). Olefins from conventional and heavy feedstocks: Energy use in steam cracking and alternative processes. *Energy*, *31*(4), 425–451. https://doi.org/10.1016/j.energy.2005.04.001

Richardson, J. (2022, February 13). Ten drivers of global polyethylene demand in 2022. *Asian Chemical Connections*. https://www.icis.com/asian-chemical-connections/2022/02/ten-drivers-of-global-polyethylene-demand-in-2022/

Satapathy, S. (2017). An analysis of barriers for plastic recycling in the Indian plastic industry. *Benchmarking: An International Journal*, *24*(2), 415–430. https://doi.org/10.1108/BIJ-11-2014-0103

Saudi Arabia's Basic Industries Corporation. (2018). *Petrochemical industry in India: Vision 2025 and beyond*. https://www.indiachem.in/brochure/Presentation%20By%20Mr.%20Janardhanan-%20SABIC.pdf

Saygin, D., & Gielen, D. (2021). Zero-Emission Pathway for the Global Chemical and Petrochemical Sector. *Energies*, *14*(13). https://doi.org/10.3390/en14133772

Schmelz, W. J., Hochman, G., & Miller, K. G. (2020). Total cost of carbon capture and storage implemented at a regional scale: Northeastern and midwestern United States. *Interface Focus*, *10*(5). https://doi.org/10.1098/rsfs.2019.0065

Shaw, R., & Mukherjee, S. (2022). The development of carbon capture and storage (CCS) in India: A critical review. *Carbon Capture Science & Technology*, *2*. https://doi.org/10.1016/j.ccst.2022.100036

Sterman, J. (2002). *System dynamics: Systems thinking and modeling for a complex world* [Working Paper]. Massachusetts Institute of Technology, Engineering Systems Division. https://dspace.mit.edu/handle/1721.1/102741

Trading Economics. (2023). *Naphtha Data* [Infographic]. https://tradingeconomics.com/commodity/naphtha

Woodall, C. M., Fan, Z., Lou, Y., Bhardwaj, A., Khatri, A., Agrawal, M., McCormick, C. F., & Friedmann, S. J. (2022). Technology options and policy design to facilitate decarbonization of chemical manufacturing. *Joule*, *6*(11), 2474–2499. https://doi.org/10.1016/j.joule.2022.10.006

Zhao, Z., Chong, K., Jiang, J., Wilson, K., Zhang, X., & Wang, F. (2018). Low-carbon roadmap of chemical production: A case study of ethylene in China. *Renewable and Sustainable Energy Reviews*, *97*, 580–591. https://doi.org/10.1016/j.rser.2018.08.008.

6. Appendix

The forecasted ethylene production is validated by two other studies from the literature (Mott MacDonald & FICCI, 2019; SABIC, 2018), as shown in Figure 11. The emission factors for grid electricity, which have been sourced from CSTEP's Sustainable Alternative Futures for India (SAFARI) model (CSTEP, 2021), are given in Figure 12.

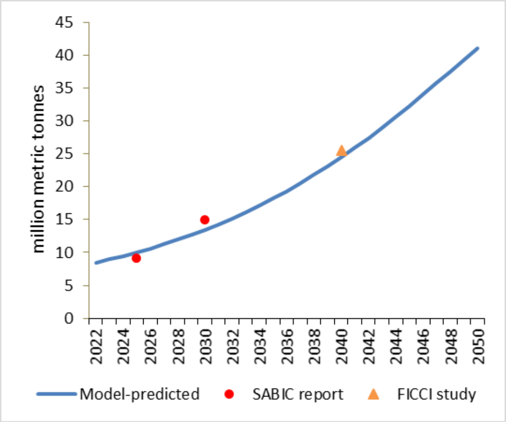

Figure 11 Validation of ethylene production by other studies

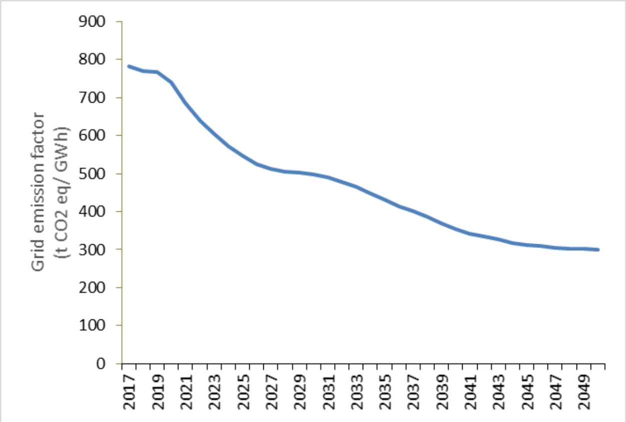

Figure 12 Emission factors for grid electricity

The financial terminologies used in this study are defined below:

Discount rate: Considering the time value of money, discount rate determines the present value of future costs. The future costs of different technologies are calculated and, using the discount rate, the value for the base year is estimated.

Depreciation rate: Due to constant use of machinery and other assets, normal wear and tear occurs. Hence, the value of an asset decreases over its lifetime. In this study, the depreciation rate has been considered as 4% over a period of 25 years.

Fixed operating cost: It is the cost that does not change with an increase or decrease in plant output. It can include costs such as interest on borrowed capital, emoluments of permanent staff, rent associated with land or premises, etc.

Variable cost: It is the cost that changes as the volume of production changes. It usually decreases with increasing production. However, there may be situations when the operating capacity is stretched upwards and out of the optimal operating range, in which case, the variable cost can show an upward movement. Feedstock price (e.g., naphtha price) is considered as a variable cost in this study.

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