

ENERGY AND ENVIRONMENTAL ACCOUNTING IN INDIA AT THE NATIONAL AND
SUB-NATIONAL LEVEL – AN ATTRIBUTIONAL AND CONSEQUENTIAL LIFE
CYCLE ASSESSMENT APPROACH

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CERTIFIED that the work incorporated in this thesis entitled "*Energy and Environmental Accounting in India at the National and Sub-national level – An Attributional and Consequential Life Cycle Assessment Approach*" submitted by Mr. Vishnu S. Prabhu was carried out by candidate under my supervision. It is an original contribution and has not been submitted elsewhere for the award of any other degree. Such material as has been obtained from other source has been duly acknowledged in this thesis. I recommend that the thesis should be considered for the award of the degree of 'Doctor of Philosophy'.

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DECLARATION

I Vishnu Sivadasa Prabhu hereby declare that this thesis on the topic entitled, "*Energy and Environmental Accounting in India at the National and Sub-national level – An Attributional and Consequential Life Cycle Assessment Approach*" is submitted for the award of Degree of Doctor of Philosophy in Economics to the Gokhale Institute of Politics and Economics, Pune 411004.

It is an original contribution and has been completed during my tenure as a research scholar at Gokhale Institute of Politics and Economics, Pune.

This thesis has not been submitted by me elsewhere for the award of any degree or diploma-part or full. The information gathered by me elsewhere for the thesis is original, true and factual. Such material as has been obtain from other source has been duly acknowledged in the thesis. I hereby request, to consider the thesis for the award of the degree of 'Doctor of Philosophy'.

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ABSTRACT

India's higher emphasis on the adoption of Green Energy for power generation in recent years is aligned with the twin Sustainable Development Goals (SDG) 2030 of tackling climate change (Goal 13) and ensuring sustainable, affordable and reliable energy for all (Goal 7). The government reiterated its commitment towards clean energy transition by announcing the ambitious targets of i) Increasing renewables capacity to 500 GW and ii) Meeting 50% of energy requirements from renewables by 2030. This study intends to evaluate the lifetime energy and environmental burden of Solar PV and Wind capacity addition using the Attributional Life Cycle Assessment (LCA) approach. Consequently, the macroeconomic impact of India's ambitious 280 GW solar and 140 GW wind capacity expansion programme by 2030 using the Consequential Input-Output LCA (IO-LCA) framework. The economic, environmental and human health cost implications of solid waste generation and waste abatement in the End-of-life phase and the GHG and non-GHG emission savings by substituting coal power generation in different scenarios has been analysed by estimating the Green-GDP using SEEA framework. The results reveal that the solid waste generation in the EoL phase is estimated to be between 1,970 to 23,778 tonnes from Solar PV modules and 5.4 to 36 million tonnes from wind turbines. The transition towards solar and wind energy by substituting coal power leads to a minimal net output loss of 0.05% to 0.3% in different scenarios, while net GDP and employment loss is also less than 0.25%. Given that the economy-wide contribution of solar and wind energy sectors is negligible due to solar and wind energy sectors being at a nascent stage in their development, further promotion of indigenous manufacturing capacity should lead to higher positive multiplier effect in the economy. The Green-GDP estimate by accounting for the net-environmental and human health burden of solar and wind energy mix and the material waste generation is estimated to be 0.09% to 0.8% increase in net loss to GDP in different scenarios. A sub-national level energy transition index was also constructed using economic, energy and environmental indicators to evaluate the state-wise contribution towards the national level green targets. It is observed that the western and southern economically developed states of Rajasthan, Maharashtra, Gujarat, Tamil Nadu, Karnataka, and Andhra Pradesh out-perform the All-India performance score, whereas the eastern, lesser developed coal-bearing states such as Chhattisgarh, Jharkhand, Odisha, Bihar, Uttar Pradesh as well as Haryana and Punjab, score lower than the All-India average. With the categorization of states, tailor-made policies and capacity building initiatives are to be proposed such that an equitable and just transition is encouraged. This study can act as a template for other developing/emerging economies which are undergoing a similar energy transition phase

when it comes to decarbonization strategies. It is hoped that this study also encourages more economic studies which consider the environmental dimension more frequently in academic as well as policymaking context.

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LIST OF ABBREVIATIONS

ADB	Asian Development Bank
ALCA	Attributional Life Cycle Assessment
BAU	Business As Usual
BCM	Billion Cubic Meters
BEE	Bureau of Energy Efficiency
BU	Billion Units
CAGR	Compound Annual Growth Rate

CE	Circular Economy
CEA	Central Electricity Authority
CED	Cumulative Energy Demand
CLCA	Consequential Life Cycle Assessment
COP	Conference of Parties
CUF	Capacity Utilization Factor
DISCOM	Distribution Companies
EAF	Electric Arc Furnace
EoL	End-of-Life
EPBT	Energy Payback Time
EPR	Extended Producer Responsibility
EROI	Energy Return on Investment
FRELP	Full Recovery End-of-Life Photovoltaic
FTT	Future Technology Transition
GBI	Generation Based Incentive
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GOI	Government of India
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IREDA	Indian Renewable Energy Development Agency
ISO	International Organization of Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCOE	Levelized Cost of Electricity
LUC	Land Use Changes
MMT	Million Metric Tonnes
mono-Si	Monocrystalline Silicon
MU	Million Units
NDC	Nationally Determined Contributions
NEP	National Electricity Plan

	Organization for Economic Cooperation and
OECD	Development
PEUM	Partial End Use Method
PLF	Plant Load Factor
poly-Si	Polycrystalline Silicon
PPP	Purchasing Power Parity
PV	Photovoltaics
REC	Renewable Energy Certification
RES	Renewable Energy Sources
RPO	Renewable Purchase Obligation
SDG	Sustainable Development Goals
SEEA	System of Environmental and Economic Accounting
SUT	Supply Use Tables
T&D	Transmission & Distribution
TPP	Thermal Power Plants
WEEE	Waste Electrical and Electronic Equipment

CHAPTER 1 INTRODUCTION

1.1 Economy and Environment Synergy

The debate between economic growth and environmental sustainability has been ongoing over the past several decades with increasing interest from academicians and practitioners. The origin of this debate can be traced back to the development of national accounts in the 1940s and 1950s which did not take into consideration the ‘environment’ as a central aspect. The estimation of the ‘Gross Domestic Product’ or GDP which is the infamous representative of a country’s economic growth was oblivious to the adverse environmental ramifications of industrialization and can be traced back to 1947, where the System of National Accounts (SNA) originated (Stone, 1947). While both the classical and neo-classical economists acknowledged the importance of environmental sustainability and economic growth to co-exist, the latter took centre stage post-World War II for three decades, between 1950 to 1980s (Thampapillai, 2002).

It was only in 1972, that the UN Conference on Human Environment, Stockholm represented the first internationally acclaimed gathering, acknowledging the adverse global economic and human impact on the environment (Kennet, 1972; Handl, 2012). Nevertheless, the global concerns raised at the conference failed to stimulate international actions towards addressing the environmental ramifications (Keeble, 1987). It was only in 1984, a global consensus for developing environmentally extended national accounts was reached and 900 days later it was comprehensively articulated in the Brundtland Commission report, published in 1987 (UN, 1987). The report highlighted that the new environmental problems faced by the world is a result of poverty in the South with unsustainable production and consumption in the North. The report further states:

‘It is impossible to separate economic development issues from environmental issues; many forms of development erode the environmental resources upon which they must be based and environmental degradation can undermine economic development. Poverty is a major cause and effect of global environmental problems without a broader perspective that encompasses the factors underlying world poverty and international inequality.’

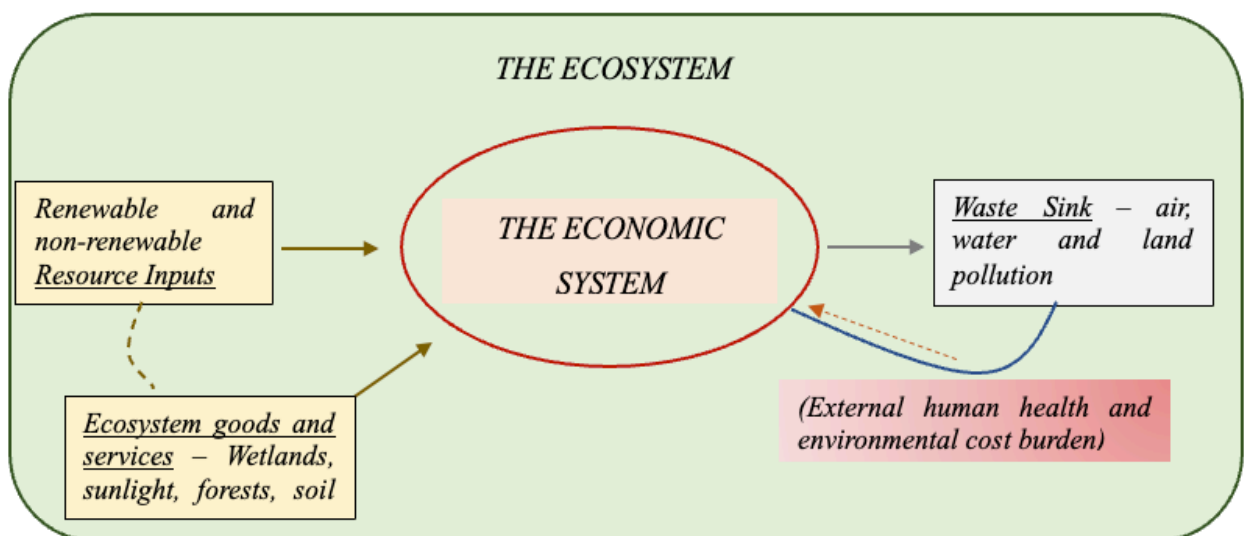
By questioning the macroeconomic framework for policymaking, the report addressed the issues at the intersection of resources, environment, economy and military expenditures. Here, for the first time, the term Sustainable Development was formally defined (UN, 1987) –

‘Development that meets the needs of the present without compromising the ability of future generations to meet their own needs.’

Today, it is a well-established and academically proven hypothesis that economic sustainability is impossible without environmental sustainability in the medium to long run (Thampapillai, 2002). The external (human health and environmental) costs of economic growth borne by the world by disregarding the environmental ramifications resulting from globalization will become irreversible if necessary actions are not taken at the earliest (Randall, 1987).

The economic system sources its inputs from the environment such as food, water, and energy which can be renewable (wind, solar or tidal power etc.) or non-renewable (coal, natural gas, lignite etc.) and ecosystem goods and services such as fisheries and forests (Hanley, Shogren, & White, 2013). The consequent result of the consumption of these resource inputs leads to the environment being treated as a ‘waste sink’ in a linear economic framework. This can be in the form of air, water and land pollution, resulting from agricultural/commercial/household or industrial activities in a macroeconomic system. The linear economy which is also referred to as the ‘take-make-waste’ model, led to significant economic benefits with the Industrial Revolution being the prime example of this concept (Ellen McArthur Foundation, 2021). The extraction of finite resources with the depletion of natural capital seemed the only way to generate economic value. It is only recently that the negative effects such as the environmental damage and loss of valuable irreplaceable natural capital have been recognized. This is represented in Figure 1.1.

Figure 1.1: Economy-Environment linkages in a linear economy framework



Source: Created by authors

The resulting external costs from environmental degradation and the steady erosion of ecosystem goods and services are not accounted for in the traditional GDP estimation as has been discussed earlier. By negating this necessity, it is bound to be a ‘negative-sum game’, with the economic system suffering losses resulting from environmental unsustainability. The unsustainable engagement with nature is endangering the livelihoods and prosperity of the current as well as future generations (Dasgupta, 2021). The anthropogenic resource use by the economic system should be brought within the biophysical limits; however, this is a complex task since it entails measuring these limits, knowing when it is breached and allocating responsibility (Smith, 1996). To this end, the ecosystem should be embedded within the economic theories, not external to it. This requires legal and institutional interventions such that the biodiversity and sustainability constraint is addressed.

In the era of globalization and inter-connectedness between the developed and developing nations in terms of dissemination of ideas, international trade in goods and services, human capital and technology transfers, the less developed nations are steadily catching up to the per-capita income levels of the wealthy western countries (barring the outlier events such as the COVID-19 pandemic or the Russia-Ukraine war which can halt or regress the economic growth trajectory in the short to medium run). However, both the developed and developing nations largely follow the ‘linear economy model’, owing to the focus on the traditional GDP estimation methodology as the sole parameter of a country’s economic progress. Historically, it is the developed Western countries where the spirit of consumerism leads to higher sourcing of material and energy inputs from the global economy, resulting in a high degree of economic activity (Sariatli, 2017). The resulting economies of scale effect led to extensive use of materials, combined with cheap labour. These were executed primarily through the evolving regulatory, accounting and fiscal rules led by the national governments along with international organizations. Nevertheless, with the breakthrough Paris Climate Accord in 2015 (UNFCCC, 2015), the announcement of the 17 Sustainable Development Goals (SDGs) in 2016 (UN, 2016) and the recently held Conference of Parties (COP) 26 and COP 27 in 2021 and 2022 (UNFCCC, 2023), the association of carbon neutrality with a circular economy framework started received due attention.

1.2 Circular Economy and Carbon Neutrality Complementarity

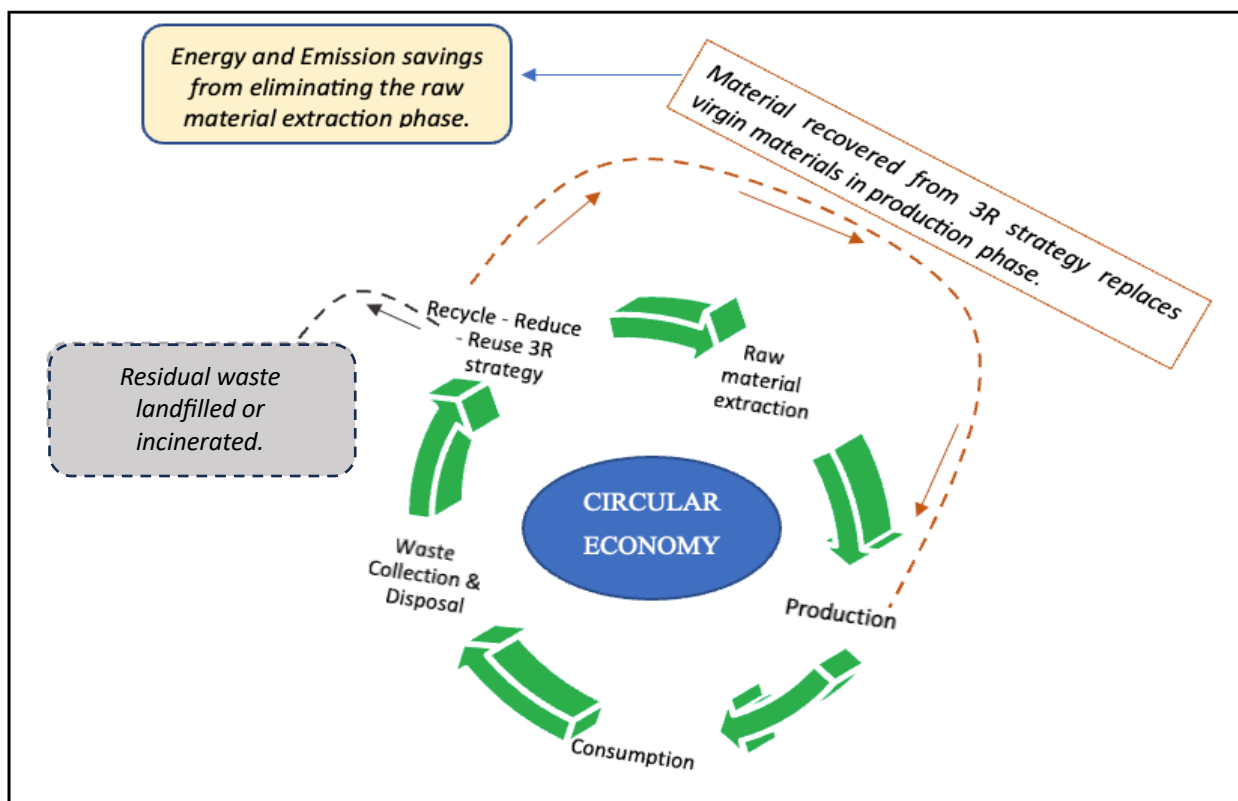
The Circular Economy (CE) concept gained significant traction amongst academicians and practitioners with more than 100 peer-reviewed articles published in 2016, compared to 30 in

2014 (Geissdoerfer, Savaget, Bocken, & Hultink, 2017). This has also led to an array of CE definitions in the public domain, leading to further confusion through its association with other relatable concepts such as ‘sustainable development’, ‘green economy’ or ‘green growth’ (Kirchherr, Reike, & Hekkert, 2017). The authors analyse 114 CE definitions, coded across 17 dimensions, and found that most academicians and practitioners associate CE with the 3R strategy of Recycle-Reuse-Reduce (Few key definitions are presented in Table A1 in the appendix. The authors outline the following definition of CE:

“A circular economy describes an economic system that is based on business models which replace the ‘end-of-life’ concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, national and beyond) with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations”.

The Circular Economy concept is presented in Figure 1.2.

Figure 1.2: Circular Economy Framework



Source: Created by Author

The circular flow presented in Figure 1.2, represents the conceptual understanding of CE and applies to any product or process in question. CE is not only a response to the material and energy unsustainability, derived from the traditional linear extract-produce-use-dump material and energy flow models (Frosch & Gallopoulos, 1989; Bocken, et al., 2017), but also provides an opportunity for economic gains. By transitioning from a linear to cyclical material and energy flow models, the global economy can benefit to the tune of USD 1000 billion annually (Arponen, et al., 2014). This is from the point of view of not only minimizing waste being dumped in the environment but also minimizing the usage of exhaustible, non-renewable resources for production activities (Sariatli, 2017).

To this end, the CE approach is very much likened to the Life Cycle Assessment approach (LCA) – a technique developed to assess the direct and/or indirect impact of the development of a product (or process) and its potential impact throughout the product’s lifetime (ISO, 2006). A combination of CE and LCA prescribes not only the minimization of waste in the ‘End-of-Life’ (EoL) phase but also its reuse in the production phase (as presented in Figure 1.2) (Hartley, van Santen, & Kirchherr, 2020). A combination of CE-LCA would entail policy prescription at the intersection of i) production and product design, ii) product use and consumption, iii) product end-of-life and waste and iv) resource circulation (Milios, 2018). Thus, the mapping of material and energy input across different phases of a product’s lifecycle can be traced and assessed such that a holistic approach towards the transition from a linear to a circular economy can be adopted (Hartley, Schulzchen, Bakker, & Kirchherr, 2023). A closed-loop supply chain for product manufacturing is essential for waste prevention environment protection and resource conservation (Rashid, Asif, Krajnik, & Nicolescu, 2013).

The advent of CE is closely interlinked and acts as a catalyst towards the attainment of Sustainable Development Goals (SDGs). During the joint meeting of the Economic and Financial Committee of the 73rd UN General Assembly and the UN Economic and Social Council, the role of CE in achieving multiple SDGs – SDG 6, 8, 11, 12, 13, 14 and 15 was repeatedly emphasized¹ (UN, 2018). CE’s contribution to limiting global warming to 1.5°C has been widely acknowledged (Sutherland, 2022). With the industry decoupling itself from the unsustainable raw material extraction and consumption that leads to higher climate risks, higher resilience towards the physical effects of climate change can be built (Ellen McArthur Foundation, 2021). Its contribution can be witnessed through the improvement in air quality,

¹ SDG 6: Clean Water and Sanitation; SDG 8: Decent Work and Economic Growth; SDG 11: Sustainable Cities and Communities; SDG 12: Responsible Consumption and Production; SDG 13: Climate Action; SDG 14: Life below Water; SDG 15: Life on Land.

reduction in water contamination and protection of biodiversity, while reducing material costs and efficient asset utilization.

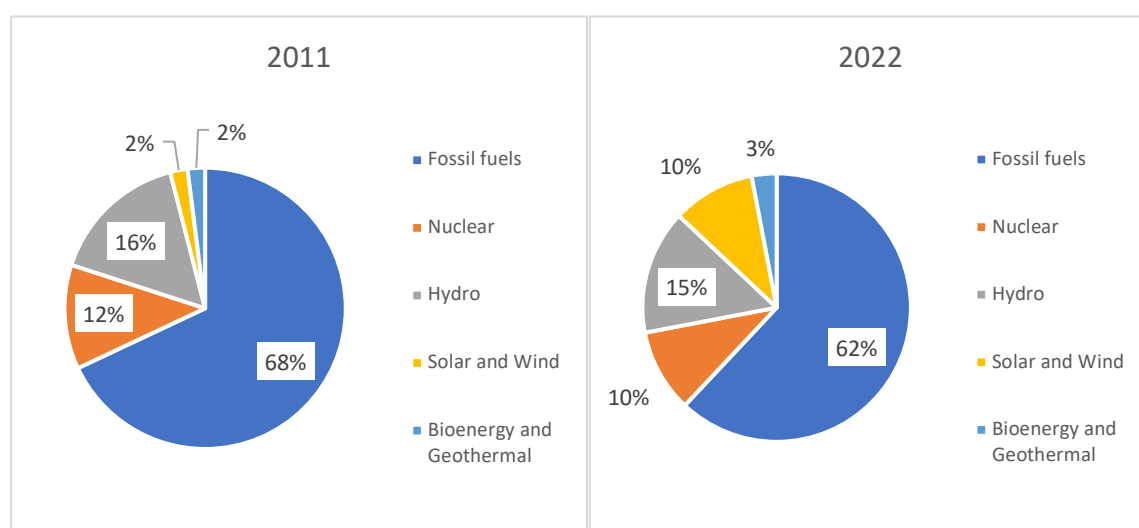
Historically, economic growth has always been positively correlated with energy use and increasing GHG emissions. The adoption of Renewable Energy (RE) can help in decoupling this correlation, thus contributing towards Sustainable Development ambitions (Sathaye, et al., 2011). RE technologies are expected to play a pivotal role, not only in terms of providing cleaner, sustainable and modern energy services to all (SDG 7) but also in addressing environmental concerns in terms of climate change-related events (SDG 13).

1.3 The Power sector and Carbon Neutrality conundrum

1.3.1 Global Perspective

With rapid population growth along with increasing economic activity with a higher degree of inter-connectedness between countries, electricity demand has played a pivotal role as a basic need for the economic system’s functioning. For several decades, fossil-fuel energy sources were key contributors and in many countries, the sole energy provider for economic purposes. Even today it constitutes the largest share globally in terms of electricity generation, however, a steady increase in RE sources in the global electricity portfolio has been observed.

Figure 1.3: Source-wise Global electricity generation in 2011 and 2022 (As a percentage of total)

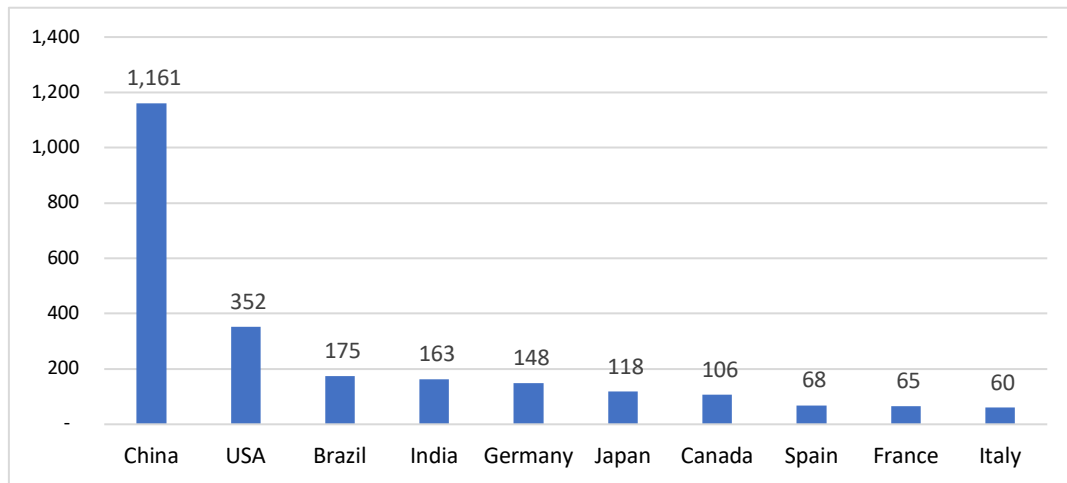


Source: (REN21, 2023)

Figure 1.3 shows that the reliance on fossil fuels for electricity generation reduced by six percentage points between 2011-22 while the share of solar and wind energy increased by eight percentage points. It is during this period that key international agreements such as the Paris Climate Accord in 2015 (UNFCCC, 2015), and the United Nation’s SDGs in 2016 (UN, 2016) were announced which have contributed to their push for higher adoption of RE technologies

in the electricity mix. The top ten countries in terms of RE capacity installations as of 2022 are presented in Figure 1.4.

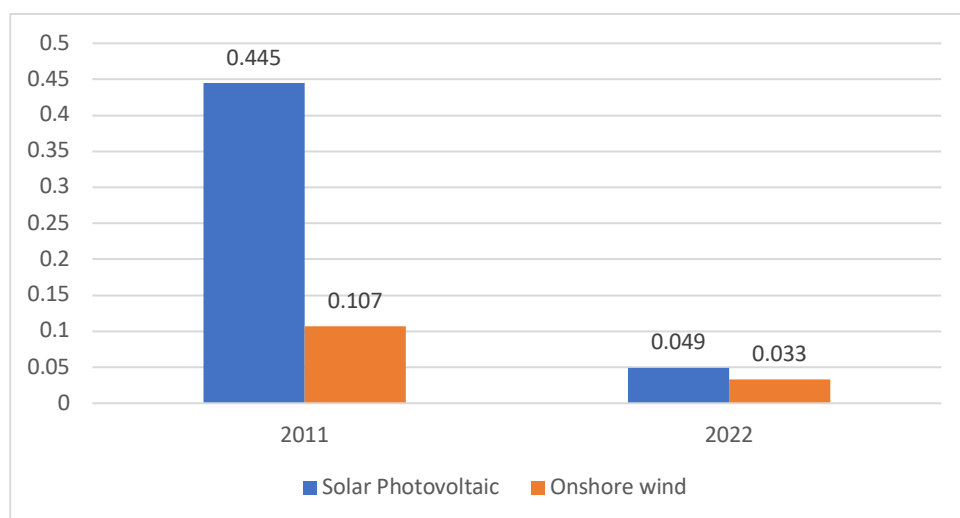
Figure 1.4: Top ten countries by installed RE capacity 2022 (in GW)



Source: (Statista, 2023a)

In 2022 alone, 295 GW RE capacity was installed globally, with the cumulative RE global capacity reaching 3,372 GW or 9.6% of global installed capacity (Enkhardt & Santos, 2023). China constitutes 34% share followed by the USA (10.4%), Brazil (5.2%) and India (4.8%). Of the total incremental capacity addition in 2022, almost 91% was composed of solar (191 GW) and wind energy (77 GW) (Enkhardt & Santos, 2023; GWEC, 2023). With the increasing share of solar and wind energy, the cost of power generation has also gone down significantly over the past decade.

Figure 1.5: Global Levelized Cost of Electricity (LCOE) from newly commissioned Renewable power technologies, 2011 and 2022 (USD/kWh)

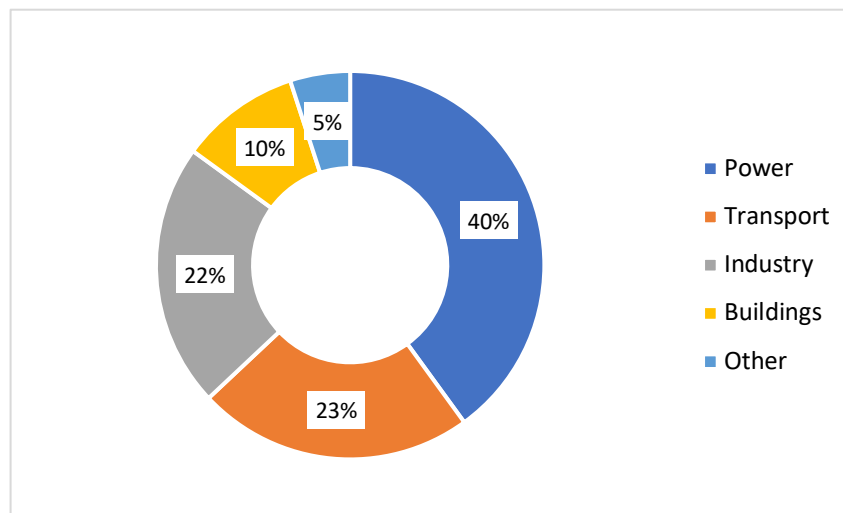


Source: Adapted from (IRENA, 2023)

Figure 1.5 shows the drop in the LCOE of solar and wind energy within the last decade. The Solar PV LCOE witnessed an 88% drop while for wind energy it was 69%. For Solar PV one of the key factors contributing towards a higher drop in its LCOE over the past decade is the drop in the costs of PV module manufacturing accounting for 45% of the total LCOE decrease (IRENA, 2023). This is a result of a rapid increase in the rate of capacity installation leading to economies of scale.

One of the factors contributing towards the higher emphasis on the rapid adoption of clean energy technologies as a substitute for fossil-fuel energy sources is due to its share in global GHG emissions. The targeting and prioritizing of the decarbonization of the power sector can lead to significant ripple effects in terms of emission reduction, as it is currently the largest source of emissions in the world (Figure 1.6).

Figure 1.6: Global GHG Emissions by sector 2022 (as percentage of total)



Source: (IEA, 2022)

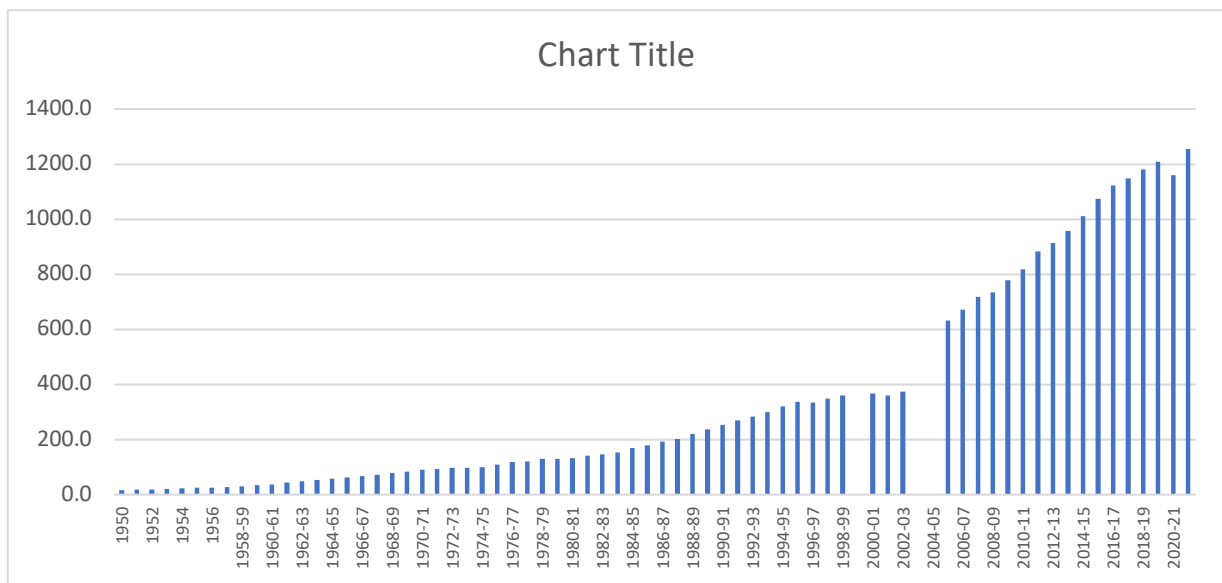
It is observed that the power sector constituted the largest share of total global emissions. (40%), followed by the transport sector (23%) and industry (22%). In 2022, the biggest sectoral increase in emissions were witnessed from electricity and heat generation (1.8%), while there was a decline in emissions from industry (1.7%) (IEA, 2023). This portrays the world's heavy reliance on coal power for ensuring energy security, especially amidst the ongoing Ukraine-Russia war and the consequent energy crisis in European and Asian markets. The region-wise analysis shows that Asia's emerging markets and developing economies (excluding China) were attributed with the highest increase in emissions in 2022, of 4.2%, compared to 0.2% for China, 0.8% for the US and 2.5% for the European Union (EU27) (IEA, 2023). Furthermore, in Asia, India has been one of the countries which has been showcasing an upward slope in terms of solar and wind capacity additions.

1.3.2 The Indian Scenario

1.3.2.1 India's rising energy demand

India is one of the fastest growing developing nations while only recently overtaking China to become the most populous nation in the world (Roy & Mascarenhas, 2023). Thus, among several other economic and social issues facing the nation, ensuring energy security for its citizens is pivotal. The growth in per capita electricity consumption in India since independence is provided in Figure 1.7.

Figure 1.7: Per Capita Electricity Consumption in India 1950 - 2022 (in kWh)

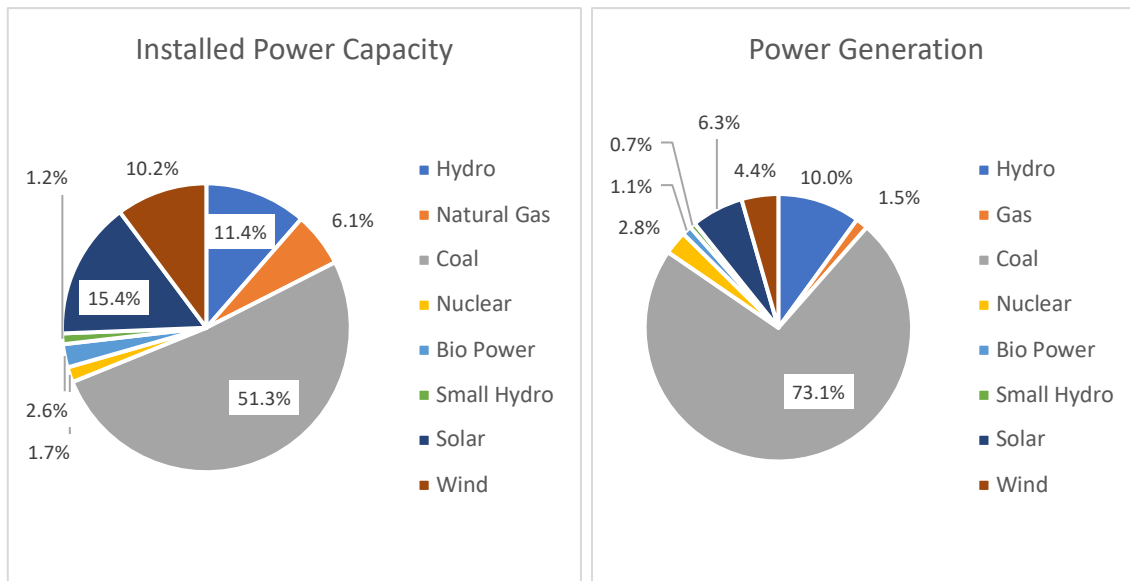


Source: (Indiastat, 2022)

Note: Data for the years 1999-2000, 2003-04 & 2004-05 not available

Figure 1.7 reveals that in the last ten years, the per capita electricity consumption increased at a CAGR of 3.5% which was the highest decadal growth witnessed thus far in India. Furthermore, according to the 20th Electric Power Survey of India, India's energy requirement is expected to increase from 1,566,023 Million Units (MU) in 2021-22 to 2,530,531 MU in 2029-30 at a CAGR of 4.9% (CEA, 2022a). India's current electricity portfolio reveals that it would have to rely heavily on coal power to meet the ever increasing industrial/commercial/agricultural/residential energy demand (Figure 1.8).

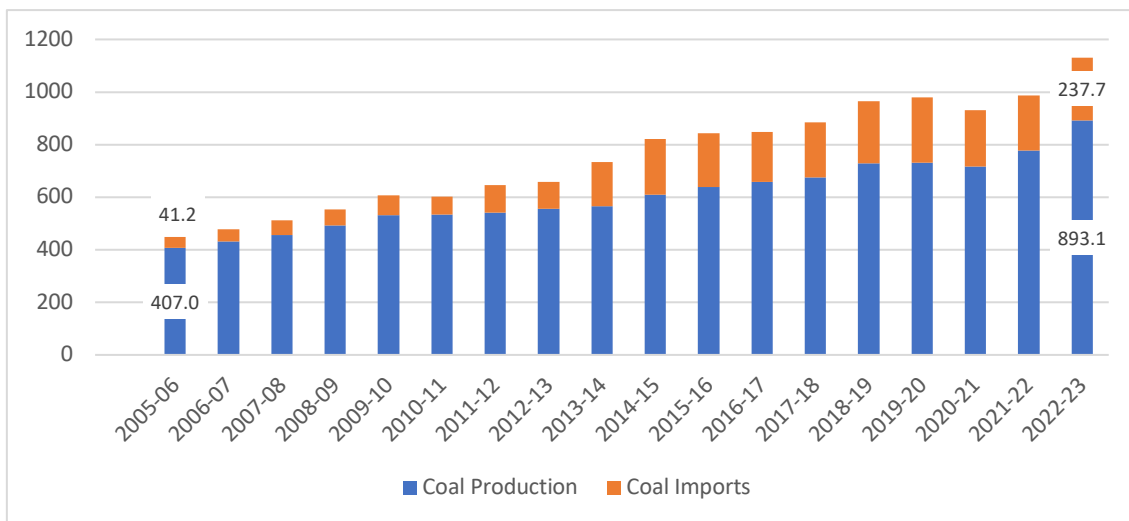
Figure 1.8: Source-wise share of installed power capacity and power generation as of December 2022 in India (as percentage of total)



Source: (CEA, 2022c)

It is observed that coal constitutes 50% of the installed power capacity portfolio of India whereas renewables such as solar and wind energy compose 26% share. While in terms of power generation to meet the domestic power demand across different categories (Agriculture, residential, industrial etc.), coal constitutes approximately 3/4th share of the total power generated in the country. This implies that the per unit power generated from the existing installed capacity is higher from coal-fired Thermal Power Plants (TPPs), while solar and wind energy constitute only 11% of total electricity generation mix. Coal mining in India dates back to the 18th century in 1774 in the Raniganj Coalfield along the Western Bank of river Damodar in West Bengal state (GOI, 2021). Given the demand and technological availability during that period, coal production, despite constituting high reserves, was very sluggish. With the introduction of steam locomotives in 1853 and then during the First World War, the annual production increased from 6.12 Million Metric Tonnes (MMT) in 1900 to 30 MMT in 1946. Post-independence, under the aegis of the Planning Commission, India started preparing the Five Year development plans in which the significance of coal was steadily increasing not only from the point of view of energy security but economic growth as well. Today, India is the second largest coal producer in the country and in 2022-23, 893 MMT coal production was achieved, which is the highest recorded annual production (GOI, 2023). Despite the high rate of coal production, India is still not able to meet the domestic demand for coal across different sectors, with the rate of coal imports also increasing steadily. This has been presented in Figure 1.9.

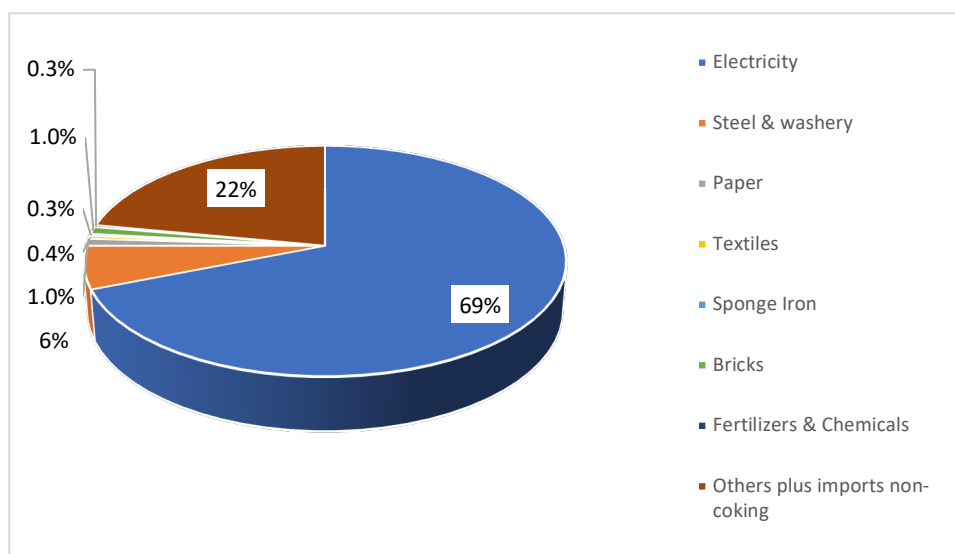
Figure 1.9: Annual domestic coal production and coal imports by India (2005-23) (in Million Metric tonnes)



Source: (GOI, 2023)

Figure 1.9 demonstrates that the annual coal production has doubled from 407 MMT in 2005-06 to 893.1 MMT in 2022-23. Coal imports have also increased five times, from 41.2 MMT in 2005-06 to 237.7 MMT in 2022-23. In the current fiscal year 2023-24, India aims to further increase its annual domestic coal production to 1 billion MT in order to reduce its reliance on imported coal (GOI, 2023). Of the total coal being supplied in the country, the thermal power plants are the primary consumers. As per the latest data available, Figure 1.10 represents the sector-wise share of coal consumption in India.

Figure 1.10: Sector-wise share of coal consumption in India (2021-22)

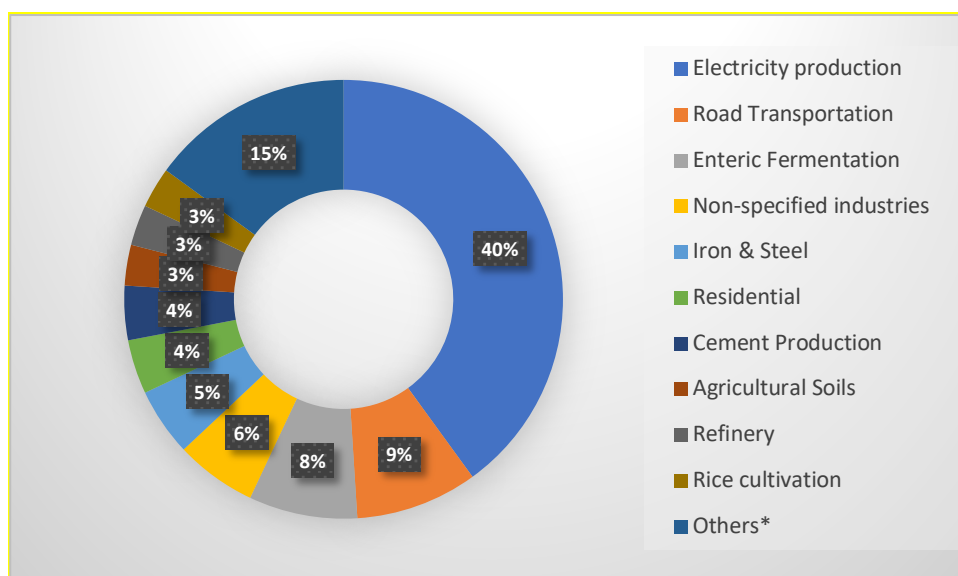


Source: (GOI, 2023)

Of the total coal supply, almost 3/4th share of coal is being consumed by the electricity sector, which is basically the coal-fired thermal power plants (Figure 1.10). Furthermore, coal is also

responsible for 51% of SO₂, 43% of CO₂, 20% of Nitrous Oxides (NO_x) and 7% of PM_{2.5} emissions in the country (Pachouri & Saxena, 2020). The GHG emission factors in coal-TPPs differ based on coal composition and power plant characteristics (Garg, Kapshe, Shukla, & Ghosh, 2002; Chakraborty, et al., 2008; Mittal, Sharma, & Singh, 2014). However, the national average for coal-TPPs is estimated to be 957 gCO₂e/kWh, in comparison to 38 gCO₂e/kWh for solar photovoltaics (PV) and 9 gCO₂e/kWh for wind energy. The sector-wise GHG emissions show that the electricity sector constitutes the highest share of GHG emissions in the country (Figure 1.11).

Figure 1.11: Sector-wise GHG emissions in India (2021) (as percentage of total)



Source: (UNFCCC, 2021)

Note: *Commercials/Institutional, Cement, Aluminium Production, Lime Production, Manure Management

According to India's latest Third Biennial Report to the United Nations Framework Convention on Climate Change, electricity production constitutes the highest share (40%) of the total GHG emissions released in the country (UNFCCC, 2021). Thus, addressing the decarbonization pathways for India's power sector will lead to significant direct and indirect benefits to the economy, in terms of curbing its GHG emissions.

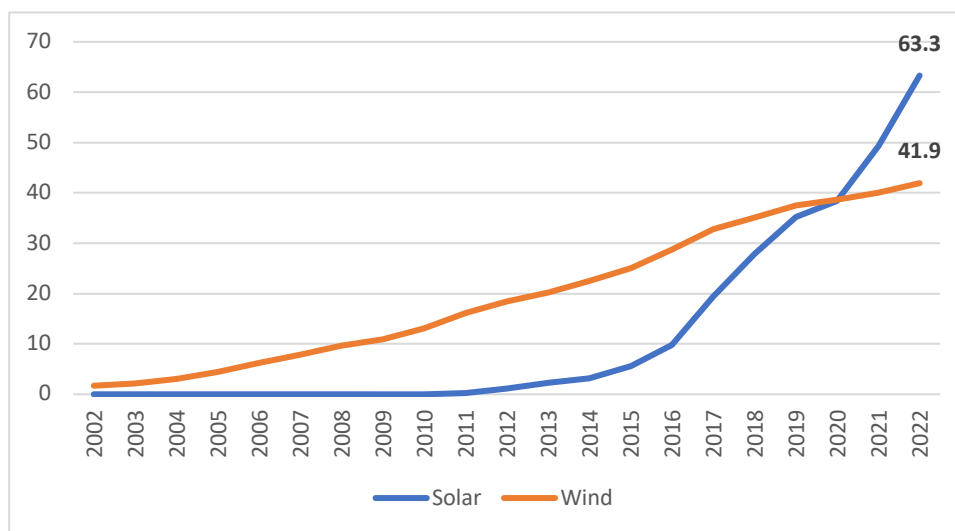
1.3.2.2 India's Clean Energy Transition Trajectory

Over the last decade, the Government of India has remained steadfast in pursuit of its goal of transitioning towards a cleaner energy portfolio to meet the domestic energy requirements. This ambition is well-aligned with its commitment to the twin Sustainable Development Goals (SDG) 2030 of ensuring sustainable, affordable and reliable energy for all (Goal 7) and tackling climate change (Goal 13). Simultaneously, the government has given due recognition towards ensuring energy security while dealing with rapid population growth. To this end, the

government during the recent COP26 event in Glasgow committed to achieving – i) non-fossil fuel capacity of 450 GW and ii) 50% of its energy requirements from renewable energy by 2030, with the ultimate long-term goal of iii) net-zero emissions by 2070 (PIB, 2021). Of the 450 GW 2030 RE target, solar and wind energy constitute the highest share of 280 GW and 140 GW, respectively (Pandey, Vidyarthi, Ram, & Sarwal, 2022). This is attributed to India’s endowment of 5,000 trillion kWh of solar energy incident over its landmass and 302 GW of wind energy potential (NITI Aayog, 2015; MNRE, 2021).

In order to achieve the potential GHG emission savings from the power sector, India still has a long way to go. The historic trend of wind and solar capacity installation in India is shown in Figure 1.12.

Figure 1.12: Cumulative Solar and Wind Capacity Installation in India (in GW)



Source: CEA Reports (various issues)

Wind capacity witnessed steady growth in installations since the beginning of the 21st century which is attributed to the financial and regulatory support received by the indigenous wind turbine manufacturing industry since the 1980s (Sharma & Sinha, 2019). The chronology of the key events supporting the wind industry is provided in Figure 1.13.

Figure 1.13: Key milestones in India's wind energy industry



Source: Adapted from Sharma & Sinha (2019)

As a result of these developments in the Indian wind industry, today India produces 70-80% of turbines indigenously (Baruah, 2023). In a similar way, the developments in the solar energy industry have been highlighted in Figure 1.14.

Figure 1.14: Key milestones in India's Solar PV industry

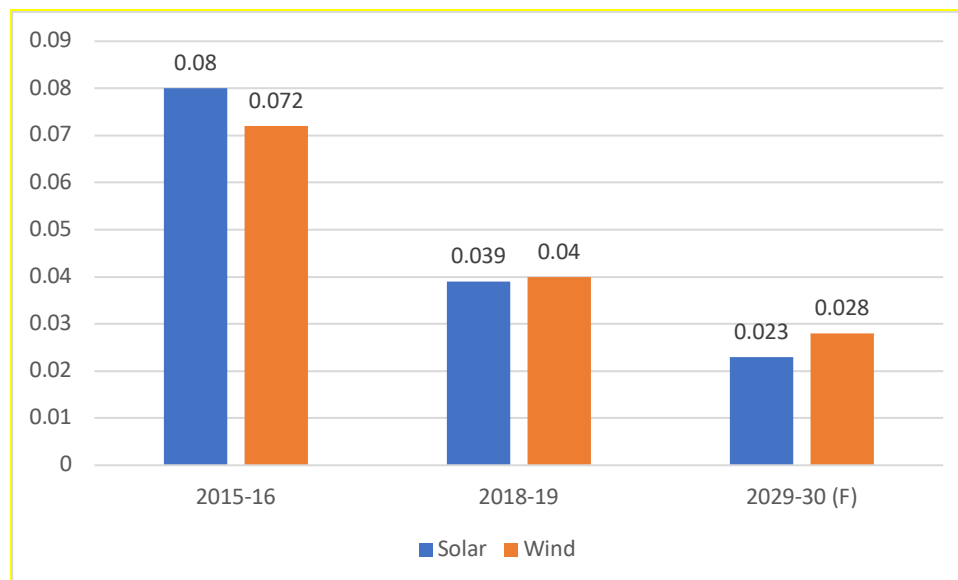
3rd Five Year Plan (1961-66)	<ul style="list-style-type: none"> The discussion on solar energy as an alternative source for power generation was discussed since it was gaining traction across the world.
6th Five Year Plan (1980-85)	<ul style="list-style-type: none"> After 20 years since the solar energy was discussed by the government, the Department of Non-Conventional Energy Sources was formed with special emphasis on solar energy.
Commission for additional sources of energy (1981)	<ul style="list-style-type: none"> A program called National Solar PV Energy Demonstration Program (NASPAD) was implemented which supported first time R&D in Multi-crystalline Silicon Solar Cells manufacturing.
7th Five Year Plan (1985-90)	<ul style="list-style-type: none"> BHEL was given the responsibility to execute a plant to manufacturing 500 kW of Amorphous Silicon Solar Cell (ASSC)
8th Five Year Plan (1992-97)	<ul style="list-style-type: none"> The central budget approved to develop a 1720 Kw of Solar PV capacity along with solar pumps, solar lightings and solar cookers.
9th Five Year Plan (1997-2002)	<ul style="list-style-type: none"> The Government of India encouraged and initiated private sector participation to mobilize additional resources for generation, transmission and distribution.
10th Five Year Plan (2002-07)	<ul style="list-style-type: none"> The Public owned Central Electronics Limited (CEL) set a target to achieve production capacity of 25 MW which during that period was the largest capacity target.
Jawaharlal Nehru National Solar Mission (JNNSM) (2010)	<ul style="list-style-type: none"> The Government of India set a target of achieving 22 GW capacity by 2022. This was for the first national level target that the central government pursued.
Updated Capacity Installation Target (2015)	<ul style="list-style-type: none"> With the arrival of the new central government in 2015, this target revised to 100 GW to be achieved by 2022 of which 60 GW was Ground-mounted PV and 40 GW Rooftop PV.

Source: Adapted from Kapoor, Pandey, Jain, & Nandan, (2014)

For Solar energy, India announced the first ever solar capacity target only in 2010, of 22 GW to be achieved by 2022 which was revised to five times the original target of 100 GW by 2022 (PIB, 2015). Given this government target, solar PV witnessed a steep growth in capacity installation post-2015. As of 2022, solar and wind capacity installation reached 63.3 GW and

41.9 GW. With rapid solar and wind capacity installation since the updated capacity targets were announced in 2015-16, the LCOE of solar and wind have also been decreasing significantly over the past few years (Figure 1.15).

Figure 1.15: LCOE of Solar and Wind (in \$/kWh)



Source: RBI (2021), Niti Aayog, (2021)

As a result of economies of scale over the last few years, the solar and wind tariffs have witnessed drastic reductions and with the ongoing and planned capacity additions till 2030, the tariffs are expected to drop further. A study by the Asian Development Bank (ADB) on analysing the competitiveness of India's solar and wind tariffs has found that the cost of solar PV modules/wind tariffs account for only 20% of the tariff (in USD/kWh) while financing costs account for the highest share of 50% (Chawla, Aggarwal, & Dutt, 2020). Thus far, the reduction in equipment-related costs has led to higher competitiveness in solar and wind tariffs and with higher private participation and government support through financial incentives, a decline in financial costs is expected to drive the decline in tariffs by 2030.

Along with the solar and wind capacity expansion, the government also aims to expand the capacity of thermal power plants since the country is not ready to completely 'phase-out' coal-fired Thermal Power Plants (TPPs) which was notified during the COP26 and COP27 events in 2021 and 2022, respectively (Sirur, 2022). On the economic front, the coal sector is one of the largest employers in the country. About 40% of India's districts have coal dependency of varying degrees (Aggarwal, 2021). Approximately 44% revenue of the Indian Railways (also one of the largest employers in the country) is generated from coal freight transport (Kamboj & Tongia, 2018). The Indian coal mining sector has also been subject to gradual mechanization

(Jacobs et al., 2019), however, compared to the advanced nations, India is still far off and the coal sector remains highly labour intensive and is a source of livelihood for millions.

To this end, the government has mapped its non-RE capacity growth simultaneously with RE sources including not only solar and wind but also hydro, nuclear and biogas in its electricity mix (CEA, 2020). This is shown in Table 1.1.

Table 1.1: India's electricity portfolio - 2022 and 2030 target (in GW)

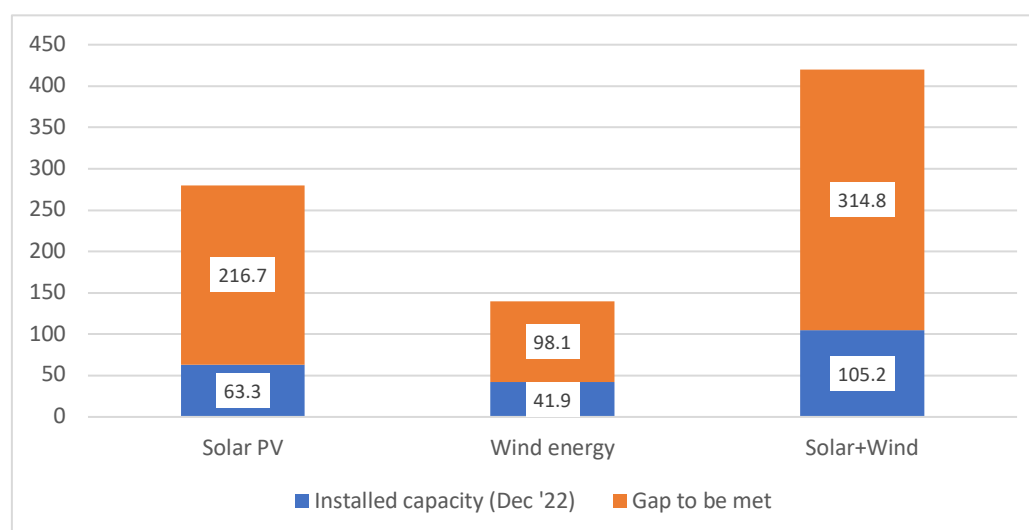
Sr. no.	Energy source	2022	2030 Target
1.	Solar	63.3	280
2.	Wind	41.9	140
3.	Coal	203.7	267
4.	Lignite	6.6	
5.	Gas	24.8	25
6.	Nuclear	6.7	19
7.	Small Hydro (< 25 MW)	4.9	5
8.	Bio-power	10.7	10
9.	Large Hydro (> 25 MW)	46.8	61
10.	Pumped Storage Power (PSP)	0	10
11.	Total	410.3	817

Source: (CEA, 2020; CEA, 2022)

Table 1.1 indicates the government's plan of doubling India's electricity capacity to meet its rising demand across all economic strata. Thus, coal power is expected to hold a robust share in India's electricity mix in the foreseeable future, with concurrent exponential increases in solar and wind energy.

The current status of India's solar and wind capacity achievement is given in Figure 1.16.

Figure 1.16: Solar and Wind capacity installation status in India (in GW)



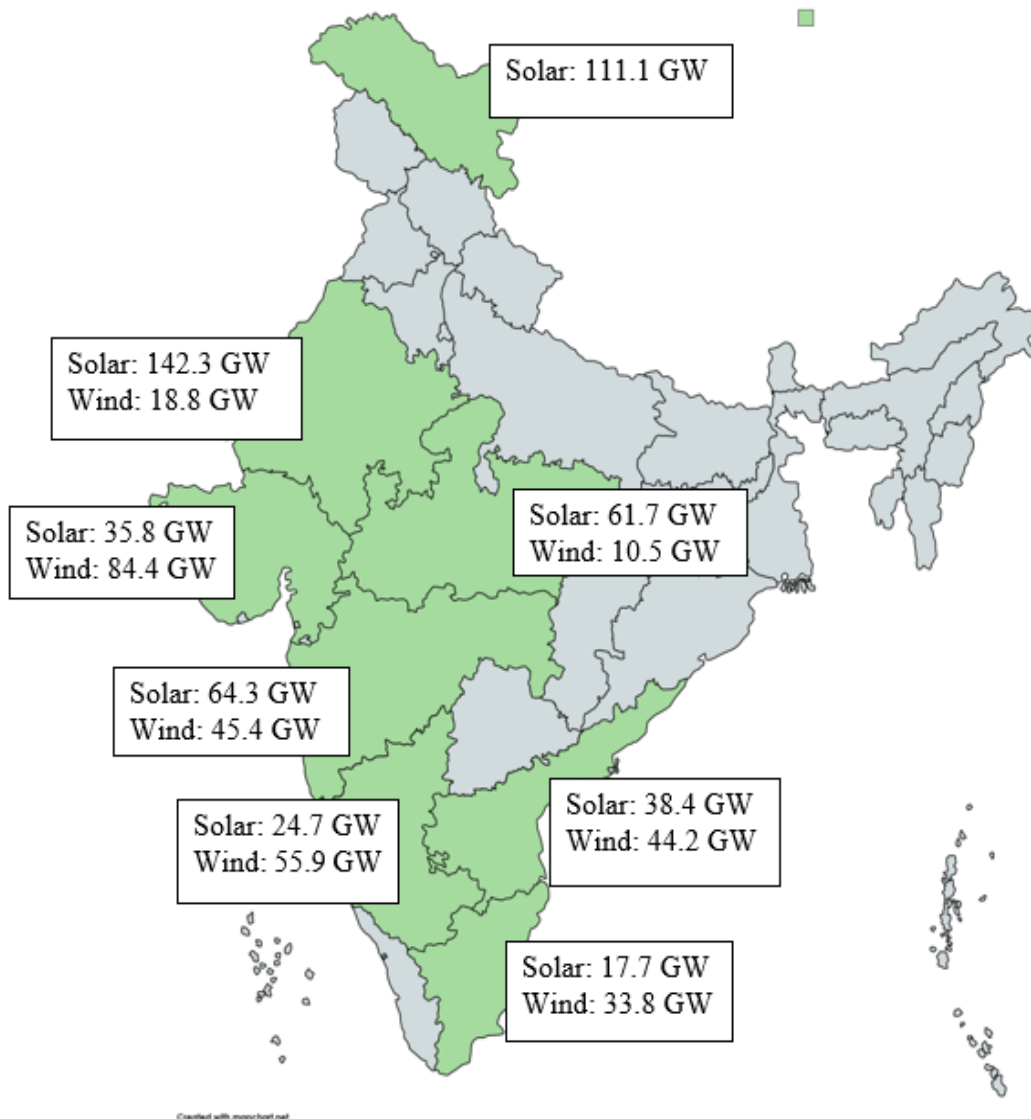
Source: CEA (2022c) and authors' calculations

Figure 1.16 shows that 77% (27.3 GW/year) and 70.1% (12.3 GW/year) of the balance solar and wind capacity respectively, needs to be installed within a span of 8 years to reach the respective 2030 targets. The peak annual capacity installation till date achieved in the calendar year 2021 was only 13.3 GW (11.8 GW solar and 1.5 GW wind) (CEA, 2020 & 2021). Thus, it is highly unlikely that the targets can be achieved by 2030 given the current rate of installation and the government needs to prepare a comprehensive strategy to speed up the process.

❖ **Regional variations**

While the government has announced the ambitious 450 GW national RE target, a roadmap for state-level contribution is missing. Accounting for regional contributions is of significant importance owing to the diversity in the economic, demographic and energy trajectories among states that exist. Figure 1.17 below gives a clear picture of the regional RE potential that exists in India.

Figure 1.17: Region-wise Solar and Wind potential in India



Source: (MNRE, 2021)

Note: States highlighted in green indicate relatively higher RE potential compared to states highlighted in grey.

It can be observed that the high solar and wind energy potential lies on the western and southern belt of the country, whereas the eastern belt is largely comprising of coal-bearing states. Furthermore, the states such as Maharashtra, Gujarat, Karnataka, Andhra Pradesh and Tamil Nadu are relatively more developed states compared to the eastern and central states such as Jharkhand, Chhattisgarh, Bihar or Madhya Pradesh. Thus, it can be deduced that there will be

a disproportional regional contribution towards the national Solar and Wind target due to the variations in the RE potential and economic status of different states.

1.4 Economic and Environmental consequences of Solar and Wind Energy transition

1.4.1 Land and water footprint for solar and wind energy transition

With the increasing expansion of solar PV and wind capacity installations, the demand for resources such as land and water are also expected to increase. Preliminary estimates suggest that in pursuit of net-zero emissions with heavy reliance on solar PV and Wind energy, the land requirement can be as high as 50,000 – 75,000 km² for solar PV modules and 1,500 – 2,000 km² for wind turbines by 2050 (Worringham, 2021). Procurement of forests and farmland for solar PV and wind turbine installations can lead to Land-Use change (LUC) emissions related to increasing global land competition, vegetation loss from forests and scrubland etc. (van de Ven, et al., 2021). The study showed that for every hundred hectares (ha) of solar PV panels, 27 – 30 ha of unmanaged forests need to be cleared. This runs counterintuitive to India's Nationally Determined Contribution (NDC) of creating an additional carbon sink of 2.5 to 3 billion tonnes of CO₂eq. by 2030.

Similarly, the water requirement for the periodic washing of solar PV modules in order to maintain its efficiency is expected to range between 7,000 – 20,000 litres/MW (Segev, 2022). Thus, proper planning for the allocation of limited land and water resources while ensuring equitable clean energy transition is essential.

1.4.2 Economic and Environmental costs of clean energy transition

With rapid growth in solar photovoltaic (PV) modules and wind turbine installations, significant solid waste is expected to be generated at the End-of-Life (EoL) phase of solar PV modules and wind turbines. In the absence of waste recycling, significant environmental and human health consequences can be incurred through the unsafe release of hazardous materials such as tin, lead, copper, arsenic and other ferrous and non-ferrous metals (Vestas, 2006; IRENA and IEA PVPS, 2016). In the case of solar PV, recycling technologies for the relatively more popular crystalline-silicon (c-Si) technology exists, whereas recycling for other technologies is still under experimentation (Chowdhury, et al., 2020; Martin, 2020). On the other hand, wind turbine blade recycling is still at an early stage and as a result, is not exercised on a large scale. Nevertheless, legislative and regulatory assistance can induce faster adoption of wind turbine recycling, for example, landfilling of turbine blades being banned in the European Union (Cherrington, et al., 2012). As of now, The European Union is the only region,

which has mandated PV waste recycling under the Waste Electrical and Electronic Equipment (WEEE) Directive.

On the other hand, India is severely placed in solar modules and wind turbine waste management not only due to a lack of national and state-level guidelines but also due to the lack of awareness or urgency amongst the stakeholders – producers, regulators, consumers (Suresh, Singhvi, & Rustagi, 2019; Prabhu, Shrivastava, & Mukhopadhyay, 2022). While RE sources contribute significantly in terms of environmental pollution reduction in the operational phase, the mismanagement of waste in the end-of-life phase has the potential to offset the positive impact on the environment.

The accounting for both, the positive as well as negative impact of the clean energy transition can be undertaken through the estimation of the Green GDP. The Green GDP is simply a conventional GDP figure adjusted for the environmental costs of economic activities (Chakraborty & Mukhopadhyay, 2014). The concept of Green GDP achieved due recognition in the early 1990s to account for the economic as well as the environmental and health costs (or external costs) from depleting natural resources with simultaneous land, air and/or water pollution. The UN Statistical Division published a System of National Accounts Handbook in 1993 provided a conceptual basis for the construction of the System of Environmental and Economic Accounting (SEEA).

While the landmark contribution of SEEA (1993) was the inclusion of some natural resources within the asset boundary of the system (land, water, air, biota and related ecosystems), several gaps still existed. One of the key developments in the latest SEEA 2012 version (UN, 2014), compared to the SEEA 1993 accounts is the inclusion of not only the physical assets such as land, water, air and related ecosystems, but also the by-products generated from human activities such as pollutants and waste disposal to nature (Bartelmus, 2014). By facilitating the costs incurred through defensive expenditures, that is expenditure incurred by the households and/or the government to reduce the effects of pollution, the SEEA framework also accounts for the costs incurred to protect the environment.

Given this backdrop, the novelty of the study lies in studying the impact of clean energy transition with special emphasis on solar and wind energy using the LCA approach at the intersection of the Economy-Energy-Environment macroeconomic dimensions. The CE-LCA combination is adopted to account for the potential of circularity in the End-of-Life phase through the 3R strategy of Recycle, Reuse, and Reduce. Furthermore, the economy-wide impact of the power sector is further disintegrated by studying exclusively the contribution of solar and wind energy to the Indian economy, separate from other electricity sources. Using

the SEEA framework, the positive as well as unintended negative consequences of solar and wind capacity addition are captured in this study.

To this end, the study intends to pursue the following objectives,

1. The lifetime direct energy and environmental burden of solar and wind energy sources is estimated using the Attributional Life Cycle Assessment (ALCA) approach. The energy requirement and the environmental impact across each phase of solar and wind energy's life cycle, namely Raw material acquisition & production phase, the Construction phase, the Operational phase and End-of-Life (EoL) phase are accounted here. The potential to reduce and manage waste in the EoL phase using the 3R strategy of Recycle, Reduce, Reuse has been studied.
2. To estimate the macroeconomic impact of the 2030 targets of 280 GW solar and 140 GW wind capacity addition while substituting coal-fired thermal power plants (TPPs) in different scenarios. For this purpose, the Input-Output-LCA (IO-LCA) framework has been used. The type and quantity of materials used as an input in the solar PV modules and wind turbine manufacturing that is accounted in the ALCA study is adopted in the Input-Output framework to study the economy-wide impact.
3. To calculate the GHG emission and local pollution savings from reduced coal power generation and the solar and wind energy waste generation in pursuit of the 2030 targets is estimated.
4. The net environmental and human health costs from reduced coal power generation and incremental solar and wind energy waste generation in the EoL phase and the economic costs incurred through the defensive expenditure for recycling technologies are accounted in the SEEA framework for estimating the Environmentally-adjusted domestic Product, or Green GDP.

The objectives of this study are aligned with SDG 7 (Providing sustainable and clean energy for all) and SDG 13 (Taking action against climate change) and the pursuit of the clean energy targets stated in the COP26 and COP27 events.

The structure of the rest of the thesis is as follows. Chapter 2 provides a comprehensive Literature Review on the linkages between economic growth and environmental impact using country-specific studies and the Attributional LCA (A-LCA) and Consequential LCA (C-LCA) studies undertaken across the globe and in India. In addition, the macroeconomic impact of clean energy transition in developed as well as developing/emerging economies has been comprehensively detailed while highlighting the existing research gap in the academic

literature. Chapter 3 details the cradle-to-grave A-LCA approach adopted to study the direct energy and environmental burden of solar and wind energy installation across its lifetime. Secondly the IO-LCA or C-LCA framework using the latest Indian Supply Use Table has been presented in which solar and wind energy sectors are treated separately from other electricity sources and the inclusion of the RE waste abatement sector has been discussed. The accounting of the human health and environmental costs using the SEEA framework has also been detailed. Chapter 4 provides the Data construction and sources for the A-LCA and C-LCA methodological framework that has been discussed in Chapter 3. Furthermore, different scenarios have been constructed to study the long-term economy-wide impact of changes in India's electricity mix by 2030 with incremental solar and wind capacity addition. Chapter 5 and Chapter 6 provide the results of the Attributional LCA study for solar PV and Wind energy, respectively. The energy and environmental impact from the raw material acquisition phase to End-of-Life (EoL) phase has been accounted and the type of waste accumulation in the EoL phase and the potential of recycling and reusing in the production phase has been estimated. Chapter 7 entails the outcome of the Consequential LCA exercise wherein the macroeconomic impact across Output, GDP and Employment and the inter-industry impact across different scenarios through the variations in solar and wind energy mix in conjunction with other electricity sources is presented. The environmental and human health cost from untreated solar PV and wind turbine waste and the cost savings from GHG and non-GHG emission savings through reduced coal power generation is accounted for to study the net impact using the SEEA framework. Chapter 8 focuses on the sub-national level impact of clean energy transition with emphasis on solar and wind energy. A unique sub-national level index is constructed where the categorization of states in terms of their contribution towards the national 2030 targets is prepared. The thesis concludes with Concluding remarks and Policy Recommendations in Chapter 9.

CHAPTER 2 LITERATURE REVIEW

In this chapter, a comprehensive literature review has been presented in three broad sections. In the first section 2.1, the ongoing academic research in the International and Indian context on the inter-connected dynamics between Climate Change, Renewable Energy Source (RES) and Economic growth using a varied set of methodologies has been elaborated in detail.

The second section 2.2 focussed on the assessment of Renewable Energy Sources, specifically the Energy and Environmental burden of Solar and Wind Energy, using a Life Cycle Assessment (LCA) approach. This includes the global literature focussing on LCA studies in different developed and developing/emerging economies in the world, followed by the Indian literature on Solar PV and Wind energy LCA studies. Special emphasis has been given to studies on the End-of-Life recycling phase, exploring the circular economy potential from decommissioned Solar PV modules and Wind turbines. Furthermore, the environmental and health consequences of unrecycled PV and turbine wastes have also been documented.

In the third section 2.3, the contribution of Input-Output Models as an extension of the LCA approach in analysing Solar PV and Wind energy transition has been thoroughly discussed. The economic ramifications across different phases of the Solar PV and Wind energy lifecycles have been presented here.

Lastly, the research gap has been highlighted, followed by the research novelty and the research objectives of the current study.

2.1 Renewable Energy and Economic Impact studies

2.1.1 RE and Economic Impact – Global Literature

Energy is unanimously considered as a key input to economic activity. The studies on the role of energy, especially fossil-fuel energy sources in economic growth of nations gained momentum during the oil boom and the subsequent energy crisis in the 1970s (Sebri, 2015). During this period, the research on causal relationships between fossil fuel energy consumption and economic growth had been extensively investigated. In the following years, the increasing magnitude of globalization and international trade only highlighted the pivotal role of fossil fuels in ensuring and coping with the high level of economic activities in different nations. Since the early 2000s, the awareness regarding the negative consequences of rising energy prices, global warming, the exhaustible nature of conventional energy sources and the necessity for sustainable development saw an upturn. These developments are largely from country-level experiences, where, mainly the economic costs of GHG emissions arising from fossil-fuel based primary energy consumption led to research on initiating structural changes through

alternative production methods or energy use (Irfan, Zhao, ehman, Ozturk, & Li, 2020). In this regard, the switch to RE as a primary energy input in economic activities was given serious consideration, given its low carbon footprint in comparison to fossil fuel sources. The causal relationship between RE and economic growth by displacing fossil fuel sources was given minimal attention until recently. Studies on the causality between RE and economic growth focussed on the following hypotheses: i) Feedback hypothesis: Indicates that there is bidirectional causality between RE and economic growth; ii) Conservation hypothesis: A unidirectional causality from economic growth to RE; iii) Growth hypothesis: A unidirectional causality from RE to economic growth; and iv) Neutrality hypothesis: Absence of causality between economic growth and RE (Sebri, 2015). The studies also vary in terms of the geographical locations, the existing economic growth trajectory of the countries, the range of control variables and the type of techniques and methodologies adopted.

In terms of Renewable Energy Sources (RES) adoption, the type of RE sources under consideration plays a significant role, since each RE technology does not contribute equally in terms of its effect on the energy portfolio or on the rest of the economy. The clean energy transition roadmap is determined on the basis of the avoided GHG emissions by substituting fossil-fuel sources while ensuring the economic growth of the nation is not compromised. Simultaneously, it is essential to evaluate the available RE options and where the country's comparative advantage lies in terms of pursuing the dual trajectory of decarbonization and economic growth. These studies have been comprehensively detailed in this sub-section. Pao & Fu, (2013) study the relationship between RE variables such as non-hydroelectric RE consumption (NHREC), total RE consumption (TREC), non-RE consumption (NREC), total primary energy consumption (TEC) and the real GDP in Brazil. The co-integration tests reveal a long-run equilibrium relationship between the real GDP and the four RE variables. The Vector Error Correction Model (VECM) reveals a unidirectional causality between NHREC and economic growth and a bidirectional causality between TREC and economic growth in the long run. Similarly, Menyah & Wolde-Rufael, (2010) study the causal relationship between CO₂ emissions, renewable and nuclear energy consumption and real GDP for the United States for the period 1960-2007. Using the Granger Causality test, the study reveals a uni-directional negative causality between nuclear energy and CO₂ emissions, while no causality between RE and CO₂ emissions. This indicates that in the US, nuclear energy is better positioned to contribute towards climate change mitigation than RE sources, while contributing towards the economic growth of the nation. Apergis, et al., (2010) study the correlation between clean energy consumption and CO₂ emissions. Using panel data between 1984 – 2007 for 19

countries for GDP, nuclear energy consumption, renewable energy consumption and CO₂ emissions, the authors adopt a panel error correction model to study the long-term results. The authors find that nuclear energy consumption and CO₂ emissions have a negative correlation whereas RE consumption such as solar, wind and biomass have a positive correlation with CO₂ emissions. This is because of the intermittent nature of energy supply by the latter causing countries to rely on fossil-fuel energy sources to ensure energy security.

The studies on RES and economic growth in different countries have shown that the richer developed countries have a higher positive correlation between RES adoption and economic growth. Ntanos et al., (2018), study the relationship between RES and the GDP per capita for 25 European countries for the time period 2007 to 2016. Using Ward's method of hierarchical cluster analysis, descriptive statistics and Auto-Regressive Distributed Lag (ARDL) model, the results reveal that GDP has a positive correlation with RES as well as non-RES consumption in the long run. In addition, the positive correlation between GDP per capita and RES consumption is higher for countries with higher GDP, compared to those with lower GDP. Inglesi-Lotz (2016) analyse the relationship between RE expansion and economic growth for thirty-four OECD member countries between 1990 to 2010 using panel data regression techniques. Using the Pedroni cointegration tests, results reveal that in the long run, a 1% increase in RE consumption leads to 0.11% increase in GDP and 1% increase in the share of RE leads to an increase in GDP by 0.089%. Thus, the authors propose that the increase in RE consumption should be in relation to the total energy mix of the country, wherein, a net increase leads to positive economic gains. Salim, Hassan and Shafiei (2014) adopt a panel cointegration technique to study the dynamic relationship between renewable and non-renewable energy consumption and industrial output and GDP growth for OECD countries during the period 1980-2011. Results reveal there is a positive long-run relationship between GDP, industrial production and RES as well as non-RES consumption. A bidirectional causality is established between industrial output and both RES and non-RES sources, thus indicating strong energy dependency of industries within OECD countries. On the other hand, a unidirectional causality between GDP growth and RES consumption in the long-run is established, thus, promoting sustainable economic growth in the long run. Al-mulali, et al., (2013) study the long-run relationship between GDP growth and RE consumption for low income, upper middle income, lower middle income and high income countries. Results reveal that 64% of low income countries show a positive bidirectional causality between economic growth and RES consumption, whereas it is 87.5% for high income countries. These results indicate that a higher level of investments in clean energy sources is essential in lower income countries, however,

the authors did not take into consideration the pivotal role of non-RES consumption in ensuring energy security in these countries. Sadorsky, (2009a) studies the drivers of RE consumption, in light of societal issues arising from energy security and global warming. The study adopts the panel cointegration techniques for the G7 countries – Canada, France, Germany, Italy, Japan, UK and the USA, over the time period 1980 to 2005. Results indicate that in the long run, 1% increase in GDP per capita and CO₂ per capita lead to an increase in per capita RE consumption by 8.4% and 5.2%, respectively, while oil prices have a smaller, but negative impact on RE consumption. The authors infer that short-term shocks should not deter policy-makers in pursuing RE expansion, since all the long-run variables considered in this study are positive and statistically significant. These studies indicate that the promotion of RES implies finding an optimal combination of RE and non-RE sources such that the positives of clean energy transition complements economic prosperity. To this end, the developed countries are better positioned for this transition.

In the case of emerging/developing economies, the results are varying in nature. Sadorsky, (2009b) identifies that the studies on the causal relationships between RE consumption and income are largely concentrated towards high income, developed economies. The author studies 18 emerging economies using panel cointegration techniques. Using the annual per capita RE consumption and per capita income data between 1994 to 2003, the model predicts a unidirectional positive causality, from per capita income to per capita RE consumption. In the long run, a 1% increase in per capita income increases the per capita RE consumption by approximately 3.5%. This indicates that, the increase in per capita RE consumption is expected to be higher than an increase in per capita income levels. Shahbaz, et al., (2015) studied the long-run relationship between RE consumption and economic growth using an ARDL model for cointegration and VECM for causality test for Pakistan. The results reveal a long-run relationship between RES and economic growth, while the unidirectional causality is from the former to the latter. Thus, increasing RES's share in the electricity portfolio leads to an increase in economic growth and not the other way around. The authors propose an 'integrated energy policy' including the expansion of RES along with other non-RES mix portfolios. Fang, (2011) studies the economic impact of RE consumption in China, between 1978 to 2008, using the multivariate Ordinary Least Square (OLS) method. The authors use the log of total RE consumption and share of RE consumption, gross capital formation, number of employees and per capita R&D expenditure as the explanatory variables. Using this Cobb-Douglas type economic well-being production function, the results reveal a 1% increase in total RE consumption increases real GDP by 0.12%, per capita GDP by 0.16%, per capita annual income

of rural and urban households by 0.44% and 0.37%, respectively. On the other hand, an increase in the share of RE consumption leads to an insignificant impact on economic growth and a negative impact on household income. This could be a result of economic, financial, technical and administrative barriers resulting from a higher share of RE consumption, which, the authors presume will also exist in other developing countries. Chen, Wang, & Zhong, (2019) study the long-run relationship between per-capita CO₂ emissions, GDP, Renewable and Non-renewable energy production and foreign trade in China during the period 1980-2014. Using the ARDL model and the Granger Causality approach, the results reveal a bi-directional causality between RE and CO₂ emissions, foreign trade and non-RE production. In the long run, RE and foreign trade have a negative impact on CO₂ emissions. Furthermore, a U-shaped Environmental Kuznets curve hypothesis is observed only after the inclusion of RE production along with the rest of the variables.

Studies on a diverse set of economics also provide mixed results, since it depends upon the economic status, geographical locations and time periods focussed upon. In the Asian context, it is observed that all the RE sources such as hydroelectric, biomass, solar PV, wind and geothermal energy have significant potential across different countries. Chen, et al., (2022) studied the association between RE consumption and economic growth for 8 Asian countries² at different stages in their growth trajectories. Using the heterogeneous panel data regression model and Dumitrescu and Hurin analysis, the results reiterate the feedback hypothesis of bidirectional causality between RE consumption and economic growth between the countries. However, the impact of RE sources displacing existing non-RE capacity in the medium to long-run is not considered, since that is the eventual target for a carbon neutral economy. Apergis & Payne, (2012) adopt the heterogenous panel cointegration test to study the long-run relationship between real GDP, RE and non-RE consumption for 80 countries between 1990-2007. Results reveal a bidirectional causality between real GDP and both, RE and non-RE consumption in the short and long run. In the short run, a negative bidirectional causality exists between RE and non-RE consumption, indicating substitutability between the two types of energy sources. Overall, the causalities between real GDP and the two types of energy sources indicate that both are important for economic growth, which in turn leads to increasing usage from both energy sources. The authors acknowledge that energy efficiency parameters were not considered for this study, which will play a pivotal role in attracting investment and financing of green growth strategies. Omri & Nguyen, (2014) study the impact of RE consumption on

² China, India, Pakistan, Taiwan, Malaysia, Maldives, Singapore and Bhutan.

not only macroeconomic variables such as per capita GDP and trade openness but also the CO₂ emissions and Oil price effects. The authors adopt three dynamic GMM income-based panel data models consisting of high, middle and low-income models, constituting a combined 64 countries over the period 1990-2011. Results reveal that per-capita GDP is statistically significant in high and low-income countries, whereas environmental degradation for which CO₂ emissions is considered as a proxy is statistically significant across all three panels. This implies, that increasing CO₂ emissions is a key driver promoting RE consumption across countries on different economic trajectories. Bhattacharya, et al., (2016) refer to the Renewable Energy Country Attractiveness Index (RECAI) to identify the top 38 RE consuming countries in the world. Using heterogeneous panel estimation techniques, the long-run dynamics of real GDP with traditional and energy related inputs for the 38 countries during the time period 1991 to 2012 are analysed. The groups showing a negative long-run relationship between RE and economic growth were India (-0.118), Ukraine (-0.162), the United States (-0.072) and Israel (-0.061), owing to the largest share of non-RES sources within its electricity mix. Jebli & Youssef, (2015) study the causal relationship between Output, RE and non-RE consumption and trade for 69 countries during the period 1980-2010. Using panel cointegration techniques, the results indicate that there is bidirectional causality between both non-RE and RE with trade. The authors highlight that non-RE consumption will continue to play an important role in the global economy, owing to its significant impact on international trade. On the other hand, trade will also play an important role in RE technology transfer, while contributing towards reducing Greenhouse gas emissions. Jia, Fan, & Xia, (2023) study the feedback hypothesis for 90 countries along the Belt and Road Initiative (BRI) for the period 2000 to 2019. By employing the Granger causality and ARDL model, the authors detect a bidirectional causality between RE consumption and economic growth. Furthermore, the study also showed a positive indirect influence on economic growth through the impact on gross capital formation and trade. The positive results, signify the promotion of a RE corridor across the BRI which can further enhance the green growth trajectory across countries.

Apart from econometric studies, there have been a rise in other sophisticated models over the last few decades, with increasing importance provided to applied economic-energy models in pursuit of supporting policies towards sustained climate change mitigation. While econometric models under the partial equilibrium assumptions study the direct and in some cases indirect impact using control variables of RE on economic growth, it constitutes only one aspect contributing towards the policy-making literature. Another aspect is the necessity to design an optimal RE policy focussing on the economic potential of the deployment of RE technologies

in decentralized markets, the market failures arising from RE deployment and the multiple policy instruments to cure these market failures (Edenhofer, et al., 2013). Furthermore, the implementation of technical methods focussing on prediction accuracy, inputs, energy carriers, economic sectors, temporal horizon and spatial granularity are the details that need to be incorporated (Birol, 2005; Bai, et al., 2016; Lopion, Markewitz, Robinius, & Stolten, 2018). An integral part of an energy policy is that it is reliable, eco-friendly and cost-effective and ensures the nexus between these three characteristics is through the implementation of energy system models (Edenhofer, et al., 2013; Verwiebe, et al., 2021) Such models are largely from the scientific background, focussing on engineering-based, metaheuristic, machine learning techniques and statistical techniques. A rise in hybrid techniques where the technical and economic aspects are combined in energy demand models has also been observed that provide a more holistic perspective towards energy policymaking. The key energy modelling studies are presented here.

Mercure et al., (2018) calculate the macroeconomic ramifications of the 2°C target by 2050 on the Stranded Fossil Fuel Assets (SFFA), using the Multi-regional Integrated Assessment Model (IAM): E3ME-FTT GENIE model. Results reveal a USD 12 trillion loss globally while the total value loss from SFFA accounts for USD 9 trillion, resulting from a reduction in GDP and employment in the fossil-fuel industry. du Pont & Meinshausen (2018), use the Integrated Assessment Model (IAM) to evaluate the Nationally Determined Contributions of major countries under the bottom-up allocation in the IAM under five categories – a) Capability-to-Pay (CA approach), b) Equality with the dynamic Equal Per Capita (EPC approach) c) Responsibility-capability-need with Greenhouse Development Rights (GDR approach), d) Historical Responsibility with the Equal Cumulative Per Capita approach and e) National circumstances regarding current emissions levels with Constant Emissions Ratio (CER) Approach. Results reveal that the NDCs in India, the EU, Brazil, USA, Japan and China lead to warmings of 2.6°C, 3.2°C, 3.7°C, 4°C, 4.3°C., respectively. Gallagher, Zhang, Orvis, Rissman & Liu (2019) assess China’s performance and gaps/constraints in achieving its NDC target of reaching its peak emissions and 20% share of non-fossil fuel energy consumption by 2030. Using the Systems Dynamics Model, results reveal that China will peak emissions well in advance to 2030 and achieve 20% share of non-conventional energy sources by 2020. The authors propose strengthening of Emission Trading system, Energy efficiency Standards and development of carbon pricing policies. Burke, Davis & Diffenbaugh (2018) analyse the macroeconomic impact of achieving the 1.5-2°C target of global warming. The authors adopt

the multi-regional Global Circulation Model (GCM) combined with Representative Concentration Pathways (RCP) and Shared Socioeconomic pathways (SSP). Results reveal that achieving the 1.5°C target will contribute towards the reduction of economic damages and reduced inequality, with the poorer countries benefiting the most. On the other hand, an increase in global warming to 2.5-3°C by 2100 will lead to a reduction of 15-25% in per capita output. The efforts towards clean energy transition also come at significant monetary costs. There are significant linkages and the presence of non-RE sources in both developed and developing economies. The introduction of RE technologies within the energy portfolios implies an onset of structural changes within the economy to which several other sectors will have to adjust for its smooth transition. Bulavskaya and Reynes (2016), study the macroeconomic impact of Renewable Energy in the Netherlands, using a Computable General Equilibrium Model (CGEM) Three Maximum Entropy (ME) model. The authors formulate a scenario in which the coal and half of the gas power plants are substituted by Solar PV and wind turbines, achieving a 75% electricity mix by 2030. The results indicate an increase in GDP by 0.85% and the generation of 48,500 additional jobs, especially in the services and construction sectors, by 2030. The gross investment increase of 6.5% is attributed to the relatively high capital intensity of RE technologies. On the other hand, the real electricity price is expected to be 3% higher compared to the baseline by 2030 while there are job losses in the fossil fuel sectors. The advantage of CGE models is that by taking into consideration the price effects and feedback loops, the overestimation of the positive impacts can be curbed. Iyer et al., (2017) evaluate the USA's NDCs of achieving an 80% reduction in GHG emissions by 2050. Using the Global Change Assessment Model (GCAM), the results reveal that in the four technology scenarios constructed by the authors, namely, i) Full tech, ii) No nuclear, iii) No CCS and No Nuclear and CCS, the average annual capital investment in all technologies between 2026-50 is three times more than the required investment between 2016-25. These studies indicate that significant capital investments and also long gestation period for the adoption of RE technologies on a large scale to materialize are unavoidable prerequisites. While these studies have been conducted in developed countries, owing to their better positioning in the energy transition process as was discussed earlier using econometric methods, there is a significant gap when it comes to such studies in developing/emerging economies.

In the case of India, studies on the macroeconomic impact of RE transition is scarce. One of the reasons could be that the upturn in RE expansion has only been observed over the past decade, in comparison to the developed countries which are better prepared. Eren, Taspinar, &

Gokmenoglu, (2019) study the long-run relationship between RE consumption, Financial Development and Economic growth in India using the time series data between 1971-2015. The authors use the Composite Financial Development Index prepared by the World Bank as a proxy for Financial Development, while the GDP per Capita is a proxy for Economic growth. Using the Dynamic Ordinary Least Squares method, results indicate a positive and statistically significant impact of financial development and economic growth over renewable energy. The Granger causality test shows a bidirectional causality between RE consumption and economic growth. The authors acknowledge that the energy intensity will vary at a disaggregated level between different RE sources which has not been considered in this study and can yield different results. Tiwari, (2011) uses the Structural Vector Autoregression (SVAR) model to study the relationship between RES, economic growth and CO₂ emissions in the Indian context. The results show that the increase in RE consumption leads to an increase in GDP and decrease in CO₂ emissions. The variance decomposition analysis showed that an increase in RES may lead to an increase in CO₂ emissions during the first few years, however, the authors do not provide justification for this result. Studies at a disaggregated level for different RE mix strategies can provide different results. Omri and Chaibi (2014) study the causal relationship between nuclear energy, Renewable energy and economic growth using dynamic panel data models for 17 countries, including India. The study presents two sets of results, showing unidirectional causality between RE and economic growth. Hungary, India, Japan, Netherlands and Sweden show a unidirectional causality from RE consumption to economic growth. These countries show evidence of the 'growth hypothesis' where energy consumption directly or indirectly plays an important role in economic growth, complementing labour and capital. du Can et al., (2019) adopt the long-range Energy Alternative Planning System (LEAP) model to investigate the key physical drivers of CO₂ emissions and economic growth. The study finds that between 2015 and 2050, the industry and transport sector will be the key drivers of final energy demand, resulting from increased use of energy for cooking, water heating and electronic equipment. Furthermore, CO₂ emissions will quadruple to 7.4 BtCO₂ while emissions per capita will reach 4.4 tCO₂ by 2050 in India, compared to 7.6 tCO₂ per capita for China. Kanitkar, Banerjee & Jayaraman (2018), using IAM attempt to formulate a balanced approach between economic growth and energy transition. Results reveal that low-income households are worse off compared to middle and high-income households as a result of the higher growth rate of RE capacity. Thus, investments in green initiatives need to be balanced with capacity building programmes in industries which are going to be worse off resulting from the clean energy transition process. Shukla, Dhar, Pathak, Mahadevia & Garg (2015) adopted

the Soft-Linked Integrated Model (SLIM) to evaluate the alternative roadmaps for India's efforts towards the 2°C global warming target. Results reveal that in the sustainable scenario, CO₂ emissions are 33% lower compared to the conventional scenario by 2050. The creation of a Carbon sink is achievable within the existing technologies available with increasing usage of RES.

Based on the literature review presented here, the following are the key takeaways:

- The studies focussing on investigating the relationship between RE and economic growth mostly adopt multivariate econometric and panel regression techniques. The advantage of these methodologies is that it is extended to cross-sectional data across different time periods. However, such models focus only on the GDP or GDP per capita as a proxy for economic growth, while other key variables such as Output and Employment are largely ignored.
- The inter-sectoral impact from incremental RE consumption across the supply chain of RES is not studied, which is also the limitations of such partial equilibrium econometric models. To this end, the new General Equilibrium and Integrated Assessment Models have witnessed increased popularity which provide not only long-term forecasts of macroeconomic impacts based on the decarbonization pathways chosen by the respective countries, but also provide the impact assessment results for a diverse set of variables.
- Both partial and general equilibrium models analysing the impact of RES technologies are largely concentrated in developed economies with developing economies given minimal attention in the literature. While the key outcomes of studies on developing economies are largely scattered with no proper policy recommendations as their key outcomes, it is observed that developed economies are better positioned for a clean energy transition which requires high capital investments as well as a strong foundation for absorbing structural changes.
- The common outcome in several studies across varying time periods show the necessity of balancing RE and non-RE sources in its electricity mix portfolio in order to ensure the economic growth and energy security of the country is not compromised. However, this will vary from country to country depending upon their current power portfolio and their comparative advantage amongst available RE options across different regions.

In the next section, the evaluation of renewable energy sources, especially the deployment of solar PV and Wind energy, using an LCA approach has been discussed in detail.

2.2 Renewable Energy Using Life Cycle Assessment Approach

It is a well acknowledged and proven hypothesis in the literature that solar and wind energy are cleaner energy sources relative to conventional fossil-fuel sources such as coal and natural gas. However, the emissions from energy sources represent only the operational phase of the unit under consideration during a particular point in time. The energy requirement (or embodied energy) and the resulting CO₂ emissions attributed to the upstream activities of raw material acquisition & manufacturing phase; and construction/installation phase are not considered in this estimation. Moreover, the downstream activities of not only the operational phase, but the End-of-Life (EoL) phase also needs to be taken into consideration, thus completing the entire lifecycle. To this end, the Life Cycle Assessment (LCA) methodology provides a holistic approach towards quantifying the energy and environmental burden of the energy source. According to the International Organization for Standardization (ISO), LCA has been described as follows: “LCA studies the environmental aspects and potential impacts throughout a product’s life cycle (i.e. cradle-to-grave) from raw materials acquisition through production, use and disposal” (ISO, 2006). The advantages of adopting LCA include i) identifying opportunities to improve the environmental performance of products at various points in their lifecycle, ii) informing decision-makers in industry, government or non-government organizations, iii) the selection of relevant indicators of environmental performance, including measurement techniques and iv) marketing (ISO, 2006). The key advantage of LCA compared to other environmental assessment tools is that the product or process system is extended in time and space (Finnveden, et al., 2009). This implies that the emission inventory represents the impacts from the sum of emissions released in the past, emissions released today and emissions released in the near and long-term future across specific locations from the functional unit.

LCA takes into consideration multiple environmental issues leading to not only global warming from GHG and non-GHG emissions, but also water and soil degradation, biodiversity loss, impact on land footprint and land transformation, and toxic impact on human health to name a few (Loisseau et al., 2013; Bjorn, Owsianiak, Milin, & Laurent, 2018; Damiani et al., 2023). Furthermore, all impact assessment studies using LCA are quantifiable, implying that the potential impact results on the environment using LCA are quantitative in nature. The LCA approach is broadly categorized as ‘Attributional LCA (ALCA) and ‘Consequential LCA’ (CLCA) depending upon the objective of the study. The ALCA is defined by its focus on describing the environmentally relevant physical flows to and from a life cycle and its

subsystems (Finnveden, et al., 2009; Ekvall, 2020). The ALCA serves to attribute the share or proportion of the total emissions emitted in the economy over a period of time (Curran, Mann, & Norris, 2005). The tracing and monitoring of energy and materials flowing in and out of the sub-system under consideration is quantified in an ALCA study. On the other hand, the Consequential LCA or CLCA approach attempts to derive how the material and energy flows to and from the environment will alter as a result of different decisions or changes in the economy such as a decrease in output demand, increase in export demand etc. for the product under consideration (Curran, Mann, & Norris, 2005). While ALCA focuses on estimating the share of the global environmental burden for the product, CLCA attempts to study how the product may affect the global environmental burden throughout its lifetime (Ekvall, 2020). The LCA methodology is a scientific and empirical method, focussing on the energy and material inventory throughout the lifecycle of the product (EPA, 2006). However, the application of LCA can go beyond the technical and material feasibility studies by adopting a holistic approach through Techno-Economic Analysis (TEA) of a product or a process. This implies looking at not only the environmental burden throughout the product's lifetime but also the economic ramifications of countering the negative environmental impact (Mahmud, Moni, High, & Carbajales-Dale, 2021). This section intends to extract such studies focussing on not only the technological implications but also the economic feasibility of carbon-neutral strategies in a circular economy framework.

In the following sub-section, the attributional LCA literature on Solar and Wind energy is elaborately discussed. Furthermore, separate attention has been given to the End-of-Life phase literature for Solar PV and Wind energy, owing to the significant circular economy potential arising from its recycling.

2.2.1 Attributional LCA studies on Solar Energy

The potential of solar energy as a sustainable alternative to non-renewable energy sources is well established in literature. The biggest advantage posed by solar energy in comparison to other conventional and non-conventional sources, is that it is the most abundant energy source available, making its supply practically inexhaustible (Parida et al. 2011). The average amount of solar energy received at the top of Earth's atmosphere is around 340 Wm^{-2} , of which around 29% is reflected back to space, leaving 71% available for harvesting (NASA 2015). Solangi et al., (2011) highlight the major advantages of solar energy in terms of reduced greenhouse gas (GHG) emissions; reclamation of degraded land; improvement of the quality of water resources; reduction of transmission lines from electricity grids; increase of regional/national

energy independence; diversification and security of energy supply; and acceleration of rural electrification in developing countries. Several other studies have reported similar advantages and have particularly elaborated on the role of solar energy as a tool for GHG emission reduction.

Technological development over the years has captured and converted this abundant energy source into three basic forms: Low temperature solar thermal, solar electric or photovoltaic (PV), and high-temperature or concentrated solar thermal energy, and it is the last two technologies that currently dominate the solar power industry (Timmons et al. 2014). Although these two technologies are fundamentally different, competitive comparison between the two is often made. Debates related to comparative advantages in renewable energies suggest that solar PV is preferred over concentrated solar power (CSP) with its technological simplicity and economic advantage (Gaspar 2012). Recent literature, however, has acknowledged the strength of CSP in terms of energy storage and dispatchable generation and suggests that a PV-CSP hybrid technology has the potential to perform better in terms of both power quality and cost of power production as compared to the PV-alone and CSP-alone technologies (Ju et al. 2017). As a relatively new technology, the development of PV-CSP hybrid systems is still catching up with the market penetration of its constituent technologies, of which the PV technology has the largest share at present. The solar PV technology itself has matured over time and currently possesses a wide range of technology options within it. These technologies mainly differ in terms of the light absorbing materials used and include wafer-based cells (traditional mono-crystalline, poly-crystalline, micro-crystalline silicon or gallium arsenide), commercial thin-film cells (cadmium telluride, amorphous silicon, copper indium gallium diselenide) and new thin-film technologies (perovskites, organic materials, quantum dots) (Kabir et al. 2018). Of the available alternatives, the crystalline-silicon (c-si) solar PV modules boast the highest global PV market share of 93% with the highest conversion efficiency for the mono-crystalline silicon (mono-Si) and multi-crystalline silicon (multi-si) of 25.8% and 22.3%, respectively (NREL, 2017). In comparison, the second-generation PV technologies such as thin film – amorphous-silicon (a-si), cadmium telluride (CdTe) and copper indium selenide (CIS) reveal lower efficiencies than silicon solar cells with corresponding efficiency of 14%, 22.1% and 22.6%, respectively (NREL, 2017). The emerging PV technologies which are at the laboratory stage such as Dye-Sensitized Solar Cells (DSSC), perovskite and quantum dot-solar cells also recorded lower efficiency levels of 11.9%, 22.1% and 12.4%, respectively.

Alsema and Scholten (2005) prepared one of the earliest Life Cycle Inventories (LCI) for crystalline silicon technology. Between the ribbon mono and multi-crystalline PV technologies,

the energy input requirement is the highest for monocrystalline technology with the PV frame constituting the highest share of energy. Subsequently, the Energy Payback Time (EPBT) is also the highest for monocrystalline technology of 2.5 to 4.6 years. As a result, the life cycle CO₂ emissions are also the highest for monocrystalline PV technology of 45 g/kWh compared to 30 and 35 g/kWh for ribbon and multi-crystalline PV technology. Sherwani et al. (2010) present a review of 19 LCA studies of solar PV-based electricity generation systems. The technologies considered in this paper include amorphous, mono-crystalline, and polycrystalline technologies. The performance of each technology is reported against three basic indicators: Efficiency (%), EPBT (years) and GHG emissions (gCO_{2e}/kWh). Overall, the study concludes that although thin film (amorphous) solar cells consume less primary energy (embodied energy) than crystalline solar cells, their efficiency is comparatively lower. Ludin, et al., (2018) summarize the LCA parameters – Cumulative Energy Demand (CED), EPBT and GHG emission rate based on the existing solar PV LCA literature. Within c-Si technology, it is the mono-Si solar cells which have higher values in each of the three parameters, relative to the multi-Si solar cells. Similarly, Baharwani et al., (2014) conducted a review of Solar PV systems, for mono-Si, multi-Si and thin film PV technologies and reached a similar conclusion, that the mono-Si technology has higher CED, EPBT and GHG emissions per unit compared to the other technologies. However, the trade-off is that the efficiency levels are also the highest for mono-Si PV technologies. The Report published by Environment Canada (2014) reviews the techno-efficiency levels of Crystalline-Si and thin-film PV technologies using an LCA approach, by evaluating the environmental performance across material sourcing, manufacturing, product use, transmission, distribution and decommissioning phases. While observing that the manufacturing phase is the most energy intensive phase irrespective of the PV technology under consideration, the crystalline technology in comparison to thin-film have better proven field stability and high conversion efficiency levels. Despite its huge technical potential for emission reduction, solar electricity generation systems are not actually emission free technologies. Stoppato (2007) presents the results of an LCA of PV panels, starting from silica extraction to the final panel assembling. The study finds that the transformation of metallic silicon into solar silicon and the panel assembling are the most energy intensive steps in the manufacture of solar panels. The former process is characterised by greater electricity consumption, even if the most efficient conversion technology is considered. The latter is by the use of aluminium frame and glass roofing, which are highly energy-intensive materials. The most effective way, therefore, to improve the modules' environmental performance is to reduce the energy input in the manufacturing phase of the modules, provided that other

parameters remain constant (Pacca et al. 2007). This result is upheld by Nugent et al., (2014) which reviews 41 of the most relevant, recent, rigorous, original, and complete solar PV and wind LCA studies and finds that the cultivation and fabrication stage accounts for the highest proportion of GHGs released. Hsu, et al., (2012) undertake a similar review of LCA studies on solar PV but focussing on only c-Si PV technology. The authors focussed on providing harmonized estimates based on the following performance characteristics – Irradiation level of 1,700 kWh/m²/year; system lifetime of 30 years, module efficiency of 13.2-14% and performance ratio of 0.75-0.8. Based on 13 LCA studies, the authors provide a harmonized estimate of the lifetime GHG emissions of 57 gCO₂eq/kWh with an inter-quartile range of 44 to 73 gCO₂eq/kWh from c-Si PV modules. Although the authors did not provide the distinction between the mono-Si and multi-Si PV technologies, the manufacturing phase is identified to constitute the highest share of GHG emissions and with scope for material efficiency improvements. Aristizabal, Sierra and Hernandez (2016) study the lifetime environmental impacts of monocrystalline silicon technology modules. The CED was observed to be the highest in the manufacturing phase (75.8%). This is mainly related to the transformation of silicon for its application in PV technology (47.5%), followed by the assembly of panels (18.4%) and production of wafers (16.5%). The environmental performance shows that the technology produces only 0.7 g/kWh of GHG emissions, compared to 3.7 g/kWh and 44.3 g/kWh from oil and coal, respectively. Baharwani et al., (2014), conduct an LCA review of three key PV technologies – mono-Si, multi-Si, thin film amorphous (a-Si) and Cadmium Telluride PV technologies. The authors find that mono-Si and multi-Si have almost similar conversion efficiency, while the latter is attributed will lower embodied energy, hence lower GHG emissions and EPBT. On the other hand, thin film PV technologies (a-Si) and CdTE have lower EPBT and GHG emissions as well as lower conversion efficiency levels. However, a harmonized level of the conversion efficiency levels, EPBT and GHG emissions is subject to different parameters such as solar irradiation levels, life expectancy, Balance of System (BOS) Components quality, solar cell type, and manufacturing processes, to name a few. Pacca, Sivaraman & Keoleian (2007) conducted a comparative LCA study of thin film amorphous and multi-Si rooftop PV modules. The comparison was done on the basis of three LCA parameters – Net Energy Ratio (NER), EPBT and CO₂ emissions. The study shows that the NER and EPBT for the multi-Si modules to be 2.7 and 7.4 years, respectively, in comparison to the thin film PV modules which are 5.14 and 3.15 years, respectively. The authors find that if PV systems are used as energy breeders then the increase in NER is expected to shave 80% of CO₂ emissions.

Given the variations in EPBT and other parameters which are subject to climatic conditions, Espinosa, Hosel, Angmo, & Krebs, (2012), thoroughly investigate and review the range of EPBTs for different PV technologies. The EPBT for mono-Si was observed to be 4.12 to 2.86 years, based on conversion efficiencies (CE) of 11.8% to 14%. For multi-Si, it was 2 years with CE 13% and for thin-film amorphous it is 1.13 years with 7% CE. Bhandari, Collier, Ellingson, & Apul, (2015) study the two most popular PV technologies – crystalline and thin-film technologies can be compared and analysed using two key parameters: EPBT and the Energy Return on Investment (EROI). By controlling for other parameters, the authors harmonize the following values: Performance ratio (0.75), PV system lifetime (30 years), solar irradiation level ($1700 \text{ kWhm}^{-2}\text{yr}^{-1}$), module efficiency (mono-Si 13%; multi-Si 12.3%; a-Si 6.3% and CdTe 10.9%). In terms of embodied energy, the variations are ten-fold, between $13,428 \text{ MJ/m}^2$ to 894 MJ/m^2 for mono-Si and CdTE, respectively, owing to differences in the manufacturing processes and BOS components. EPBT ranges between 1 to 4.1 years with CdTe constituting the lowest and mono-Si, the highest EPBT. The EROI ranges between 8.7 to 34. As it is calculated by dividing lifetime with the embodied energy, naturally mono-Si has the lowest EROI, owing to its high embodied energy levels. The authors conclude that the development of PV technologies will rely largely on curbing the embodied energy levels, since the efficiency levels do not vary significantly. Zhou (2016) studies the relation between EPBT, EROI and CED for three different PV technologies over time. The author also reaches a similar conclusion, where mono-Si technology, which has the highest efficiency is also attributed with the lowest EROI, since its embodied energy is the highest. Over time, as the CED goes down, the EROI increases in due course. Guerra et al., (2017) study six different PV technologies in Madrid, Spain. The advantage of such comparison is that all the PV technologies are located in the same climatic condition with the similar irradiation levels, thus, making the comparisons more credible. Using the Performance Ratio (PR) which is the ratio of Array Yield by Reference Yield as the parameter, the study finds that the mono-Si and multi-Si technologies have an average PR of above 80% compared to less than 75% for the other technologies such as amorphous thin film technologies and Cadmium Telluride (CdTe) technologies. This again reiterates the popularity of crystalline silicon technologies owing to their high performance levels.

In the case of India, Solar PV LCA literature is scarce. Nawaz and Tiwari (2006) conducted an embodied energy analysis of a 1.2 W_p mono-Si PV system within an irradiation level of $800\text{-}1200 \text{ W/m}^2$. The authors find the EPBT ranges between 7-26 years, and net- CO_2 emissions saved by assuming it can substitute coal-fired TPP of similar capacity is $0.24\text{-}0.77 \text{ kg/kWh}$.

Prabhu, Shrivastava and Mukhopadhyay (2022), study the cumulative embodied energy levels and GHG emissions for mono-Si and poly-Si PV systems, in pursuit of the 100 GW solar PV capacity national target for India, to be achieved by 2022. By controlling for other parameters such as solar irradiation level (1700 kWh/m²/year), performance ratio (0.75), module efficiency (14% m-Si & 13.2% p-Si) and lifetime (30 years m-Si & 25 years p-Si) authors study the phase-wise embodied energy requirement and GHG emissions from 100 GW solar PV panels. The ground-mounted mono-Si PV constituted the highest embodied energy requirement, along with the highest EPBT (2.2 years).

One of the major limitations of the solar PV LCA studies is that the analysis of the environmental impact is concentrated on the upstream processes of the manufacturing and construction phases. This is primarily attributed to the GHG emissions being heavily weighted towards the upstream operations. Nevertheless, the downstream activities of decommissioning and recycling are expected to be a major cause for concern for all countries in the future with rapid PV expansion. By 2030, the Asian economies currently exhibiting higher growth of solar PV are collectively expected to generate 55.8 Million Metric Tonnes (MMT) of solar PV waste compared to 40.8 MMT in Europe by 2040. According to the International Energy Agency (IEA), global PV panel waste is expected to be 60-78 MMT by 2050 with a recoverable material value of USD 15 billion (IRENA and IEA PVPS, 2016). This amount can be reused to produce approximately 2 billion panels, or 630 GW globally. As of today, the prior preparation for dealing with PV waste generation in the near future, the European Union was one of the first to adopt the 'Directive on Waste Electrical and Electronic Equipment (WEEE)', in which PV waste is to be mandatorily treated for recycling (Heath, et al., 2020). In the US, the Washington State was the first to introduce legislature for PV recycling as the US has recently started to invest more in PV power systems. In Japan, 23 organizations have been listed by the government for properly treating PV modules and Australia recently introduced the PV product-stewardship schemes in terms of the responsibilities to be undertaken by different stakeholders for EoL treatment. In 2023, India also introduced solar waste treatment under the E-waste Management Rules, 2022 in which the data inventory of solar modules and solar cells operational have to be registered along with complying with the guidelines laid down by the Central Pollution Control Board in this regard (PIB, 2023).

In the End-of-life phase of PV systems, the recoverable percentages of materials are the most significant for glass and aluminium (>95%), constituting more than 82% of the total panel weight (Sica et al., 2018). The BOS components (inverters, circuitry etc.) constitute the highest share of the total environmental impact of PV systems. This is because of not only the

hazardous materials constituted by these components, but also the complexities in recycling them. While there are recycling processes available for different PV technologies such as c-Si modules and CdTe modules, they are still at the testing and experimental stage. Furthermore, there are some materials such as polymers which cannot be recycled and have to be either landfilled or incinerated for which proper planning is also essential. Latunussa et al., (2016), studied the environmental impacts of PV panels, including the End-of-life phase, using the LCA approach. Through the scientific studies available on the treatments to recover silicon metal, silver, copper, aluminum and the incineration of the panel's encapsulation layers, the environmental consequences are estimated. Throughout the entire recycling process, the overall climate change impact is largely attributed to the incineration of PV (34%), transport (29%) and metal recovery treatments (24%). Dominguez & Geyer, (2017) study the End-of-life impact of rapid solar PV expansion in Mexico. With the national government's approval of 7.8 GW solar PV projects across the country, the authors estimate that by 2045, 1.2 million tonnes of waste is expected to be generated, with the assumption of 30 years lifespan. Approximately 75% of waste (or 920 thousand tonnes) can be recovered with the adoption of state-of-the-art recycling technologies which constitutes 271 thousand tonnes of silver, 10 thousand tonnes of indium, 139 thousand tonnes of cadmium and 100 thousand tonnes of tellurium. Kim & Park, (2018) investigate the end-of-life impact of PV waste in pursuit of the South Korean government's ambition of achieving 20% electricity generation from renewables by 2030. Using a Weibull distribution function, the authors find that in an early-loss scenario, approximately 130,000 tonnes of waste is expected to be generated by 2045, then gradually start decreasing post-2063, with an assumption of 25-30 years lifespan of PV modules. With the absence of appropriate recycling technology in South Korea, the authors do not investigate the circular economy potential through PV waste recycling. In view of the European Union's Directive 2012/19/EU to include PV waste under the Waste of Electrical and Electronic Equipment (WEEE) for recycling, Paiano (2015) studies Italy's circular economy prospects from PV waste generation. The author also estimates the waste generation by type of inputs, such as glass, cable, aluminium, silicon etc., in which glass constitutes approximately 75% share of total PV waste generated between 2012 and 2050. According to the WEEE provisions, approximately 65% to 75% of total waste needs to be recycled. While the recovery and reuse of materials in quantity terms is estimated, the authors do not provide the monetary valuation of the recovered materials that can be traded at market prices, thus satisfying the circular economy prospects. Peeters et al., (2017), emphasises adopting the appropriate forecasting methods since there are large variations in the product lifetime and material compositions of

PV modules that are installed in a particular region, where the complete data inventory is not available. In their forecasting, the authors adopt the modified Weibull distribution (also called the ‘bathtub curve’) to calculate the probability of the product being discarded by considering the following three reasons – Early failures, constant accidental failures, and wear-out failures. The authors apply this method for PV waste streams in Flanders, Belgium. The forecasts reveal annual waste generation of 22,000 tonnes, or up to 3.4 kg per capita of silicon-based PV panels. In terms of material composition, waste generation is also expected to vary over time, for example, silver concentration was approximately 0.14 – 0.2% in 2003, compared to 0.07 – 0.16% in 2023. Santos & Alonso-Garcia (2018) analyse the photovoltaic waste generation in Spain in an ambitious scenario of 100% RE portfolio by 2050. Using a Weibull distribution function, the authors estimate waste generation of 700,000 tonnes by 2050 of which 75% of raw materials can be theoretically recovered and reused in the manufacturing of waste, provided the state-of-the-art PV technology is available in the country. McDonald and Pearce, (2018) highlight that the recycling and landfilling/disposal costs of PV modules are not favourable without policy incentives. The authors gather data on the recycling and recovery cost for indium (In), gallium (Ga), silicon (Si), cadmium sulphide (CdS), Cadmium (Cd) and tellurium (Te) from decommissioned PV modules. The authors find that diseconomies of scale and lack of policy support makes PV recycling a non-profitable business. While energy and environmental policy standards to regulate PV recycling is essential, the policies directed towards encouraging producer responsibility towards PV recycling need to be promoted. This can be done in two ways – The government can regulate the usage of toxic, hazardous materials in the PV manufacturing phase, thus reducing the environmental burden in the end-of-life phase, or create a competitive field of instituting recycling systems, post decommissioning of PV modules. Given that the c-Si technology modules constitute the highest share of global PV market of approximately 95% (Fraunhofer ISE, 2020) the GHG emission intensity and its distribution across different phases will also be similar. Furthermore, the waste generation in the end-of-life phase and the recycling technology adoptions will also be aligned with the c-Si PV technology in developed and developing countries. However, the magnitude of waste generation across regions varies. According to IRENA and IEA PVPS, (2016), the developing countries in Asia will constitute the highest amount of waste accumulation by 2030 (3.5 million tonnes), led by China (1.5 million tonnes). The developed countries in Europe will constitute the second largest PV waste market, estimated to be 3 million tonnes while US leads in third with 1 million tonnes. Finally the Africa and Latin America with nascet, yet expanding PV markey is expected to generate waste as high as 300,000 tonnes by 2030.

Apart from the environmental consequences, decommissioned Solar PV waste if left unrecycled can also lead to significant health related complications through direct or indirect contact with toxic substances released from disposed PV modules. In the absence of PV waste management guidelines, PV modules are disposed of as per generation waste laws in unsanitary landfills which can lead to potential human health risk concerns from groundwater or surface exposure pathways. The most hazardous toxic waste that poses health risks through contact with different pathways is led by c-Si PV, cadmium from CdTE PV modules and selenium from thin-film PV modules (Sinha, Heath, Wade, & Komoto, 2020). Su, Ruan, Ballantine, Lee, & Cai, (2019) investigate the release of metal pollutants into the soils from thin-film solar panels after their burial. If left untreated or unrecycled, heavy metals such as Zinc, Nickel and Copper may be released in the surrounding environment once the protective layers are broken and exposed to acidic conditions. Such exposures are common during acidic precipitations leading to acidic rains in the region, leading to corrosion of the semiconductor materials in the PV modules. The metal leaching effects post-decommissioning occur in four ways – i) dermal contact with contaminated soil due to solar PV leachate, ii) dermal contact with contaminated groundwater, iii) accidental ingestion of contaminated soil and iv) ingestion of contaminated groundwater (Nain & Kumar, 2020). Toxical compounds such as cadmium, indium, and molybdenum pose maximum human health risks via soil-dermal contact, followed by soil-ingestion pathways. Lead also poses significant cancer risk through all pathways. Suresh et al., (2019) highlight that while glass and aluminium, constituting more than 80% of PV weight are non-hazardous in nature, other materials such as polymers, lead, cadmium telluride, silicon, metallic compounds are classified as potentially hazardous. The metal leaching studies indicated environmental impact such as loss in biodiversity and imbalance in growth and reproductivity rates of plants and animals while human health impacts include adverse effects on the kidney, nervous and cardiovascular systems.

In the case of India, Jain et al., (2022) analyse the PV waste management scenario using the DPSIR (Drivers, Pressures, State, Impact and Response) approach. Under the Pressure category, the authors highlight the generation of approximately 2.95 billion tonnes of solar PV waste between 2020 and 2047. Another Pressure is the competitive consumption of critical metals like silicon, germanium, lithium etc. in which India is highly import dependent. On the State or government front, the lack of any solar PV waste management guidelines is a cause for concern, not only on the environmental and health front, but also economic impact as well. A recent study analyzing the circular economy potential from solar PV waste in the end-of-life (EoL) phase in India was undertaken by Gautam et al., (2021). The study uses a forecasting

model to project the amount of waste generated by EoL solar PV panels and its balance of system (BOS) using the Weibull reliability function for panel failure. For this purpose, the study estimates the annual solar PV installation until 2030. The authors show that 347.5 GW of solar PV installations by 2030 are expected to generate 2.95 billion tonnes of e-waste between 2020 and 2047 with potential recovery of critical metals worth USD 452 trillion at EoL. However, given the current rate of capacity installation, these forecasts seem highly ambitious. Prabhu, Shrivastava & Mukhopadhyay (2022) study the 100 GW 2022 Solar PV target of the Indian government and estimate that, with a lifespan of 25 years for multi-Si PV modules and 30 years for mono-Si PV modules, approximately 6,576 tonnes of PV module waste (excluding BOS) is expected to be generated between 2034-59. Moreover, apart from only quantifying the module waste, the authors calculate the EoL treatment to incur power requirement, GHG emissions and monetary cost of 678.6 gWh, 648 tonnes CO_{2eq.} and USD 11.8 billion, respectively. Moreover, the economic value of recovered materials at USD 11.74 billion can contribute towards additional solar capacity installation worth 19 GW.

2.2.2 Attributional LCA studies on Wind energy

A comparative LCA study between wind energy and coal power portrays the magnitude of lifetime GHG emission savings. Li et al., (2020) undertook such a study for China, estimating the lifetime pollutant emissions of five types – Carbon Dioxide (CO₂), Particulate Matter (PM), Carbon Monoxide (CO), Nitrogen Oxide (NO_x) and Sulphur Dioxide (SO₂) per kWh of electricity generated from wind power to be only 4% of the total amount emitted by coal power and the related environmental costs are 1/24 of that of coal power. For wind power the pollutant emissions are higher in the production phase, however, the lifecycle environmental cost is moderately higher in the construction phase (47%) compared to the production and manufacturing phase (46.8%) which is attributed to the higher purchase of electricity from the grid. The GHG emissions for wind power are largely attributed in the production phase, whereas for coal power it is concentrated in the operation and maintenance phase. This is a key observation as it provides the direction of targeting decarbonization strategies. Lenzen & Munksgaard, (2002) study the energy and CO₂ intensity of wind turbines in 10 countries across the time period 1991 to 2002. The range of results reflect differences in lifetime energy requirement between smaller wind turbines (<1 KW) and larger ones (> 1 KW) with the former requiring three times more life-cycle energy per unit power. The variation arises from the differences in values for the energy content and materials, country of manufacturer, and recycling or overhaul of components in the EoL phase. The CO₂ intensity varies according to

the fuel mix in the location of wind turbines. Lee, Tzeng, & Su, (2006) adopt an LCA approach for wind power utilization from three turbine systems – a Vestas (V-47) 660 KW turbine in southwest Taiwan, Enercon (E-40) 600 KW in Penghu Islands and Vestas (V-66) 1,750 KW in northwest Taiwan. The study finds the manufacturing phase to be the most energy and emission intensive while closely followed by the Construction phase in all three locations, with cumulative embodied energy and CO₂ emission intensities of 0.05 MJ/kWh and 3.6g/kWh, respectively. The authors also estimate the resource inputs needed in the manufacturing and construction phases to generate 1 kWh of electricity which constitutes, Concrete (6.515g), Steel (1.568g), Reinforced steel (0.279g), plastics (0.068g), and glass (0.043g) as the top five inputs. Based on the location of production, Lenzen & Wachsmann, (2004) undertake a comparative LCA study for wind turbines located in Brazil and Germany. The production phase of wind turbines in both countries is largely oil-based liquid fuels. However, natural gas and nuclear energy are more important in Germany, while hydraulic energy, bagasse firewood and sugar-based ethanol fuel dominate Brazil's energy portfolio. In terms of primary energy embodiment, wind turbines in Brazil have lower energy requirements compared to the wind turbines manufactured in Germany due to the higher conversion efficiency of electricity generation in the former. In both countries, the tower (30-40%), generator (20-30%) and nacelle (10-15%) constitute the highest embodied energy in descending order. Haapala & Prempreeda, (2014) undertake a comparative LCA of two 2 MW wind turbines in Columbia, USA – one manufactured for high speed wind sites (Gamesa) while the other for medium and low wind sites (Vestas). The manufacturing and raw material acquisition phase constitutes the highest environmental impact (78%) in both cases. The tower, rotor and nacelle compose the highest share of the manufacturing phase. The main outcome of this comparative LCA study is the attribution of high environmental impact from the manufacturing phase, irrespective of the onshore wind technology adopted. Gomaa, Rezk, Mustafa, & Al-Dhaifallah, (2019) undertook an LCA study for 38 Vestas turbines wind farm in Tafilah, Jordan using SimaPro 7.1 LCA software. Results show the environmental impacts per kWh of electricity generation to be the highest for the manufacturing phase of the life cycle. This is attributed to the usage of fossil fuels for the turbine blades which is made of composite materials such as fibreglass and resins which goes through various processes such as lamination, grinding, sanding and heating. The electricity consumption constitutes the highest share of inventory emissions and impacts whereas burning of coal leads to release of pollutants such as sulfur oxides, particulate matter and mercury. After manufacturing phase, installation and transportation phase constitute modest environmental impacts. The usage of renewable power in the installation phase is

proposed which can offset significant emissions. Tremeac & Meunier, (2009), is another study which undertakes the comparative LCA of two wind turbines (4.5 MW and 250 W) located in France. However, this study excludes the manufacturing phase of wind turbines. In its absence, the construction or installation phase constitutes the highest impact followed by transport in the case of both wind turbines. Transportation by truck constitutes a higher impact from the 4.5 MW wind turbine compared to the smaller 250 W turbine. However, the primary energy payback time for the smaller wind turbine is higher, at 2.29 years compared to 0.58 years for the 4.5 MW wind turbine, primarily because of the lower rate of electricity generation potential for the former. This implies that the 4.5 MW wind turbine corresponds to an energy saving of 646 gWh throughout its lifetime of 20 years, compared to 6 mWh for the 250 W turbine. Although the exclusion of the manufacturing phase is a significant absence from the LCA study, it does provide emphasis on the environmental impact from other phases of the wind turbine which are naturally overshadowed by the manufacturing phase. Oebels & Pacca, (2013) undertook LCA of a 141.5 MW wind turbine in Brazil by excluding the EoL phase for two reasons – Firstly, the authors acknowledge the fact that there is no turbine recycling technology existing in Brazil and secondly, the absence of turbine recycling technology in the market renders it to be developed based on hypothetical scenarios and assumptions. Results show that the production phase accounts for 93.8% of GHG emissions which is found to be far higher compared to other studies in literature. This is attributed to the absence of EoL phase from the study. The steel used in the tower manufacturing constitute the highest share of emissions. The blade manufacturing also leads to the release of pollutants arising from the epoxy resins and fibreglass. The authors propose replacement of steel towers with concrete towers which is expected to save 26% emissions from the production phase. Garrett & Ronde, (2013) study the V80 2 MW Vestas *GridStreamer*TM turbines using LCA analysis by individually assessing 25,000 parts of wind turbine components. The potential environment and non-impact indicators are assessed for a 50 MW onshore wind farm. Results show the manufacturing phase followed by the EoL phase composing the highest environmental impact. The tower (25-30%), site cables (20%), nacelle (15%), blades (10-15%) and foundation (10%) constitute the key components contributing to global warming potential per kWh electricity generation. Based on net energy requirement, the return on energy is expected to be 8 to 11 months. This implies, the Vestas wind plant with 20 years lifetime will return between 22 and 30 times more energy back to the economy. Ardente, Beccali, Cellura, & Brano, (2008) investigate the embodied energy requirement and consequent GHG emissions from an Italian wind farm using an LCA approach. Results indicate the manufacturing phase to be the most energy and emission

intensive (61%), followed by building works (32.5%) and transportation (6.5%). The global energy requirement varies between 42.1 to 50.7 TeraJoule (TJ), while CO₂ emission varies from 2.7×10^6 to 3.7×10^6 kgCO₂. Xu, Pang, Zhang, Pogonietz, & Marathe, (2018) studied a 1 MW onshore wind plant in Saihan plant in Inner Mongolia, China. LCA analysis shows the production phase to constitute the highest share of 56% (Terrestrial Eco-toxicity Potential) and 118% (Freshwater Aquatic Eco-toxicity Potential). The Abiotic Depletion Potential (ADP) of fossils is largely attributed to the tower (41.8%), Nacelle (28.3%) and Rotor (20.6%). The installation and operation phase constitute minimal embodied energy due to the lack of fossil fuel consumption. The proper disposal in the EoL phase leads to positive environmental impact across different parameters. However, it does not overcome the negative impact arising from the rest of the phases of wind turbines. Wang, Wang, & Smith, (2015) adopt a systematic literature review of LCA processes to study the local and global scale impact of onshore wind farms on ecosystem services. The authors identify the mining of steel and concrete in the production phase to have the highest impact on land, air and water ecosystem services at the global scale, with the magnitude of negative impact expected to be higher in developing nations. The construction and EoL phase impacts are largely restricted to local scale. Kubiszewski, Cleveland, & Endres, (2009) estimate the EROI of onshore wind power systems - based on the energy input across all lifecycle phases and energy output in terms of electricity generation. The authors conduct the meta-data analysis for each year, from 1977 to 2007. All the countries included in the study are developed countries, except Brazil. The study shows an average EROI of 25.2 for all studies (operational and conceptual wind turbines) and 19.8 for operational wind turbines. However, the variation between countries is also found to be high with Germany showing EROI as low as 4.7 in 2004 while Brazil provided the lowest result of 18.9 in 2007.

In the case of India, Das & Banerjee, (2018), undertake the LCA study of two different turbine manufacturers – Vestas V90 turbine (2 MW) and Siemens Gamesa G80 Turbine (2 MW) with manufacturing locations in Kutch, Gujarat and Tuticorin, Tamil Nadu. The authors consider two scenarios – one in which the turbines are 100% landfilled in the absence of appropriate recycling technology and second scenario in which partial recycling occurs. Results show very minimal difference in phase-wise energy consumption between both types of turbines. The Energy Payback Time (EPBT) is in the range of 0.5 – 1.6 years considering the two scenarios, with higher EPBT in the 100% landfill scenario. However, the authors do not elucidate on the reasons for differing results for the two locations for the two different turbines. Prabhu & Mukhopadhyay, (2022) analyse the government of India's 60 GW national

onshore wind capacity installation target with its bifurcation at the sub-national level by 2022 using an LCA approach. Using the E3-India model the study finds that India will achieve the capacity target only by 2026. Based on the status of wind capacity installation at the sub-national level, Gujarat, Tamil Nadu, Karnataka and Maharashtra were identified to be the 'first mover' states, achieving their respective state targets by 2023. In the course of the capacity installation, the cumulative embodied energy and GHG emissions are expected to be 123.3 TWh and 118 million tonnes CO_{2eq.} respectively.

Currently, there is no wind turbine recycling technology available on a large scale across the world. A wind turbine structure constitutes 80-85% metal which can be recycled, however, the turbine blades made of composite materials such as fibreglass and resins provide minimal scope for recycling (Psomopoulos, Kalkanis, Kaminaris, Ioannidis, & Pachos, 2019). The glass or carbon fibre used in blades constitutes the highest embodied energy of 32-386 MJ/kg, followed by cast iron and steel used in the drive train and the tower hub with 60-260 MJ/kg. With increasing awareness of the environmental impact of landfilling and incineration of turbine blades in the EoL phase, countries are passing legislation against it, thus highlighting the urgency of promoting recycling technologies for composite materials. Liu, Meng, & Barlow, (2022) propose a financial performance model for blade recycling and the financial costs are segregated into disassembling, transport and recycling costs. EoL treatment options including mechanical, fluidized bed, pyrolysis, chemical treatment, and High-Voltage Fragmentation (HVF) are evaluated for Glass Fibre (GF) and Carbon Fibre (CF) separately. For GF recycling the main obstacle lies in the form of low resale costs, thus making the recycling unsustainable with advanced technologies. The mechanical process serves as the only solution for GF recycling to make a profit. In comparison, CF recycling is relatively more attractive due to its high resale value and can be undertaken through pyrolysis or chemical processes. The study finds a landfill tax of USD 200/tonne which can be used to fund the recycling technologies on a larger scale. The authors urge the adoption of recycling technologies to be supported with stringent national and local policies for discouraging landfilling and incineration of turbine blades. Jensen, (2018) assumed a hypothetical scenario in which 100% of the components of a 60 MW wind farm in Denmark can be recycled, which is also called as closed-loop recycling. Ferrous metal (steel and cast iron) is expected to constitute the highest energy (49,200 GJ) and CO₂ emissions savings (5,510 tonnes CO_{2eq.}), through recycling and reuse in the economy, followed by composite materials such as fibreglass and resins and NdFeB magnets. The cumulative energy savings from 100% recycling of 60 MW wind farm is expected to be 81 TJ while complemented with 7,351 tonnes of CO₂. The main objective of the author was to

disseminate the circular economy potential of wind turbines through recycling and reuse; however, it does not provide any recommendations on the recycling technology to be adopted, nor the recycling and disposal costs expected to be incurred. Deeney, et al., (2021) evaluate the EoL alternatives for wind turbine blades in light of the UN Sustainable Development Goals. The authors prepare the economic, social and environmental sustainability indices based on the Multiple Criteria Decision Analysis (MCDA). The author provides innovative alternatives such as furniture making and bridge fabrication using composite materials from turbine blades, which score the highest in terms of sustainability indices, while landfill and incineration options score the least. Cherrington, et al., (2012) explore the Extended Producer Responsibility (EPR) scenarios in which the manufacturers are responsible for the turbine recycling post-decommissioning and offset the environmental impacts from landfilling and incineration. The authors estimate the turbine recycling and disposal costs for two Vestas turbines (1.65 MW and 1.5 MW). After recovering the value of steel from its resale, it still incurs a net expenditure of Great Britain Pounds (GBP) 14,432 and GBP 57,917 for the Vestas turbines and GBP 11,418 for GE Energy turbine. Composite materials such as thermoplastic resins have high embodied energy and hence, the constituent material recovery is essential for environmental, energy and economic benefits (Cousins, Suzuki, Murray, Samaniuk, & Stebner, 2019). The dissolution recycling technology which is exclusively used for thermoplastic allows for the recovery of polymer-based materials. The dissolution – distillation – extrusion process would lead to primary energy consumption of 20 MJ/kg. A 90% recovery rate of thermoplastic blade recycling would demand approximately USD 11,767/blade in the year 2019 as the cost to operate the facility which includes the labour cost, equipment installation and maintenance costs, electricity consumption and building costs. The authors also highlight the high capital cost of the dissolution process compared to the grinding and pyrolysis process as the main disadvantage. Fonte & Xydis, (2021) focus on the upper and lower economic value of recovered glass fibre from turbine blades with the appropriate recycling technology in the European market. Four methods are evaluated – Mechanical grinding, fluidized bed, pyrolysis and solvolysis. The pyrolysis method demands relatively higher energy (30 MJ/kg) while the estimated economy value of recovered glass fibre is also the highest (EUR 0.87/kg), compared to fluidized bed (EUR 0.83/kg) and mechanical grinding (EUR 0.32/kg). Apart from recovering glass fibre, other constituent materials such as fillers, oils and gases can also be recovered using this method. On the other hand, mechanical grinding provides a lower economic value of recovered glass fibre due to lesser fibre tensile strength (20% less compared to recovered glass

fibre from the pyrolysis method) and is also the cheaper method with total cost of only EUR 0.09/kg compared to EUR 0.29/kg using the latter method.

Based on the ALCA studies on solar and wind energy discussed in Sections 2.1.1 and 2.1.2, the key takeaways are as follows:

- For both, the Solar PV and wind energy lifecycle, the manufacturing phase is estimated to be the most energy and emission intensive phase, owing to several raw materials acquired and processed for the production of solar PV modules and wind turbines, respectively.
- For Solar PV, the c-Si PV module technology, especially, mono-Si PV modules is the most widely used, owing to the higher conversion efficiency levels presented in literature across different countries and time periods. Hence considering c-Si technology for this study will provide more practical outcomes for the benefit of the policymakers.
- Majority of the studies focus on constructing the material and energy inventory throughout the lifetime of the product with the integration of Techno-economic feasibility with LCA studies is a gap existing in the literature. Several articles quantify the total solid waste that is expected to be generated in the EoL phase. However, the monetary valuation of the reuse of waste materials is lacking. The cost-benefit analysis of minimizing the environmental burden arising from the decommissioning of PV modules and wind turbines in the EoL phase through the 3R strategy of Recycle-Reduce-Reuse in a Circular Economy Framework is an area not explored enough.
- The environmental and health costs of untreated waste, especially in developing countries like India, have been given minimal attention in the literature.
- A comprehensive ALCA of solar and wind energy in the Indian context is scarce. Prabhu, Shrivastava and Mukhopadhyay (2022) and Prabhu and Mukhopadhyay (2022) attempt an ALCA of the Government of India's 2022 target of 100 GW solar and 60 GW wind targets, respectively. To this end, the 2030 target 280 GW and 140 GW solar PV and wind targets, respectively is to be attempted by referring to the ALCA framework.

Given the direct Lifetime energy and environmental burden of Solar PV and Wind energy using the ALCA approach, the macroeconomic impact of the RE technologies, across different phases (or phases combined together), also called as the CLCA can be studied using the Input Output models. This has been presented in the next section.

2.3. Macroeconomic impact of Solar and Wind energy transition using Input-Output models

The methodologies adopted to study the impact of RES technologies depend upon the focus area and the variables that the studies intend to analyse. CGE models include the anticipation of actions from economic agents such as households or the government with the aim of utility maximization. Input-Output models address the interactions within an economy owing to changes in the final use of the RES technology through the multiplier effect. I-O modelling is identified as the most suitable approach as it not only helps in assessing the employment impacts, but also the future impacts on other economic sectors as well (Jenniches, 2018). Garrett-Peltier, (2010) conducted a survey of firms and integrated their responses to construct RE industries using input-output tables, thus differentiating from fossil fuel sources. The model shows that in the US, a one million dollar expenditure on fossil fuels generates on average 2.65 full-time jobs whereas RE sources generate 7.49 jobs in the economy. The study finds RE industry to be more labour-intensive in the US compared to fossil fuel sources. Thus, clean energy transition is expected to have a positive impact through generation of employment in the economy as well. Haerer & Pratson, (2015) study the direct and indirect impact on employment resulting from the changes in the electricity portfolio of the United States, using an economic Input-Output LCA model. Between 2008 and 2012, the authors report that a decrease in coal powered electricity generation by 24% with a simultaneous increase in natural gas, solar and wind electricity by 39%, 154% and 400% respectively, led to a decrease in employment by 49,000 jobs in the former and increased by 175,000 jobs in the latter. Of the incremental employment in the alternative energy sources, solar and wind industries projected a net increase of 124,184 jobs in the given period, showing high productivity levels. Furthermore, the jobs per \$1,000,000 of economic activity for solar and wind industries exceeded the fossil fuel industries by 200% in the given time period. Mikulic, Lovrinevic, & Kecek, (2018) studied 11 wind power plants constituting 70% of the total installed capacity in Croatia. Using a closed input-output model that is with endogenous personal consumption, the authors report the total effect of GVA and employment multipliers to be 2.65 and 2.34, respectively through the channel of investment and 1.38 and 18.51, respectively through the channel of intermediate consumption. The intermediate consumption channel provided more pronounced employment effects with total employment effects of 4,192 full-time equivalent jobs. Part of the positive impact in the manufacturing sector is transferred abroad to economies which export wind turbine-related equipment to Croatia, while transport and construction

sectors also witness a positive impact. The European Wind Energy Association (EWEA) undertook a comprehensive analysis of employment potential in the wind industry using European Union IO tables (EWEA, 2004). The results show that Denmark, Germany and Spain constitute 90% of total employment in the wind energy sector across the manufacturing, installation and operation phases of wind turbines. The metal products contributing to the Tower manufacturing is estimated to have the highest employment multiplier (15.08) whereas the office and data processing machines constitute the least impact (8.15). Tourkolia & Mirasgedis, (2011) use the input-output table for Greece to study the total impact on employment after incorporating RES into the model. The total employment effects show solar PV units generate 1,503 man-years/TWh and 588 man-years/TWh for wind energy, compared to 265 man-years/TWh from geothermal units. The high employment impact of PV units is largely attributed to the construction phase and high investment costs complemented with a relatively low load factor. On the other hand, other energy sources, namely biomass and geothermal units incur high employment effects during the operational phase of their life cycles. Using a multi-regional input-output model, Ragwitz, et al., (2009), estimated the GVA and employment benefits from RE transition in EU member states to be 0.58% of GDP and 0.64% of total employment. A total of 410,000 additional jobs and 24% additional GDP contribution is expected across the EU from a 20% increase in RES in final consumption. Wind energy technologies contribute the highest to employment growth, especially in Germany, Denmark and Spain. Bachner, Steninger, Williges, & Tuerk, (2019) use a multi-regional and multi-sectoral CGE model for Europe to estimate the economy-wide impact of solar PV and wind energy expansion. Results show positive societal welfare benefits ranging between +0.1% to +0.7% for solar PV and +0.1% to +0.3% for wind energy. However, the results are in some scenarios negative for both technologies when taking into consideration the integration cost of electricity generated from wind and solar energy. Integration costs constitute 'balancing costs' emerging from uncertainty due to the varying supply of variable RE in location specific sites which are normally far away from the actual supply point. Lastly, profile costs because of variable supply of renewables which do not ideally follow proper load profiles. Due to these differences in relation to conventional energy sources, the incorporation of integration costs gives a different picture. Bae & Dall'erba, (2016) adopt a combination of input-output models using Impact Analysis for Planning (IMPLAN) software and Jobs and Economic Development Impact (JEDI) model to study the construction and operation and maintenance (O&M) phases of solar power plant in Arizona and California states. The total impact of O&M phase is higher than construction phase in both states using both models. The significant difference observed

between the two models is in the labour income changes in which the JEDI model shows relatively higher impact. This is attributed to the incorporation of high VA activities such as permitting business overhead and ‘other services’ in the JEDI model, compared to IMPLAN. Connolly, Lund and Mathiesen (2016) investigate the potential scenario of achieving a 100% RE electricity mix in Europe by 2050. Using the Energy PLAN model – A smart energy systems approach tailor-made for the 28 EU countries, the hourly modelling of the complete energy system constituting electricity, heating, cooling, industry and transport is undertaken. Considering the technical feasibility, the authors find that the annual cost of the EU energy system will be 3% higher than fossil fuel alternatives to achieve a CO₂ emission reduction of 85% by 2050, compared to 1990 levels and 12% higher to achieve 100% RE mix. Furthermore, a transition towards RE will lead to a reduction in imported fuels and an increase in local investments, leading to 10 million direct jobs within the region. Lehr, et al., (2008) undertake the survey method to incorporate the RES vector in the systematic input-output table for Germany to study the employment effect. Results show that the wind industry constitutes the highest investment and export value, thus leading to a gross employment share of 40% in the RES industry, while the solar photovoltaic industry constitutes an 11% share. This includes direct employment in the wind industry and indirectly in industries producing intermediate inputs and services. Blazejczak, Braun, Edler, & Schill, (2014) study the macroeconomic impact of renewable energy expansion in Germany using a macro econometric model- ‘Sectoral Energy Economic Econometric model (SEEM)’. Using this 71-sector input-output model constituting 14 renewable energy system sectors the study finds that incorporation of RES sectors is possible without compromising on economic growth or employment generation. Under the scenario in which unit prices remain unchanged, the RE sectors contribute 2.8% and 3.1% to GDP in 2020 and 2030 respectively, while generating employment of 14,000 jobs respectively. On the other hand in another scenario in which price wage relation is not assumed to be constant, the contribution to GDP is 1.1% and employment generation of 2,000 by 2030. While the magnitude of the impact varies, it is observed that the net employment effects are positive, irrespective of the labour markets being rigid or flexible. O'Sullivan and Edler, (2020) modify the 71-sector IO table for Germany by adding 11 RES technologies. The authors find that between 2000 and 2018, 70% of the total investments in RES technologies were in solar PV and wind energy, which led to an increase in domestic demand by 25% for solar PV and 48% for wind. Even in exports, the onshore wind sector constituted the largest share of >50% and the highest share of employment post-2012. Ciorba, Pauli, & Menna, (2004), study the induced demand in the photovoltaic sector for Morocco using the 33x33 input-output model.

The authors differentiate between the impact of solar module manufacturing indigenously as well as through imports. Results indicate the domestic production of solar cells compared to imported solar cells leads to employment of 2,570 and 489 jobs respectively. Through indigenous solar module manufacturing, devaluation in the economy is observed to be the highest from electric and electronic products, basic metals and chemical products. In order to reap the benefits of indigenous manufacturing, the authors highlight the necessity of technology transfer in developing and underdeveloped nations as well as ensuring the availability of intermediate inputs domestically. Caldes, Varela, Santamaria, & Saez, (2009), study the socio-economic impact of incremental solar thermal power generation for Spain, using an input output model. The construction and operation of 500 megawatt solar thermal plants leads to direct employment impact of 63,485 while the indirect employment generated was 45,508 equivalent jobs. The sectors that will be benefited the most are financial services, electricity production, business activities, machinery and equipment as well as construction.

Regional input-output analysis was undertaken for a 7.8 GW wind power plant in the state of Nebraska which shows an employment generation potential of 1,600 to 2,925 full-time jobs (Lantz, 2009). The local economy is expected to witness an increase of USD 140 – 260 million annually from construction-related activities and USD 250 – 442 million from operation-related activities between 2011-30. With the wind turbine lifetime assumption of USD 7.8 – 14.1 billion over a 20-year lifetime, the economic output over the course of this period is expected to increase to USD 7.8 – 14.1 billion. Itoh & Nakata, (2004), study the economic effects of RE systems using the regional input-output model for Iwata prefecture in Japan. The results show the highest positive economic impact on services such as business services, banking, insurance and transportation. The employment impact is witness to be highest in construction and installation activities. Overall economic effect was increased by USD 2.7 million and total of the employment effect was 35.1 jobs in the Iwata prefecture. Simultaneously a negative economic effect was observed on the gas and electricity sector.

In the case of India, Joshi and Mukhopadhyay (2021) analyse India's Nationally Determined Commitments (NDC) announced during the Paris Climate Accord in 2015, while studying the means to attain sustained growth in the Indian economy. The authors adopt the E3-India model, which is a macro-econometric dynamic simulation model that constitute 38x38 regional input-output models for 32 states and union territories in India. Results reveal that the economic impact across GDP, employment and household income is positive in almost all states, except in Jharkhand, which is one of the biggest coal-bearing states in India. Another coal-bearing state such as Madhya Pradesh also shows a reduction in employment by 2030. Furthermore,

the indirect impacts are witnessed to be highest for construction (+2.05-4.75%), metal goods (2-3.8%), other manufacturing (+1.2-1.4%) and also services such as Land transport (+0.86-1.16%), Trade and logistics (+0.19-0.3%), Hotels and catering (1.01-1.28%), Other business services (0.02-0.31%) and banking and insurance (+0.04-0.08%).

From the discussion above, following key points are highlighted:

- There is wide literature available on the macroeconomic impact of Renewable Energy Sources at the national level using econometric methods, however, the application of Input-Output analysis to estimate the total (direct, indirect and induced) impact is relatively modest and largely focussed on capturing the effects on the labour market.
- The I-O based literature is concentrated in the USA and EU regions, with more emphasis on wind energy compared to solar PV. With solar PV and wind capacity installations occurring at a rapid pace in developing countries like India, China, and other Southeast Asian nations, due attention should be given to these regions as well.
- Given the pretext of Solar PV and Wind energy being relatively cleaner energy sources compared to conventional sources such as coal and natural gas, it is observed that the academic literature has not provided due attention to the macroeconomic and financial consequences of the End-of-Life phase of the Solar PV and Wind turbines recycling.
- All the I-O models adopted for evaluating RE technologies have been focussing on evaluating the impact of upstream activities of the manufacturing and construction phase and to a small extent, the operational phase. However, the end-of-life recycling impact has been completely disregarded.

The studies on interconnection between the climate change impacts and economic growth across different countries and different time periods have been covered largely for the developed country case studies, using partial equilibrium econometric methods as well as general equilibrium models. Apart from the significant gap in the thorough research on emerging economies in this context, the extension towards establishing the direct and indirect impact of RES technologies through an ALCA and CLCA framework has been, to the best knowledge of the authors not been attempted in the existing studies on developed economies either.

In terms of the selection of RES technologies for this study, the literature review has elaborated upon the significance of different RE alternatives contributing differently to the economy's energy portfolio and economic growth. The significance of opting for Solar PV and Wind energy alternatives in the Indian context is not only because of its significant potential that

exists over the Indian geographical landmass, but also the emphasis provided by the policy-makers in India's ambitious decarbonization strategies, with more than 90% of 450 GW RE target 2030 attributed to solar and wind³. To this end, a thorough literature review on the ALCA and IO-LCA studies on solar and wind energy has been conducted, which again is largely concentrated in the developed USA and EU regions.

Finally, the literature on macroeconomic impact of RE deployment and solid waste management in the End-of-life phase is observed to be mutually exclusive. While interest in macroeconomic impact of RE capacity installation has gained due recognition in the last decade, the impending solid waste burden from solar photovoltaics and wind turbines is an area less explored. The macroeconomic impact of EoL waste management for solar and wind technologies is scarce in the literature. In the case of India, studies on the macroeconomic impact of RE solid waste abatement are minimal, primarily because the large-scale RE deployment in India is at a very nascent stage and as a result, the adverse impact of solid waste pollution post-decommissioning of solar modules and wind turbines at end-of-lifetime in the long-term is not given due attention.

To this end, the main novelty of the study is presented below:

- To present an integrated Economy-Energy-Environment macroeconomic framework by combining the Attributional LCA and Consequential LCA methodologies towards analyzing the economy-wide impact of solar and wind capacity addition has been undertaken. Until now, the Indian Input-output tables treated electricity as a homogenous aggregated sector, without distinction between energy generation by source. Thus, the solar PV and wind energy sector's unique linkages with the rest of the economy is established.
- To the best knowledge of the authors, this is the first study of this kind being presented not only in the case of India, but in the global context as well. In this study, the electricity sector has been treated by distinguishing between the source of power generation, that is Solar, Wind and Other electricity sources, which is also a unique aspect of the Indian Input-Output framework.
- The consequent economic and environmental impact of Solar PV and Wind turbine waste generation in the End-of-Lifetime (EoL) phase has been measured.
- Finally, both the positive as well as unintended negative consequences of the clean energy transition are captured in this study by estimating the Environmentally Adjusted Domestic

³ Further elaboration has been provided in chapter 1

Product (EADP) using the System of Economic and Environmental Accounting (SEEA) framework.

Given the novelty of the study, the key objectives are presented below:

- The lifetime energy and environmental burden of solar and wind energy sources is estimated using the Attributional LCA analysis. The cumulative RE waste generation and the Circular Economy prospects of solar PV modules and wind turbines post-decommissioning in the End-of-Life (EoL) phase are analyzed.
- To estimate the macroeconomic impact of RE capacity addition by replacing coal-fired thermal power plants (TPPs) and the whole economy impact of RE waste abatement sector by 2030 in different scenarios.
- To calculate the GHG (CO₂, CH₄, NO_x) emission and non-GHG emission (Hg, PM, SO_x, Fly Ash) savings and the land and water resource footprint from solar and wind capacity addition.
- The Environmental Impact Assessment is conducted using the System of Economic and Environmental Accounting (SEEA) framework for the Green GDP estimation. The net impact of the environmental and health cost savings from RE capacity addition and environmental and health cost incurred from the RE waste generation in the End-of-Life (EoL) phase is measured.

CHAPTER 3 METHODOLOGICAL FRAMEWORK

The Life Cycle Assessment (LCA) methodology amongst all available techniques, is the best-suited methodology for exercising the detailed economic implications of a product or a process using the material and energy inventory across its lifetime. The focus of this study lies in analysing the implications of additional solar and wind capacity installation in an Economy-Energy-Environment framework using an Input-Output (IO-LCA) approach.

This chapter is broadly divided into four sections – Section 3.1 and 3.2 provide the Attributional Life Cycle Assessment (ALCA) and the Consequential Life Cycle Assessment (CLCA) approach in a General Equilibrium Framework using the National Input-Output Table, respectively. Section 3.3 deals with the incorporation of environmental and human health impact of solar and wind waste generation in the End-of-Life phase using the System of Energy and Environmental Accounting (SEEA) framework.

Over the past few decades, the quantification of the environmental burden of end-products entering the economy has gained importance, primarily due to the involvement of several economic activities across its supply-chain. The examination of material and energy flows across the stages through which the assembly of a product engages, became increasingly relevant with the advent of globalization (Lifset, 2006). The most effective way of finding solutions to reducing the negative environmental burdens through industry-specific interventions was by studying the product's lifecycle.

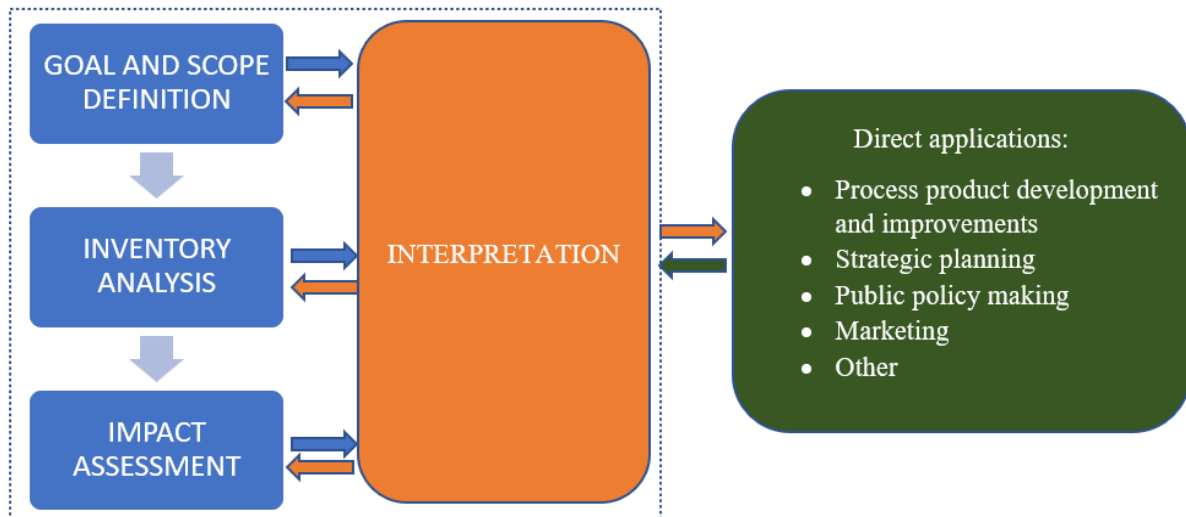
Pursuing an LCA methodology can lead to facing several constraints such as time consuming data collection process, limited data sources, lack of expertise and complexity of the product in question (Fleischer, Kunst, & Rebitzer, 1998; Koffler, et al., 2008; Henriksson, et al., 2015; Kiemel, Rietdorf, Schutzbach, & Miehe, 2022). Several recommendations for streamlining the LCA framework were proposed (Weitz, Todd, Curran, & Malkin, 1995; Curran & Young, 1996) with the most comprehensive and collectively acceptable by all researchers was the development of the LCA standards by the International Organization for Standardization in 1997 (Hauschild, Rosenbaum, & Olsen, 2018; Gradin & Bjorkund, 2021). While there are several definitions for LCA available in the literature, the most comprehensive one is provided by the International Organization of Standardization (ISO) which is given below (ISO, 2006):

“LCA addresses the environmental aspects and potential environmental impacts (e.g. use of resources and the environmental consequences of releases) throughout a product's lifecycle

from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e. cradle-to-grave)”

All LCA studies have a fixed framework and are applied/practiced according to the ISO manual, titled, ‘Environmental management – Life Cycle Assessment – Principles and framework’ (ISO, 2006). This has been presented in Figure 3.1.

Figure 3.1: Life Cycle Assessment framework

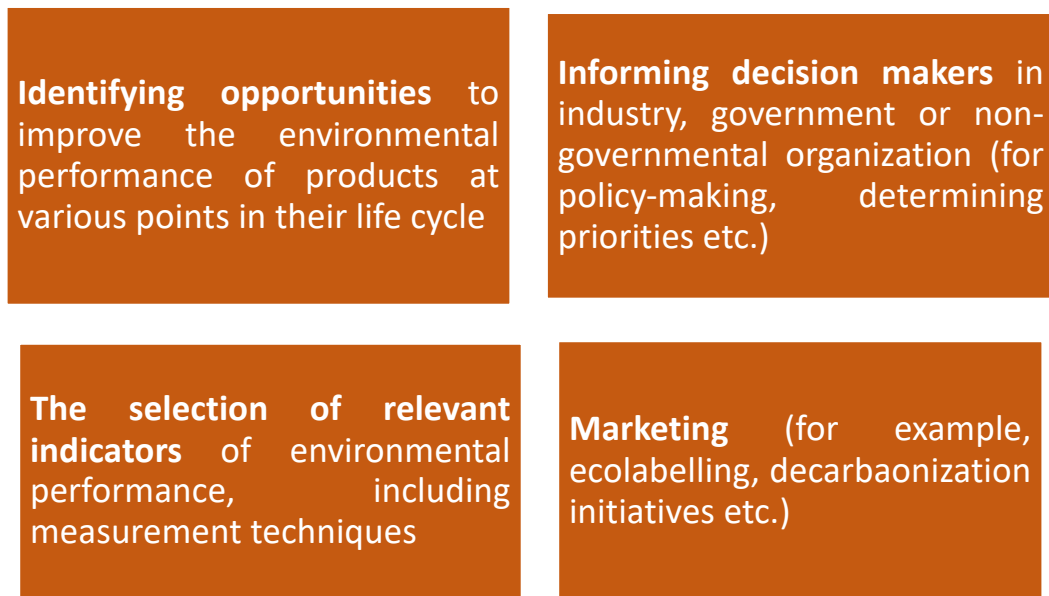


Source: Created by the Author; adopted from ISO, (2006)

- i) Goal and Scope Definition – It establishes the purpose and objective of the study and its intended practice. It defines the system boundary of the study under which the LCA framework will be applied.
- ii) Life Cycle Inventory (LCI) analysis – The input/output inventory data collected and used for the assessment of the product/process/service is provided.
- iii) Life Cycle Impact Assessment (LCIA) – LCIA is the third phase which provides the presentation of the results and its critical review to highlight its environmental significance.
- iv) Life Cycle Interpretation – It is the final phase of the LCA analysis in which the results of the LCIA are summarized, discussed along with its implications towards decision making process. Policy recommendations (if any) are also further highlighted.

The applications of LCA approach is objectively addressed in Figure 3.2.

Figure 3.2: Application of LCA methodology

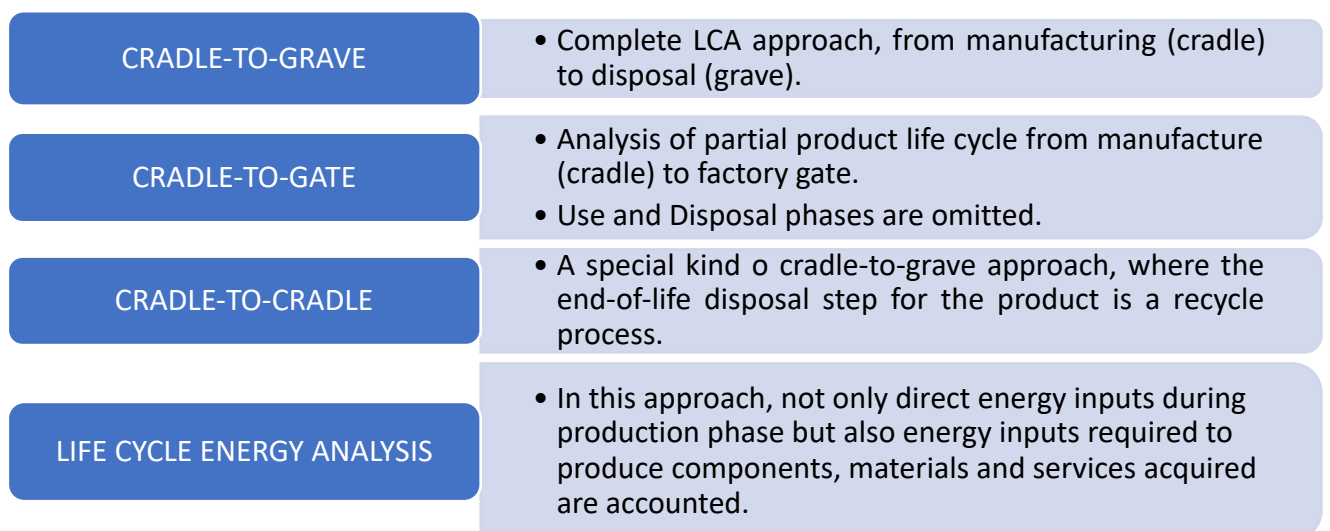


Source: Created by the author; adopted from ISO (2006)

The LCA approach has evolved in its coverage with LCA analysis of products, processes and services (Haque, 2020). It provides scope for comparison and alternatives in the decision-making process, based on a holistic outlook towards environmental aspects (Muralikrishna & Manickam, 2017; Haque, 2020).

The LCA approach can constitute different objectives and as a result, several types of LCAs have been in practice (Figure 3.3)

Figure 3.3: Types of Life Cycle Assessment methodologies



Source: Created by the author; adopted from Muralikrishna & Manickam, (2017)

The Cradle-to-cradle approach, in other words, represents the Circular Economy (CE) framework that is the basis of this study. The LCA approach is complementary in comparing

and evaluating the CE strategies with the aim of improving the environmental and economic performance in a macro framework (UNEP, 2011; Pena, et al., 2021). The LCA analysis provides insights into the potential of the CE solutions and the extent of their applicability. The material and energy efficiency associated with the recovery and reuse of decommissioned products in the end-of-life phase in LCA analysis can aide in choosing the best CE strategies with optimal outcomes (Gallego-Schmid, et al., 2016; Cordella, et al., 2020).

Given the objective and scope of the study, the LCA apporach has two inter-linked branches which form the basis of this study, the ALCA and CLCA frameworks, discussed in sections 3.1 and 3.2, respectively.

3.1 Attributional LCA

ALCA determines the share of the global environmental impact attributed to a product under consideration (Ekwall, 2020). Depending upon the material and energy characteristics of the product, ALCA provides results for not only the emitting potential of the product but also the environmental benefits derived from its deployment. For example, solar PV manufacturing consumes energy with complementary emissions, however, it leads to environmental benefits when compared to emissions from coal-fired power plants. The ALCA study is entirely derived from within the life-cycle and its subsystems with no interaction beyond this system boundary (Finnveden, et al., 2009).

The ALCA of Solar Photovoltaic power and Wind turbines is studied by analysing the energy inputs and subsequent GHG footprint attributed to each of its subsystems within the respective energy source's lifecycle. Several studies elaborated in Chapter 2 focussed on the cradle-to-grave LCA approach, compiling the material and energy inventory across manufacturing to disposal phase for Solar PV (Pacca, Sivaraman & Keoleian 2007; Hsu, et al., 2012; Baharwani et al., 2014; Aristizabal, Sierra and Hernandez 2016; Prabhu, Shrivastava & Mukhopadhyay, 2022) and for Wind energy (Ardente, Beccali, Cellura, & Brano, 2008; Nugent et al., 2014; Haapala and Premreeda 2014; Li et al., 2020; Prabhu & Mukhopadhyay, 2022). Few studies have also attempted the Cradle-to-cradle approach for Solar PV and Wind energy, quantifying the Circular Economy approach through recycle and reuse of decommissioned waste in the EoL phase (Sica et al., 2018; Latunussa et al., 2016; Dominguez & Geyer, 2017; Kim & Park, 2018, Cherrington, et al., 2012; Prabhu, Shrivastava & Mukhopadhyay, 2022; Psomopoulos, Kalkanis, Kaminaris, Ioannidis, & Pachos, 2019; Prabhu & Mukhopadhyay, 2022). An additional component in the ALCA approach that has not been given due attention in the literature is the economic implications and the environmental benefits of adopting recycling

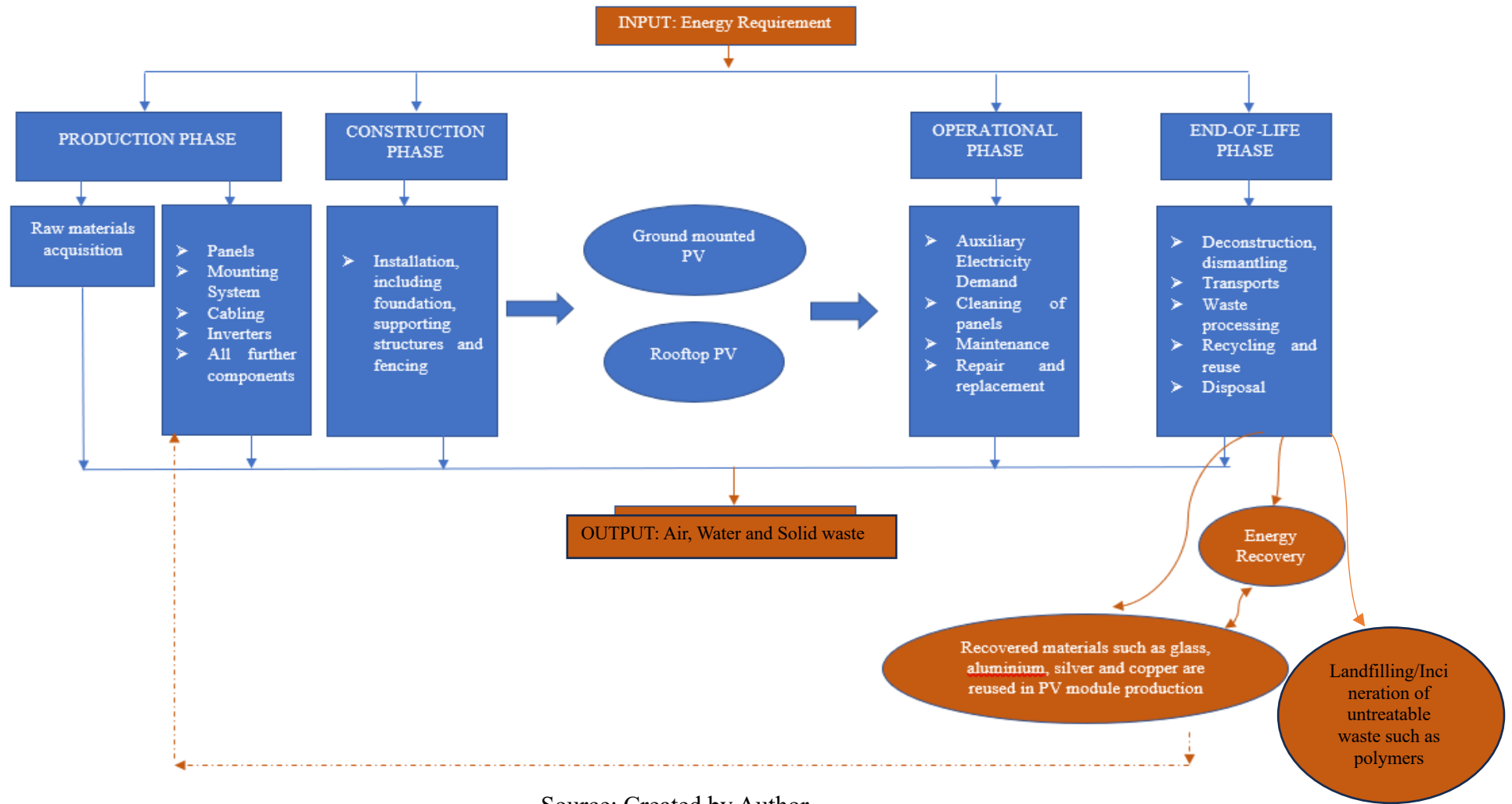
technologies for solar PV modules and wind turbine technologies. Furthermore, the health impact of waste generation in the EoL phase can also be quantified in an CLCA framework. This has been incorporated into the current study.

The system boundaries are defined under which the ALCA analysis is conducted, that is the energy and environmental impact of solar and wind capacity installation across its lifetime. The lifecycle phases include both, the upstream activities of raw material acquisition with the manufacturing phase and construction phase and the downstream activities of the operational phase and End-of-life (EoL) phase (the phase-wise energy and environmental burden for each RES technology is presented in the subsequent chapter on Data construction and sources). In the EoL phase, the decommissioned solar PV and Wind turbine components are dismantled and transported to the recycling units whereas non-recyclable materials are either incinerated or landfilled. The recycling materials are assumed to be reused in the respective industry's manufacturing phase as a result of which the potential energy and environmental benefits gained through the circularity of solar PV modules and wind turbines are measured. Next, the phase-wise discussion for the Solar energy is provided followed by Wind energy.

❖ **Solar Energy**

The attributional and comparative LCA of the two most popular PV technologies, namely, mono-crystalline (mono-Si) PV modules and multi (or poly)-crystalline (multi-Si) PV modules has been considered here. The direct energy and environmental burden across the different phases have been discussed here. Before that, the system boundary and life-cycle flow of Solar PV modules have been presented in Figure 3.4.

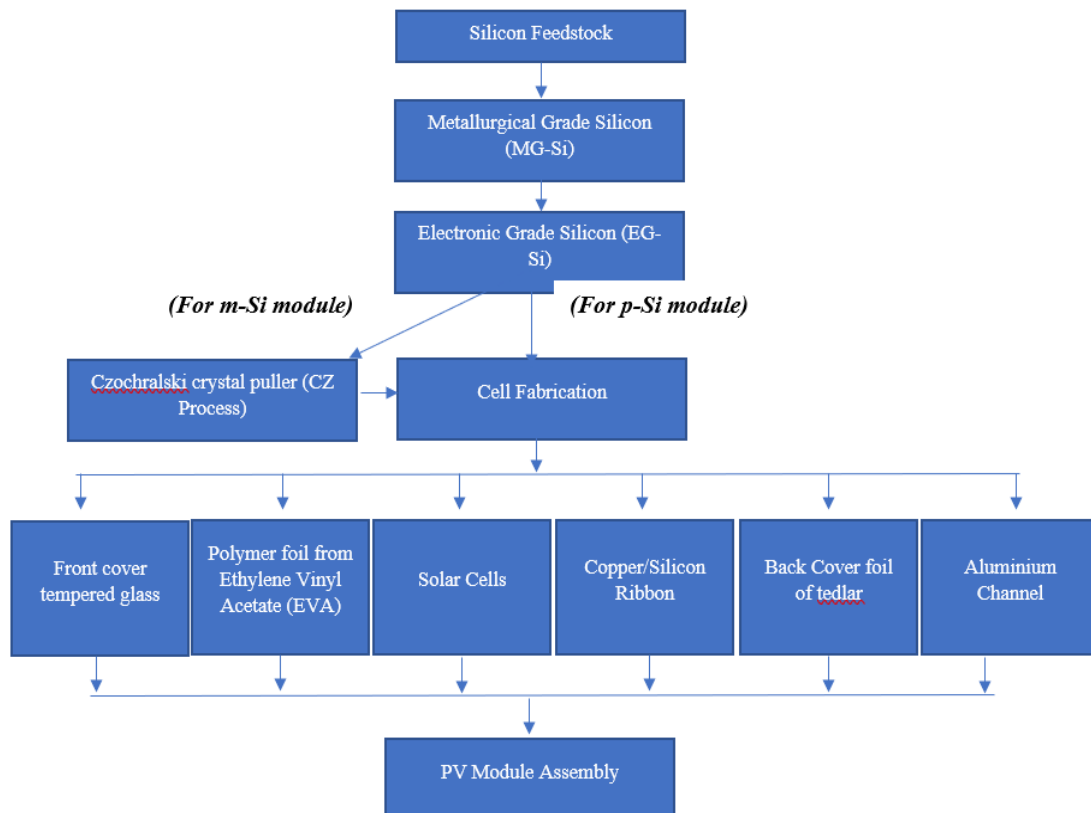
Figure 3.4: A-LCA flow of solar PV in a circular economy framework



i. Production Phase

In this stage, the silicon feedstock is procured as raw materials which then goes through a series of scientific procedures (Nawaz & Tiwari, 2006; Ludin, et al., 2018). First, the Metallurgical-Grade Silicon (MG-Si) is prepared by carbothermic reduction of Silicon-Oxide (SiO₂) or silica from Quartz Sand. Second, the Electronic Grade-Silicon (EG-Si) is produced from MG-Si which is a highly purified version and will be used in silicon wafers. Third, for mono-Si PV, the EG-Si undergoes the highly energy intensive Czochralski Process (Cz process) which operates at temperatures of 1100-1200°C and crystallizes the silicon to form a single crystal ingot of silicon (Nawaz & Tiwari, 2006; Ludin, et al., 2018). On the other hand, the multi-Si PV does not require Cz process, hence its energy requirement is always lower than m-Si PV. Next, the cell fabrication undergoes high temperature diffusion, oxidation and deposition after which the solar cells are interconnected with copper ribbon, encapsulated layer and assembled with aluminium frame and tempered glass to form a PV module. The stepwise procedure for the manufacturing phase which has been observed across all c-Si technology PV modules over the years is shown in Figure 3.5.

Figure 3.5: Stages of Mono-crystalline and Multi-crystalline silicon module manufacturing



Source: (Prabhu, Shrivastava, & Mukhopadhyay, 2022)

Given that c-Si technology modules constitute the highest share of the PV market (Fraunhofer, ISE, 2020), the stages of PV module manufacturing is also expected to be the same for all c-Si module manufacturers. The transformation of metallic silicon into solar silicon and the panel assembling are considered as the most energy intensive steps in the manufacturing of solar panels due to high level of electricity consumption in the former and the use of highly energy-intensive materials like aluminium frame and glass roofing in the latter (Stopatto, 2008).

ii. Construction Phase

The ground-mounted PV, which is installed in large open areas has higher levels of sophistication per kW of PV panel compared to rooftop PV construction, owing to factors such as preparation of foundation, land levelling and fencing. Thus, the energy requirement in general will be higher for ground-mounted PV compared to rooftop PV.

iii. Operational Phase

The operational phase constitutes cleaning of panels, repair or replacement of any electronic/electrical component throughout the PV system's life-cycle. Here again, due to the larger scale of installation and supporting structures for ground-mounted PV, it has higher embodied energy requirements compared to rooftop PV.

iv. End-of-Life phase

The quantification and potential recycling of decommissioned Solar PV modules in the EoL phase have been discussed in detail in the Chapter 2. However, a step-by-step procedure of recycling and prospective cost-benefit analysis for the cumulative PV waste generation in a particular region has not been conducted thus far in varying studies. Furthermore, the differences between c-Si PV modules and thin-film technologies have also been comprehensively elaborated in the previous chapter. This also implies that the recycling technologies and methods also vary by the PV technology under consideration.

As of now, India does not have any regulations for EoL recycling treatment designed specifically for PV waste. In fact, it is only the European Union which has a legislative framework in place for the recycling and disposal of PV waste materials as part of the producers' responsibility (EU, 2012). The EU solar industry has also established 'PV CYCLE', an initiative to study innovative business models to undertake PV recycling systems more efficiently. The Full Recovery End-of-Life Photovoltaic (FRELFP) method, prepared by an Italian PV Waste recycling company, SASIL S.p.A, in collaboration with PV CYCLE is considered to be the most advanced PV recycling system till date, expected to decrease lifetime

environmental impact by 10-15% compared to other recycling methods (Latunussa, Mancini, Blengini, Ardenete, & Pennington, 2016). The EoL treatment of PV waste using the FRELMP method is broadly covered in fifteen steps, demonstrated in Figure 3.6.

Figure 3.6: Steps in c-Si PV module waste treatment based on FRELMP method



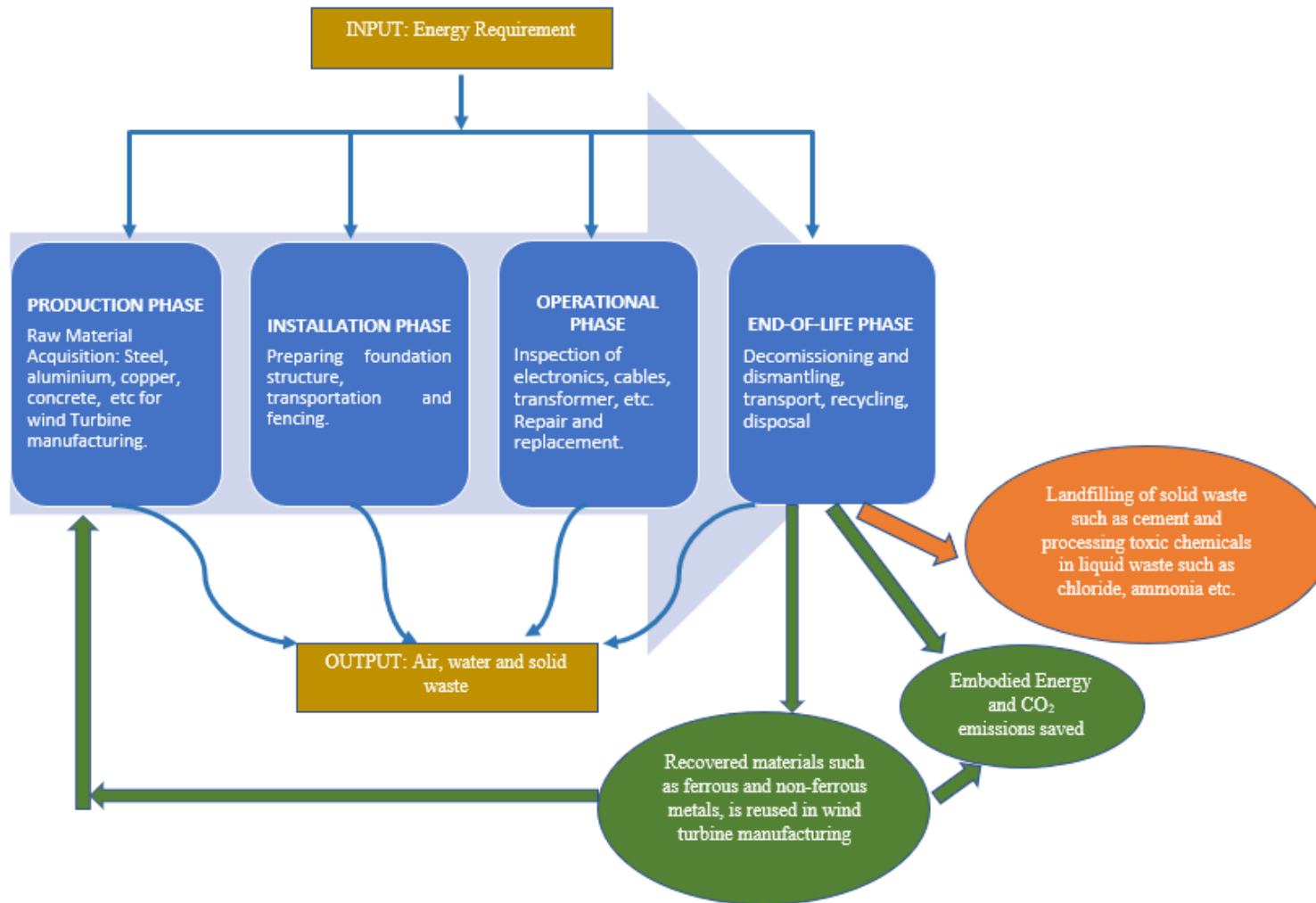
Source: (Prabhu, Shrivastava, & Mukhopadhyay, 2022)

Given the procedure, the embodied energy and avoided GHG emission savings per tonne of PV waste recycling is provided later in the next chapter on Data construction and sources.

❖ **Wind Energy**

For Wind energy, the wind turbine technologies adopted for the LCA studies is not as sophisticated or diverse as has been found for Solar PV technologies in literature. While there are several companies that manufacture wind turbines, using their own unique manufacturing, Operations & Maintenance (O&M) standards, the embodied energy and GHG emissions largely remain the same and will be presented in the next chapter on data construction and sources. The system boundaries of Wind turbines is presented in Figure 3.7.

Figure 3.7: A-LCA flow for wind energy in a circular economy framework



Source: Created by author

The activities involved in the production, installation and operations phases is similar to the one already discussed earlier for the Solar PV technologies, but with its application for wind turbines. The phase-wise embodied energy and GHG emission across its lifetime will be captured. For the End-of-life phase, it has already been established in chapter 2, that currently there is no large-scale turbine recycling technology existing in the world. However, there have been ongoing research at the laboratory scale, projecting the expected costs and the inputs required in recycling decommissioned wind turbines. However, the other components of wind turbines constituting various ferrous and non-ferrous metals have high potential of recycle and reuse in the economy which has been proposed here. A cost-benefit analysis of the recycling and resale of recovered materials has been conducted in this study (The assumptions and data compilation is discussed further in the next chapter).

Given the phase-wise physical energy flows and environmental GHG footprint measured in the ALCA for the respective RES technologies, the LCA parameters considered for evaluating the energy and environmental burden is elaborated here.

❖ LCA Parameters

The parameters considered in this section include Capacity Utilization Factor (CUF), Energy Payback Time (EPBT) and Energy Return On Investment (EROI).

i. *Capacity Utilisation Factor (CUF)*

The CUF is calculated at the all-India level based on the ratio of the actual electricity generated by the total plant capacity operational for the maximum no. of hours (24) throughout the year (365 days). The CUF is calculated as follows:

$$CUF = \frac{\text{Actual Electricity Generation (GWh)}}{\text{Potential Electricity Generation (GWh)}} \dots \text{Eq. (3.1)}$$

Source: (Prabhu & Mukhopadhyay, 2022)

ii. *Energy Payback Time (EPBT)*

The calculation of EPBT⁴ is different for solar PV and Wind energy which is attributed to the technical differences between the two energy sources. For solar PV it is calculated as follows:

$$EPBT \text{ (years)} = \frac{CED}{(E_{agen}/\eta_G) - E_{O\&M}} \dots \text{Eq. (3.2)}$$

Source: (Gupta, 2018)

⁴ EPBT is the time period required to recover the energy consumed throughout its lifetime through electricity generation.

Where,

CED: Cumulative Energy Demand of a PV system, calculated as a sum of the embodied energy starting from raw materials extraction up to construction and decommissioning phase.

E_{gen} : Annual electricity generation, given by Eq. 3.3

$$E_{gen} = irradiation \times performance\ ratio \times module\ efficiency \dots Eq. (3.3)$$

Source: (Gupta, 2018)

$E_{O\&M}$: Embodied Energy for Operational Phase

η_G : Conversion efficiency, i.e. the average life-cycle primary energy to electricity conversion at the demand side. It is assumed to be 20% (Gupta, 2018).

For wind energy, the EPBT is calculated as follows,

$$EPBT = \frac{\text{Embodied energy requirement for onshore wind (GWh)}}{\text{Annual Electricity output from onshore wind (GWh)}}$$

Source: (Marimuthu & Kirubakaran, 2013)

iii. *Energy Return on Investment (EROI)*

Based on the EPBT estimate, the energy return on investment provides an evaluation of the long-term viability of onshore wind by looking at the overall energy performance over its entire lifetime⁵. It is calculated as follows:

$$EROI = \frac{\text{lifetime}}{EPBT}$$

Source: (Kubiszewski, Cleveland, & Endres, 2009)

In the next sub-section, the Consequential LCA framework using an Input-Output model has been discussed.

3.2 Consequential LCA

3.2.1 The Basic Input-Output Model

In the input-output framework, the economy is divided into sectors and the flow of goods and services among these sectors are recorded to study their relationship in a systematic and

⁵ EROI is defined as the ratio of the usable energy returned during a system's operating life, to all the energy needed to make this energy usable

quantitative manner (Miller & Blair, 2009; Chakraborty & Mukhopadhyay, 2014; Sengupta & Mukhopadhyay, 2016).

For the rectangular Indian Supply-Use Table 2018-19 which has been adjusted to the incorporate the splitting of the industries (discussed in detail in the next sub-section 3.3.2), the ‘commodity-by-commodity’ technology assumption is applied (UN, 2009 & 2018). The accounting equations are as follows:

$$q = Bx + e \dots \quad \text{Eq. (3.1)}$$

where B is represented as follows:

$$b_{ij} = \frac{z_{ij}}{x_j} \dots \quad \text{Eq. (3.2)}$$

In which,

z_{ij} = value of input from industry ‘i’, required to produce one unit of output in industry ‘j’.

x_j = Total output of industry ‘j’.

b_{ij} = Input-output technical coefficients.

q = $n \times 1$ vector of values of total commodity output (in which ‘n’ signifies number of sectors).

B = $n \times n$ matrix of input-output technical coefficients representing value of inputs of each commodity per Rupee worth of industry j’s output.

x = $n \times 1$ vector of output

e = $n \times 1$ vector of final demand (less imports)

In Equation (1), B relates to output levels of industries to intermediate demand for commodities. Commodity output levels are further related by the market shares equation,

$$x = Dq \dots \quad \text{Eq. (3.3)}$$

Where,

D = $n \times n$ matrix of market share coefficients.

Substituting Equation (3.3) in (3.1),

$$q = BDq + e \dots \quad \text{Eq. (3.4)}$$

which has the solution,

$$q = (I - BD)^{-1}e \dots \quad \text{Eq. (3.5)}$$

The inverse on the right-hand side in Eq. (5) is called the commodity-by-commodity total requirements matrix which connects commodity final demand to commodity output (UN, 2018).

3.2.2 Modified Input-Output Model

- **Incorporating RE sectors in the IO model**

In the IO table, the electricity sector is not categorised by the source of power generation. For this study, the IO table has been modified by splitting the electricity sector into ‘Solar energy’, ‘Wind energy’ and ‘Other electricity sources’. Due to the unavailability of information on the sector-wise electricity consumption, transmission and distribution of electricity by source either in physical units or in monetary terms, the output flow from the aforementioned three electricity sectors has been determined based on the existing share of power generation from the solar (2.53%), wind (4.1%) and other electricity sources (93.6%) in 2018-19 (Niti Aayog, 2021). Furthermore, the Indian SUT does not distinguish between the three electricity components, namely generation, transmission and distribution as they are subsumed within the electricity sector in the original SUT and by energy source in the modified SUT.

- **Preparation of RE solid waste abatement sector in the Indian IO structure**

The cost of solar photovoltaics and wind turbine recycling at the End-of-Lifetime (EoL) is attributed to the ‘RE waste abatement sector’ which is a new sector added in the model. The impact of solid waste recycling on the economy resulting from the additional monetary burden is estimated using the modified monetary IO model.

As a result of the inclusion of the solar, wind and RE waste abatement sectors, the B and D matrices in equations (1) to (5) are revised accordingly with the addition of the aforementioned sectors.

3.2.3 Updating the Final Demand Vector to 2030

Prior to the preparation of different scenarios for simulation exercises, due attention was given in updating the final demand vector⁶ to 2030 using the sector-wise forecasts provided by the E3-India model (Mukhopadhyay, 2021). The E3-India model is an impact assessment tool used to simulate the effects of economic and energy policy at the regional and national level in India. It is developed in accordance with the internationally recognized E3ME global modelling framework (Pollitt, 2021). The model is based on the Keynes–Leontief–Klein framework, which is a macro-econometric dynamic simulation model integrating the macroeconomic parameters and sectoral behaviour of the economy (Mukhopadhyay and Chewpreecha, 2021). The five key dimensions of the E3-India model are provided in Figure 3.8.

⁶ Final demand vector implies the GDP components – Private Consumption, Government Consumption, Investment, Net Exports

Figure 3.8: E3-India model dimensions

<p>Detailed Coverage</p> <ul style="list-style-type: none"> • 32 Indian states and territories • 39 economic sectors • 21 users of 5 different energy carriers • CO₂ emissions by 21 users 	<p>Comprehensive</p> <ul style="list-style-type: none"> • whole energy, environment and economy system • two ways feedbacks between each module • many policy instruments 	<p>Highly Empirical</p> <ul style="list-style-type: none"> • 16 sets of econometric equations • accounting identities • database 1993-2016
<p>Consistent</p> <ul style="list-style-type: none"> • based on system of national accounting • input-output tables 	<p>Forward Looking</p> <ul style="list-style-type: none"> • annual projections to 2035 • behavioural equations with effects from previous outcomes • ex-ante scenario analysis (ex-post is also feasible) 	<p>Modular</p> <ul style="list-style-type: none"> • E3: Energy, Environment, Economy • power generation sub-module (FTT-Power) • research can be decentralised

Source: (Cambridge Econometrics, 2020)

Unlike the more common Computable General Equilibrium (CGE) approach to economic modelling, E3-India does not assume full employment or perfectly competitive markets; instead, it estimates behaviour based on available historical data. The econometric pedigree and empirical grounding of the model makes it better able to represent performance in the short to medium term, as well as providing long-term assessments without being too reliant on rigid assumptions. A non-linear interaction between the economy, energy demand/supply and environmental emissions is a significant advantage over other models (Cambridge Econometrics, 2020).

The forecasts by the model are based on the energy source used for electricity production and to this end, E3-India provides a comprehensive treatment of the electricity sector, which is called the Future Technology Transformation (FTT) (Pollitt, 2021). FTT Power is a bottom-up model of technology diffusion across 24 power sector technologies (Table A2 in the Appendix). The model was originally built with core features by Cambridge macroeconomic models, based on E3ME (CE, 2023). The model provides a framework for the dynamic selection and

diffusion of innovations, which in E3-India is applied to the power sector in each Indian state. FTT adopts the pairwise differential equations to establish relationship between the different technologies that shows rates of substitution between each technology using determining factors, namely, existing market share of new technology, cost, and ease of transition etc.

Given the characteristics of the model, the sector-wise growth rates between 2019-30 are considered and are mapped with the Indian Supply-Use Table Commodities for projecting the final demand vector till 2030 (The discussion on the Indian SUT is elaborated in the next chapter).

3.3 The Environmental impact of substituting coal-fired TPPs by RE sectors

The coal-fired TPPs generate GHG emissions – CO₂, NO_x, CH₄ and local air pollution – SO_x, PM₁₀, Mercury (Hg) and Fly Ash which is harmful not only to the environment, but to human health as well. The negative environmental impact which is offset by RE transition in different scenarios is quantified. Simultaneously, the external (environment and health) cost avoided through phasing down of coal-power capacity installation is estimated and utilized to determine the net benefit/loss in the economy.

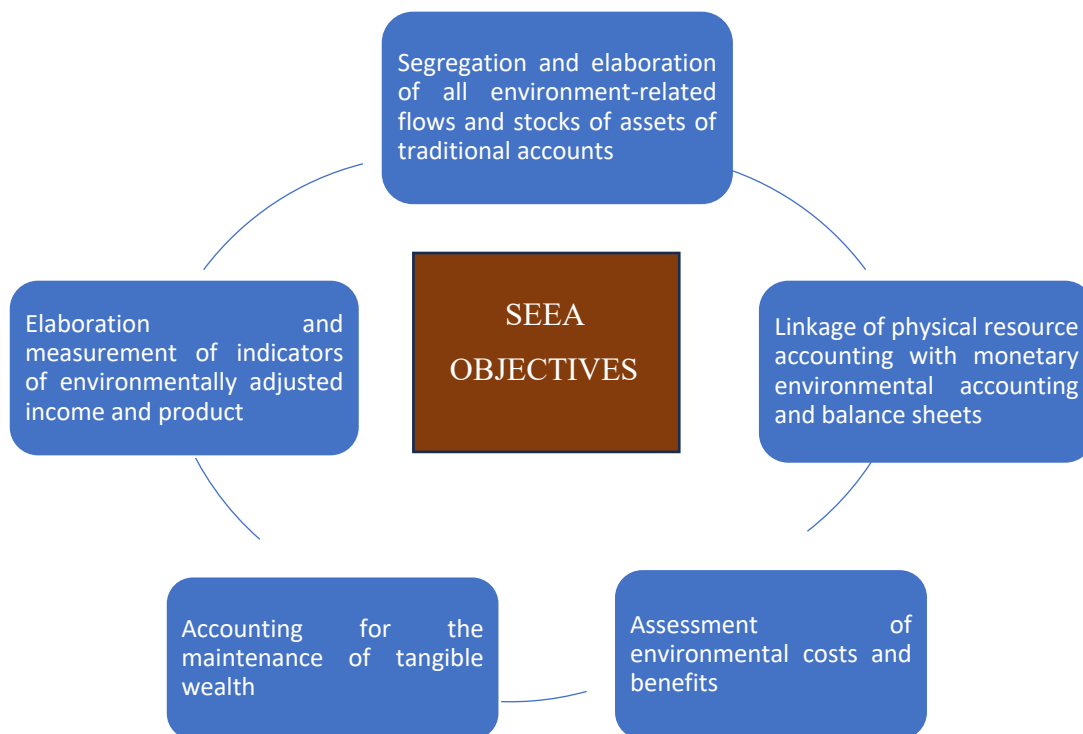
On the other hand, a higher rate of solar and wind capacity installation is expected to generate a significant amount of solar Photovoltaic (PV) and wind turbine waste by the end of their lifetimes. Unlike coal power-plants which can operate for more than half a century, solar PV and wind turbines have a lifespan of 25-30 years (Patel, 2018; Rajput, Tiwari, Sastry, Bora, & Sharma, 2016) and 20 years (Mali & Garrett, 2022), respectively. To this end, significant amount of waste is expected to be generated along with the steep 2030 capacity targets in the long run. The waste, if left untreated can lead to serious environmental and human health hazards which can be avoided through the adoption of proper recycling technologies (Suresh, Singhvi, & Rustagi, 2019). The data for cost estimation are discussed in detail in the next chapter.

3.3.1 Green-GDP estimate

In 1984, a global consensus for developing environmentally extended national accounts was reached and 900 days later was comprehensively articulated in the Brundtland Commission report, published in 1987. By questioning the macroeconomic framework for policymaking, the report addressed the issues at the intersection of resources, environment, economy and military expenditures. Here, for the first time, the term Sustainable Development was formally defined – development that meets the needs of the present without compromising the ability of future generations to meet their own needs (UN, 1987).

The report was debated in the UN General Assembly in 1989. The outcome of the discussion on the landmark report was the need to develop a ‘Satellite System of Integrated Environmental and Economic Accounting (SEEA), compatible with the System of National Accounts (SNA) (Bartelmus, Stahmer, & van Tongeren, 1991). The structure of SEEA emphasised the following objectives (Figure 3.9):

Figure 3.9: SEEA Objectives



Source: Author’s delineation

The efforts towards an internationally accepted handbook of environmental accounting were further strengthened through the adoption of Agenda 21 in the UN Conference on Environment & Development 1992 in Rio de Janeiro. The objective was clearly stated in paragraph 8.42:

‘The main objective is to expand existing systems of national economic accounts in order to integrate environment and social dimensions in the accounting framework, including at least satellite systems of accounts for natural resources in all member States. The resulting systems of integrated environmental and economic accounting (IEEA) to be established in all member States at the earliest date should be seen as a complement to, rather than a substitute for, traditional national accounting practices for the foreseeable future. IEEAs would be designed to play an integral part in the national development decision-making process’

One year later, the System of Environmental and Economic Accounting (SEEA), 1993 was published and was deemed to be the first comprehensive response towards the existing structure of GDP and national accounting. During the early 1990s, the countries that contributed to this effort were, Australia, Canada, Denmark, Finland, Germany, Indonesia, Italy, Japan, the Netherlands, the Philippines, Sweden and the United Kingdom (Smith, 2007). The individual country efforts vary conceptually and empirically owing to the varied environmental challenges and diverse expertise employed for the statistical evaluations. As a result, only a few countries such as Germany and Japan took the initiatives to align their national accounts with the SEEA framework, whereas rest of the countries continued to focus on their own national environmental priorities.

While the landmark contribution of SEEA (1993) was the inclusion of some natural resources within the asset boundary of the system (land, water, air, biota and related ecosystems), there were several gaps that still existed. These included, lack of accounting for the net losses from emissions resulting from economic activity and does not include natural capital within the asset boundary (Smith, 2007). As a result, in 1998, the London Group of Environmental Accounting undertook the initiative of reviewing the SEEA 1993 and explore the prospects of its global adoption which was lacking since its publication (Smith, 2007; Bartelmus, 2014). The result of the group was a revised accounting framework approved by the United Nations Statistical Commission in 2003 – SEEA (2003). The SEEA (2003) handbook made landmark breakthroughs on three fronts. 1) The physical and hybrid flow accounts – The material and energy flows accounting provides insights into the significance of an industry's usage of resources in physical terms, which can be in stark contrast to its determination in monetary value. Accounting for the physical and material attribution to an industry's economic activity also contributes towards monetising the consequent environmental degradation. 2) Environmental protection and management accounts – The explicit contribution of environment-related transactions such as investments in pollution control technologies (PCT), natural resource conservation etc. is accounted. The benefits and costs incurred through curbing the incremental human health and environment impact can be addressed using this framework. The monetisation of this degradation is undertaken through i) structural adjustment costs, ii) abatement costs and iii) restoration costs. 3) It is structured in four broad categories – i) physical flow of materials, ii) environmental protection expenditure, iii) physical and monetary accounting of environmental assets, iv) environmentally modified macro-aggregates. The framework provides a methodology for the valuation of the natural capital depletion (economic

value of quantity reduction in a natural resource) and degradation (economic value of quality reduction in a natural resource), which is termed as ‘green accounting’ (Dietz & Neumayer, 2007).

This study aims to estimate the Environmentally adjusted GDP or ‘Green GDP’, which is a modified GDP figure, adjusted for the environmental costs of economic activities, using the SEEA framework (Chakraborty & Mukhopadhyay, 2014). Conducive to the national accounting structure, the United Nations Statistical Division published the *SEEA* framework for the first time in 1993, with periodic updates leading to the SEEA (2012) being the latest version which is adopted in this study. The evolution of SEEA framework has come a long way since its inception in 1993. One of key developments in SEEA 2012, compared to the SEEA 1993 accounts is the inclusion of not only the physical assets such as land, water, air and related ecosystems, but also including the by-products generated from human activities such as pollutants and waste disposal to nature (Bartelmus, 2014). The SEEA 2012 framework also incorporates the material inputs and outputs in Material Flow Accounts (MFA).

The SEEA stock and flow accounting framework is provided in Table 3.1.

Table 3.1: SEEA flow and stock accounts with environmental assets

Sr. no.		Domestic production	Final cons. (households, govt.)	Capital formation	Rest of the world
1	Supply of products	i) Other sectors output			Imports (M)
		ii) Environmental sectors output			
2	Use of products (intermediate cons.)	i) Other sectors output	i) Other sectors final consumption	i) Gross capital formation of other sectors (GCF1)	Exports (X)
		ii) Environmental sectors output	ii) Environmental sectors final consumption	ii) Gross capital formation of environmental sectors (GCF2)	
3	Use of fixed capital	Fixed capital cons. Of other sectors (CC)		Capital consumption (CC)	
4	Value added (VA/NDP)	$NVA = O - IC - CC$			
		$NDP = \sum NVA$			
5	Use of natural assets (depletion and degradation and defensive expenditure)	Environmental cost of industries defensive expenditure (EC1) + loss of production (EC2)	Environmental cost of household (Ech)	Natural capital consumption $EC = EC1 + EC2$	
	Environmental-adjusted indicators	$EVA = NVA - EC$		$ECF = (CF - CC) - EC$	
		$EDP = \sum EVA - Ech$			

Source: (Chakraborty & Mukhopadhyay, 2014)

The accounting identities in the SEEA framework are presented in the following way (equations 3.6 to 3.9) (Chakraborty & Mukhopadhyay, 2014):

1) Supply use identity

$$O + M = IC + C + CF + X \quad \dots \quad \text{Eq. (3.6)}$$

where,

O is the supply of goods and services produced by different sectors

M is the imported goods and services used in intermediate consumption

C is the final consumption

CF and X are the Capital Formation and Exports, respectively

IC: Intermediate Consumption

2) Value added (environmentally adjusted) identity for different sectors:

$$EVA = O - IC - CC - EC = NVA - EC \quad \dots \quad \text{Eq. (3.7)}$$

where,

EVA is the environmentally adjusted value added of industries

CC is the fixed capital consumption

EC is the environmental depletion and degradation costs

NVA is the Net Value Added of industries

3) Domestic-product identity (environmentally adjusted) for the whole economy

$$EDP = \sum EVA - ECh = NDP - EC = C + CF - CC + X - M \quad \dots \quad \text{Eq. (3.8)}$$

where,

EDP is the environmentally adjusted net domestic product

ECh is the environmental costs generated by household

The estimates for health cost incurred by the households and the environmental cost of mining and the agricultural impact due to reduced insolation due to coal power generation is used to estimate the Green GDP in different scenarios. The SEEA framework is in monetary terms which is directly linked to the modified SUT components which is also in monetary terms. The GHG and non-GHG emissions which is in physical units is converted into monetary terms to be incorporated in the SEEA framework to account for the environmental and human health cost. This is discussed in detail in the next chapter on data construction and sources.

To summarize this chapter, the Attributional LCA framework for Solar and Wind energy has been discussed. In the Consequential LCA framework, the application of the Indian supply use table that is used to prepare a modified Indian Input-Output table by the inclusion of Solar and Wind energy sectors as well as the RE abatement sector for recycling has been elaborated. Furthermore, the contribution towards environmental impact of GHG emissions from coal-fired power plants along with the recycling of RES technologies in the End-of-life phase is quantified and analysed using the Green-GDP estimation through the SEEA framework.

CHAPTER 4 DATA CONSTRUCTION AND SOURCES

In this chapter, first, a detailed compilation of the data sources adopted for this study has been provided in sections 4.1 and 4.2. Section 4.3 constitutes the Scenario Development discussion in which different baseline electricity generation and capacity mix projections by 2030 provided by the apex governing body – Central Electricity Authority (CEA), Ministry of Power, Government of India as well as national/international research organisations undertaking modelling exercises for identifying the long-term optimal electricity generation mix, are considered in this study. Given the Indian government's challenge of meeting the rising energy demand without compromising the nation's economic growth, two scenarios are proposed.

4.1 Data Compilation for A-LCA

4.1.1 Solar Energy

For this analysis, the total effective area of a 1 kW mono-Si or multi-Si PV system is assumed to be 10m² (Nawaz & Tiwari, 2006; Home Scape, 2019). Some of the harmonized characteristics defined for the purpose of this analysis are given below,

- i. Solar irradiation – The amount of energy received from the sun per unit area of solar PV panels is assumed to be 1700 kWh/m²/year in India (World Bank, 2018).
- ii. Performance ratio – The ratio of the actual electrical energy generated by the PV plant to the theoretically possible electrical energy generated by the PV plant is assumed to be 0.75 in India (Hsu, et al., 2012).
- iii. Module efficiency –The percentage of sunlight on the panel that is converted into electricity is assumed to be 14% for m-Si and 13.2% for p-Si PV technology in India (Yue, You, & Darling, 2014).
- iv. Lifetime – The c-Si based technology used in m-Si and p-Si technologies have a lifetime of approximately 30 and 25 years, respectively in India (Rajput, et al., 2016; Patel, 2018).

Given this context and the phase-wise energy consumption discussion in section 3.1 for solar PV modules, the embodied energy per KW c-Si ground-mounted and rooftop mono-Si and multi-Si PV modules is provided in Table 4.1.

Table 4.1: Phase-wise embodied energy ground-mounted and rooftop m-Si and p-Si PV modules

Sr. no.	Stages	Ground-mounted PV		Rooftop PV		Unit
		m-Si	p-Si	m-Si	p-Si	
1.	Raw material acquisition phase	569324				kWh/tonne
	Glass	4160				
	Aluminium	43055				
	Copper	27				
	Polymer based adhesive	17361				
	Polyvinyl fluoride	88055				
	Silver	416666				
2.	Production Phase	1083	836	1083	836	kWh/m²
	Silicon Feedstock	342	340	342	340	
	Czochralski Process	399	0	399	0	
	Wafer Process	85	183	85	183	
	Cell production	86	94	86	94	
	Module Assembly	171	219	171	219	
3.	Construction Phase	533	533	233	233	kWh/m²
	Foundation and Support structure	500	500	200	200	
	Inverter	33	33	33	33	
4.	Operational Phase	155	155	125	125	kWh/m²
	Overall Operation & Maintenance, electronic components, cables and miscellaneous, etc.	155	155	125	125	
5.	End-of-Life Phase	113.6				kWh/tonne

Source: (Nawaz & Tiwari, 2006; Wong, Royapoor, & Chan, 2016)

For the EoL treatment, the quantity and type of PV module waste expected to be generated is to be estimated first. Given that the 1 MW of PV module weighs approximately 69.2 kgs (EU-TCP India, 2021), the material composition of PV modules is presented in Table 4.2.

Table 4.2: Material Composition per KW of c-Si PV modules

Sr. No.	Particulars	Weight (in kgs)	As % of total	Recycling rates (in %)
1	Glass	48.5	70.0%	90%
2	Aluminium frame	12.5	18.0%	76%
3	Copper connector	0.7	1.0%	43.8%
4	Polymer-based adhesive (EVA) encapsulation layer (from cables)	3.5	5.10%	
5	Back-sheet layer (based on polyvinyl fluoride)	1.0	1.5%	
6	Silicon metal solar cell	2.5	3.7%	
7	Silver	0.04	0.053%	94.3%
8	Aluminium, internal conductor	0.4	0.53%	76%
9	Copper, internal conductor	0.1	0.1%	43.8%

10	Various metal (tin, lead)	0.0	0.1%	
11	Total	69.2	100%	

Source: (Lunardi, Alvarez-Gaitan, Bilbao, & Corkish, 2018; Latunussa, Mancini, Blengini, Ardente, & Pennington, 2016; UNEP, 2011; IAI, 2023)

It is observed that glass constitutes 70% of total materials used in the production of PV modules that will be converted to waste in the EoL phase. Approximately 90% of glass can be recycled and reused in the economy along with 76% of aluminium and 43.8% of copper.

4.1.2 Wind Energy

For this study, the latest technologically advanced wind turbine with a lifespan of 20 years has been referred⁷ (Mali & Garrett, 2022). Vestas constitutes the third largest share in wind turbine manufacturing in India (11%) in 2019 (Jaganmohan, 2021). Vestas Wind systems is the only wind turbine manufacturer that publishes periodic LCA studies of its wind turbines. As a result, several academic papers have referred to Vestas turbine life cycle inventory datasets to establish their LCA analysis at the global level (Lee, Tzeng, & Su, 2006; Gomaa, Rezk, Mustafa, & Al-Dhaifallah, 2019; Garrett & Ronde, 2013; Haapala & Prempreeda, 2014; Cousins, Suzuki, Murray, Samaniuk, & Stebner, 2019; Jensen, 2018) and in the Indian context (Das & Banerjee, 2018; Marimuthu & Kirubakaran, 2013; Cherrington, et al., 2012; Prabhu & Mukhopadhyay, 2022). Das & Banerjee, (2018) also show through their study that there is minimal difference between the LCA results from wind turbines of two different manufacturers across different lifecycle phases, except in the EoL phase which depends on the assumptions made regarding the recycling technology. Thus, the LCA results from the adoption of a single turbine manufacturer for our study at the macro level do not undermine the results as the wind energy portfolio with different manufacturers is also expected to resemble similar results.

The per unit energy requirement across different phases of wind energy is presented in Table 4.3 here.

⁷ V150-4.2 MW Vestas wind turbines.

Table 4.3: Phase-wise embodied energy per KW of wind capacity

Sr. no.	Stages	Wind Turbines (kWh/kW)
1.	Raw material acquisition and production phase	1469.6
2.	Construction Phase	226.7
3.	Operational Phase	275.3
4.	End of Life Phase	84.2
5.	Total	2055.8

Source: (Gomaa, Rezk, Mustafa, & Al-Dhaifallah, 2019)

The energy consumption across different phases also leads to complementary air and water pollution and waste as by-products which are disposed of in the environment. The air, water and solid waste generation per kWh attributed to each phase is presented in Table 4.4.

Table 4.4: Air, water and solid waste generation per kWh of electricity generation per turbine (mg per kWh)

Sr. no.	Particulars	Turbine Manufacturing	Construction			Operation	Total
			Foundations	Site parts	Set up		
I	Stockpile goods	428.4	135.7	25.5	0.9	49.1	639.6
1	Slag (deposited)	0.0	0.0	0.1	0.0	0.0	0.1
2	Spoil (deposited)	0.0	42.0	0.4	0.6	0.2	43.2
3	Waste (deposited)	11.5	11.4	2.5	0.1	-0.3	25.2
II	Emissions to air	2788.8	432.6	177.7	41.9	194.9	3635.8
II(i)	Inorganic emissions to air	2137.8	370.0	145.7	41.5	150.4	2845.4
1	Carbon dioxide	351.5	72.7	12.7	2.6	15.5	455.0
2	Carbon dioxide (biotic)	10.8	3.4	0.1	0.0	1.0	15.4
3	Carbon dioxide (land use change)	0.4	0.1	0.006	0.036	0.0	0.5
4	Carbon monoxide	1.9	0.4	0.033	0.015	0.1	2.5
5	Nitrogen (atmospheric nitrogen)	8.8	0.0	0.013	0.000	0.1	8.9
6	Nitrogen oxides	0.9	0.1	0.022	0.026	0.0	1.1
7	Oxygen	1.1	0.1	0.012	0.001	0.1	1.3
8	Sulphur dioxide	0.7	0.1	0.040	0.003	0.0	0.9
9	Water (evapotranspiration)	1058.4	206.2	11.8	38.4	96.6	1411.5
10	Water vapour	705.6	86.5	120.5	0.4	37.3	950.3
II(ii)	Organic emissions to air (group VOC)	1.0	0.1	0.1	0.0	0.0	1.3
III	Emissions to fresh water	314160.0	19740.0	108780.0	158.8	13860.0	456698.8
III(i)	Analytical measures to fresh water	0.2	0.0	0.0	0.0	0.0	0.19402
III(ii)	Heavy metals to water	0.1	0.0	0.0	0.0	0.0	0.07273
1	Iron	0.058380	0.009198	0.000714	0.000015	0.003377	0.07168
2	Lead	0.000045	0.000004	0.000002	0.000001	0.000004	0.00006
3	Manganese	0.000132	0.000019	0.000004	0.000000	0.000006	0.00016
4	Molybdenum	0.000040	0.000004	0.000001	0.000000	0.000002	0.00005

5	Nickel	0.000054	0.000008	0.000002	0.000002	0.000004	0.00007
IV(iii)	Inorganic emissions to fresh water	6.6	0.4	0.1	0.1	0.2	7.4
1	Acid (calculated as H ⁺)	0.00101	0.00002	0.00076	0.00002	0.00001	0.00182
2	Aluminium	0.00039	0.00003	0.00003	0.00000	0.00002	0.000478
3	Ammonia	0.00017	0.00001	0.00001	0.00000	0.00001	0.000201
4	Barium	0.00037	0.00005	0.00001	0.00002	0.00003	0.000486
5	Carbonate	0.04036	0.00011	0.00098	0.00142	0.00020	0.043070

Source: (Mali & Garrett, 2022)

For the End-of-Life phase, first we quantify the cumulative waste expected to be generated per KW wind turbines. This has been provided below in Table 4.5.

Fonte & Xydis, (2021) reviewed and quantified the monetary cost across different segments of onshore wind recycling technologies.

Table 4.5: Material composition per KW wind capacity

Sr. no.	Material classification	In kgs	As % of total	Recycling Rates
1	Steel and iron materials	171	25.1%	52%
2	Lights alloys, cast and wrought alloys	3.3	0.5%	76%
3	Non-ferrous heavy metals, cast and wrought alloys	1.4	0.2%	45%
4	Polymer materials	8	1.2%	
5	Other materials and material compounds (concrete, ceramic/glass)	493.4	72.5%	
6	Electronics / electrics	0.9	0.1%	
7	Lubricants and liquids	0.49	0.1%	
8	Not specified	1.9	0.3%	
9	Total mass	680.3	100%	

Source: Mali & Garret, (2022); IAI, (2023); UNEP, (2011)

It is observed that almost 75% of total material composition is attributed to ‘Other material compounds’ which largely constitute cement/concrete. It is an important component that forms the foundation structure on which the wind turbines are installed. Furthermore, there are three components of wind turbines that constitute steel, copper and aluminium which can be recovered, recycled and reused in the economy. On the other hand, polymer materials which constitute plastic and chemical compounds may have to be incinerated, while concrete/ceramic may have to be landfilled, since they cannot be reused.

In the next sub-section, the data discussion related to the Consequential LCA analysis using Input-Output tables is presented.

4.2 Consequential LCA

4.2.1 Indian Supply and Use Tables

The Indian rectangular Supply-Use Table (SUT) 2018-19 constitutes 140 commodities and 66 industries and is published by the Ministry of Statistics and Programme Implementation (MOSPI), Government of India (GOI, 2022). The 140-sector classification of products in the SUT is based on the National Product Classification for Manufacturing Sector (NPCMS) used in the Annual Survey of Industries (ASI), comprising 29 products of Agriculture and allied, 11 sectors of Mining, 72 sectors for manufacturing and 28 sectors for Services.

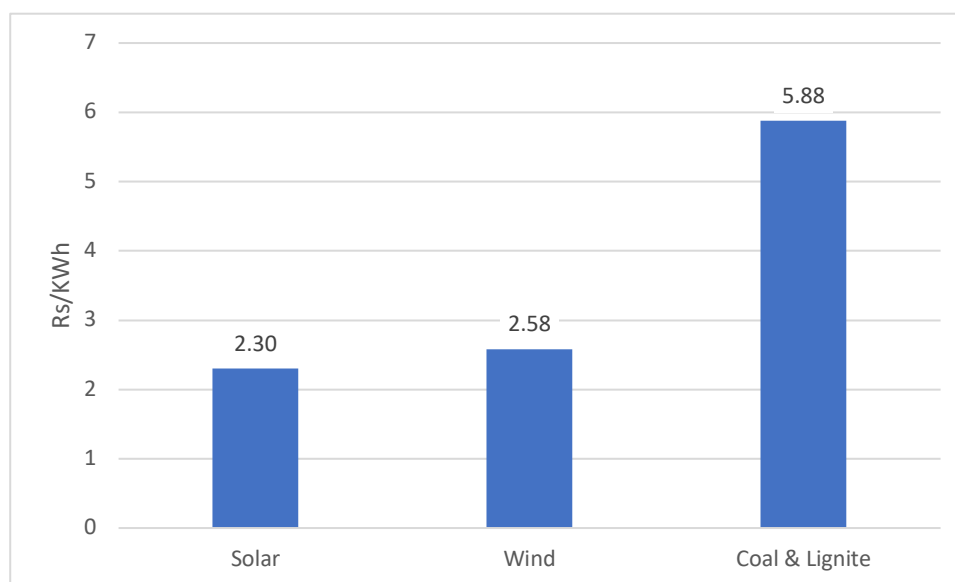
4.2.2 Aggregation Scheme and Modified Input-Output Table

Based on the commodity-by-commodity technology discussed in section 3.1, the 140x66 SUT is converted into a 140x140 sector IO table which has further been aggregated into 71 sector IO table. The 71-sector aggregated IO table constitutes 15 primary sectors, 45 secondary sectors, 3 utilities and 8 services sectors (Table A3 in the Appendix).

Post aggregation, the electricity sector was split into ‘Solar energy’, ‘Wind energy’ and ‘Other electricity sources’ and the new input structure were created based on the material composition of Solar and Wind energy presented in Tables 3.3 and 3.6, respectively in Section 3.2.

Since the IO table is in monetary terms, power generation from the solar, wind and other electricity sources which is dominated by coal power plants is converted into monetary terms as per the respective forecasted electricity tariff rates by 2030. This is presented in Figure 4.1.

Figure 4.1: Solar, Wind and Coal tariff rates in 2030 (in Rs./kWh)



Source: Pachouri, Spencer, & Renjith, (2019); RBI, (2021)

The two aforementioned sources are the only references which provided tentative forecasts of Solar, Wind and coal tariffs by 2030 that have been considered in this study.

Next, the RE Waste abatement sector was added for which the solar and wind solid waste recycling cost was compiled and presented in Table 4.6 and 4.7, respectively. Given that the year of the study is 2018-19, the Input cost for the installed Solar PV and wind capacity until March 2019 is considered.

Table 4.6: Input cost of solar PV recycling 2018-19 (28.2 GW)

Sr. no.	Inputs	Value (in Rs. million)
1.	Electricity	1122
2.	Diesel Fuel	73
3.	Water	34
4.	HNO ₃	7490
5.	Ca(OH) ₂	
6.	Transportation by truck	18855
7.	Contaminated glass landfilling	17396
8.	Fly ash (hazardous waste) landfilling	
9.	Liquid waste landfilling	
10.	Sludge (hazardous waste) landfilling	
11.	Labour cost	5323
12.	Total	50292

Source: Latunussa, et al., (2016)

Note: The monetary value was estimated by converting from US dollars to Indian rupees at Purchasing Power Parity (PPP); The input cost calculated is the potential cost of recycling and not the actual cost that will depend upon different stakeholders' contribution and willingness to accept/compensation rate that needs to be determined.

It can be observed that the transportation cost, from the source of PV waste generation to PV recycling centres is attributed with the highest share (37%), followed by the landfilling cost (35%).

Table 4.7: Input cost of wind turbine recycling 2018-19 (35.6 GW)

Sr. no.	Sectors	Value (in Rs. million)
1.	Electricity	6,876
2.	Maintenance with chemical treatment	7,459
3.	Labour	21,561
4.	Total	35,896

Source: (Fonte & Xydis, 2021)

Note: The monetary value was estimated by converting from US dollars to Indian rupees at Purchasing Power Parity (PPP)

4.2.3 The environmental pollution and external cost estimation

Coal-fired TPPs lead to GHG emissions – CO₂, NO_x and CH₄ as well as non-GHG emissions – SO_x, PM₁₀, Mercury (Hg) and Fly Ash. The emission factors in coal-TPPs differ based on coal composition and power plant characteristics (Garg, Kapshe, Shukla, & Ghosh, 2002; Chakraborty, et al., 2008; Mittal, Sharma, & Singh, 2014). Nevertheless, the national average emission factors from coal-TPPs in India has been compiled (PIB, 2015; GOI 2019; CEA,

2019; Guttikunda and Jawahar 2014; Agarwalla, Senapati and Das 2021) and provided in Table 4.8.

Table 4.8: Emissions from coal-fired power plants

Sr. no.	Particulars	Emission factor	Unit
I	GHG emissions		
1.	CO ₂	957	g/kWh
2.	NO _x	4.8	g/kWh
3.	CH ₄	892,636.3	g/tonne
II.	Non-GHG emissions		
1.	SO _x	7.3	g/kWh
2.	PM ₁₀ 10	0.98	g/kWh
3.	Mercury (Hg)	0.14	g/tonne
4.	Fly Ash	325,187.6	g/tonne

Source: PIB, (2015); GOI (2019); CEA, (2019); Guttikunda and Jawahar (2014); Agarwalla, Senapati and Das (2021)

Note: The emission related to combustion of coal and mining for thermal power plants is considered and not the non-combustion sources.

The GHG and non-GHG emissions from coal-TPPs will have negative repercussions on the environment and human health. The monetization of the environmental and human health consequences of coal-power generation (TERI, 2013; Chakravarty & Somanathan, 2021; Gupta et al., 2017) (provided in Table 4.9) is used for measuring the total cost savings from substituting coal-TPPs with solar and wind energy sources.

Table 4.9: Quantifiable external cost of coal power generation (INR/kWh)

Sr. no.	Parameters	INR/kWh
1.	Environmental cost of mining	0.20
2.	Mortality cost of air pollution	1.40
3.	Agriculture impact due to reduced insolation	0.04
4.	Total	1.64

Source: Mining –(TERI, 2013), Mortality-(Chakravarty & Somanathan, 2021), Agriculture-(Gupta et al., 2017)

4.2.4 The environmental and human health cost of RE waste

In section 4.2.3, the cost of recycling technologies adopted for handling the solar PV and wind turbine waste at the end of their lifetime is discussed in detail. In the event of mismanagement

of RE waste, the environmental and human health cost of waste generation, is estimated and discussed in detail in Tables A4 to A6 in the Appendix.

Given the methodological framework and data discussion on the linked ALCA and CLCA exercises, the next section deals with the scenarios constructed for this study.

4.3 Scenario Development

In pursuit of clean energy transition trajectory, the government bodies, namely the Central Electricity Authority (CEA), under the Ministry of Power as well as other independent research organizations have proposed an electricity capacity mix in their baseline projections until 2030, including solar, wind and other electricity sources. Given below is the brief background of these baseline projections, followed by their key assumptions.

In 2019, the CEA published a report titled, *Optimal Generation Capacity Mix for 2029-30* in which the projections for the conventional and RE sources were provided (CEA, 2019). The least cost optimal generation mix was simulated by studying the short-term economic generation dispatch and the long-term adequacy of the capacity generation mix at the least production cost. In 2022, the CEA published its fourth National Electricity Plan (NEP) in which the electricity capacity mix baseline is provided by taking into consideration the intermittency of renewable generation, seasonal spikes in electricity demand etc., thus proposing a flexible power system (CEA, 2022a). E3-India model also provides the forecasts for all power sources by 2030 with the contribution of its unique Future Technology Transition (FTT) module (Mukhopadhyay, 2021). The Energy and Resource Institute (TERI) in 2018, under the Energy Transitions Commission (ETC) India project 2030, forecasted the solar and wind capacity targets in the Current Policy Scenario (CPS) or the baseline scenario to be 190 GW and 132 GW, respectively. The study assumes the annual solar and wind capacity addition to be aligned with the CEA's third National Electricity Plan (NEP), published in 2018 (Pachouri, Spencer, & Renjith, 2019). In 2020, TERI, using the Python for Power Systems (PyPSA) India model updated their baseline in which the transmission flexibility concept was introduced, since solar and wind integration into the electricity grid would also imply an expansion of the transmission lines with varying flexibility (Spencer, et al., 2020).

The key assumptions underlying the baseline projections provided by different organizations is briefly presented in Table 4.10.

Table 4.10: Scenario-wise assumptions

Sr. no.	Baseline forecasts	Assumptions	Source
1.	BAU 2030	Using the Growth rates of energy-source-wise installed capacity growth between 2015-22 (since the RE sector received renewed emphasis only since 2015) as well as other electricity sources, the 2030 installed capacity has been projected.	Baseline data
2.	CEA Base case 2030	The annual energy requirement in the base case study is considered to be 2,300 gWh with peak demand of 340 GW. The base case considers a 5% increase in projected electricity demand to 2,516 gWh by 2029-30	CEA (2020)
3.	CEA National Electricity Plan 2030	Using ORDENA software – A mixed integer linear optimization program that minimizes the NPV of investment and operating costs subject to constraints such as balancing electricity supply and demand, resource supply limits, planning and operation reserve limits and policy targets. Based on hourly dispatch studies as a constraint in the model, the capacity mix in the long run by 2030 has been obtained.	CEA, (2022)
4.	TERI Current Policy Scenario 2030	The long-term 2030 target is prepared considering the major short-term policy driver – 175 GW RE capacity by 2022 and the National Electricity Plan (NEP) 2018. Given the existing trend, the 2030 capacity numbers have been derived.	Pachouri, Spencer, & Renjith, (2019)
5.	TERI Base Case 2030	The technology-wise gross capacities and net generation by considering the capacity mix as exogenous to the PyPSA model, based on the capacity expansion scenarios prepared by CEA. Given this novelty (where capacity expansion is not considered endogenous to the model), the forecasts are provided on the basis of hourly dispatch data, thus relying on the real-world operation of the power system	(Spencer, et al., 2020)
6.	E3-India	The E3-India model provides non-linear energy forecasts based on the Future Technology Transition (FTT) module. It provides a framework for the dynamic selection and technology diffusion which incorporates the reduction in production costs, increase in investment and market share over a period of time.	Mukhopadhyay, (2021)

Given below are the capacity and electricity generation forecasts in Tables 4.11 and 4.12.

Table 4.11: Electricity capacity mix baseline projections 2030

Sr. no.	Energy Source	Installed Capacity		Published in 2020	Announced in September 2022	Published in 2018	Published in 2020	Published in 2021
		Dec-22	BAU 2030	CEA BASE CASE 2030	CEA NEP 2030 BASE CASE	TERI CURRENT POLICY SCENARIO 2030	TERI BASE CASE SCENARIO 2030	E3 BAU 2030
1.	Hydro	46.9	50.0	71.1	73.8	80.4	74.0	53.7
2.	Small Hydro	4.9	5.9	5.0	4.9	10.4	10.0	10.7
3.	Biomass	10.7	15.5	10.0	13.7	22.6	23.0	
4.	Solar Photovoltaic	63.3	247.4	299.4	238.2	190.0	189.0	141.7
5.	Wind	41.9	106.9	140.0	106.2	132.0	129.0	73.4
6.	Nuclear	6.8	6.8	19.0	17.7	16.9	17.0	14.6
7.	Coal and lignite	210.4	222.3	268.5	240.6	238.1	238	259.9
8.	Gas	24.8	24.3	25.1	25.2	24.9	24.9	
9.	Diesel	0.6	0.3	-	0.6	0.8	0.5	0.6
10.	Total	410.3	680	838	721	716	705	555

Source: CEA (2020); CEA (2022a); Spencer et al., (2020); Pachouri, Spencer, & Renjith, (2019); Mukhopadhyay (2021)

Table 4.12: Electricity generation mix baseline projections 2030

	Power generation		Published in 2020	Announced in September 2022	Published in 2018	Published in 2020	Published in 2021
Power sources	2022-23*	BAU 2030	CEA BASE CASE 2030	CEA NEP 2030 BASE CASE	TERI CURRENT POLICY SCENARIO 2030	TERI BASE CASE SCENARIO 2030	E3-india BAU scenario
Hydro	119531.5	149006	211000	232638	220000	231000	130943
Small Hydro	6327.4	11184	7200	8022	31000	14000	
Biomass	5829.5	27388		59000.0	59000	27000	5980
Solar Photovoltaic	55999.1	352104	484200	615020	275000	286000	185643
Wind	52761.8	195061	309100	320880	280000	292000	124198
Nuclear	26120.3	37882	113000	133700	91000	91000	84638
Coal and lignite	679283.3	1341617	1357700	1337000	1365000	1319000	1238307
Gas	14814.1	67680 2836	35400	26740	68000	14767.64	14768
Diesel							
Total	960666.9	2184757	2517600	2674000	2389000	2260000	1784476

Source: CEA (2020); CEA (2022a); Spencer et al., (2020); Pachouri, Spencer, & Renjith, (2019); Mukhopadhyay (2021)

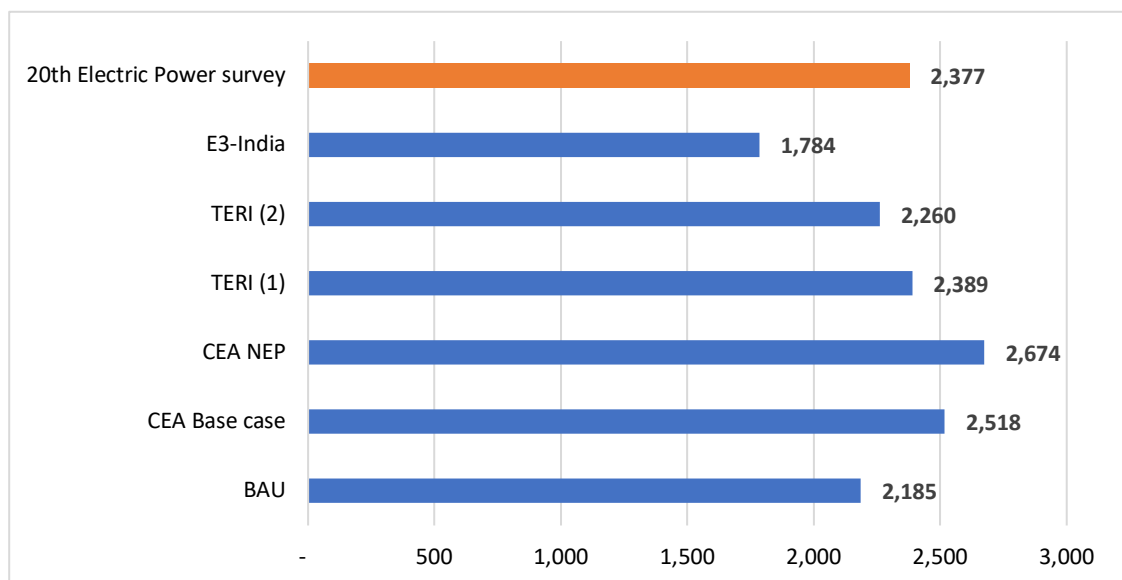
Note: *As of December 2022

The timeline of these projections ranges across the pre and post-COP27 announcement of achieving 450 GW RE capacity. While each baseline constitutes different assumptions and different modelling philosophies, the projections are directly or indirectly aligned with the 19th Electric Power Survey forecasts published in 2017, which states the electrical energy requirement to be 2,531 BUs by 2031-32 compared to 1,576 BUs in 2021-22 (CEA, 2017), Based on the Compound Annual Growth Rate (CAGR), this would imply electricity demand projection of 2,325 BUs by 2030.

In November 2022, the 20th Electric Power Survey was published in which the forecasts were reassessed and updated. The electrical energy requirement was deemed to be 2,377 BUs by 2030 (CEA, 2022b). The latest survey, similar to the previous one uses the Partial End Use Method (PEUM) for long-term forecasting. However, by incorporating factors such as reduction in transmission and distribution losses (T&D), energy efficiency measures, roof-top solar etc, as well as the penetration of electric vehicles the electricity energy requirement is deemed to be lower than the previous survey forecasts.

Given below is the comparison of different baseline projections with the 20th electric power survey projects (Figure 4.2).

Figure 4.2: Power demand projections 2030 across different model assumptions (in TWhs)



Source: CEA (2017); CEA (2020); CEA (2022a); CEA (2022b); Spencer et al., (2020); Pachouri, Spencer, & Renjith, (2019); Mukhopadhyay (2021)

It can be observed from Figure 4.2 that except the E3-India projections which is based on the 2016 baseline, all the other baseline projections are almost equal to or exceed the 20th Electric Power survey forecasts.

Given this backdrop, the scenarios presented here do not propose an increase in electricity demand over the baseline scenarios, since they already exceed the forecasted power demand in the country. Rather, the scenarios propose a change in the composition of the electricity generation mix to meet the given electricity demand in the country (Figure 4.2). The main agenda for the preparation of the scenarios is the development of a ‘Greener energy mix’ with a steady reduction of the reliance on coal power in India’s electricity mix portfolio by 2030.

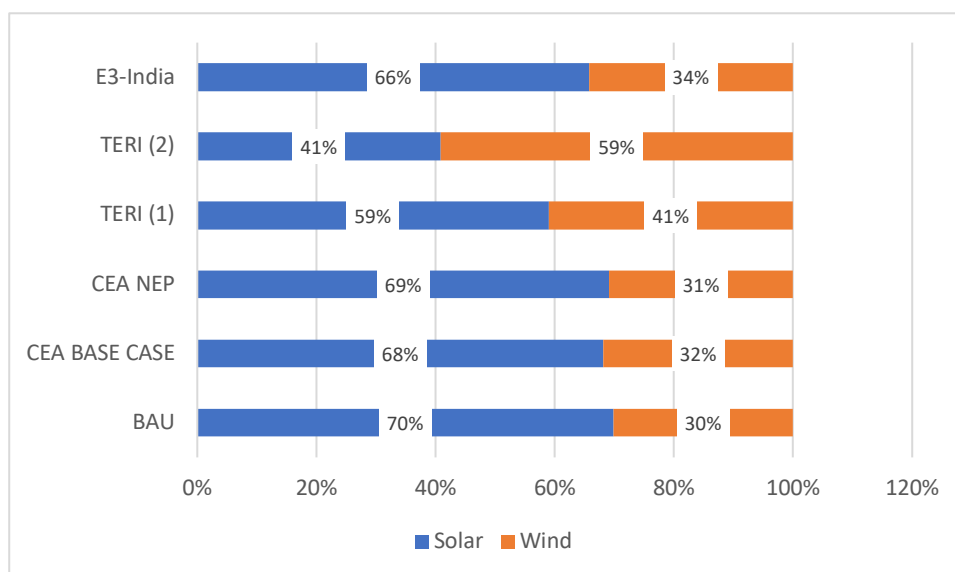
With the Input-Output model encompassing Solar, Wind and Other electricity sources as three different sectors, a change in the composition between these three energy source mix while keeping the cumulative energy demand constant will lead to varying impacts on the economy, through the underlying simultaneous equations propagating different multiplier effects. The rationale for referring to different 2030 projections is to evaluate different alternatives in which solar and wind energy can contribute towards this goal such that rising energy demand is met through cleaner energy sources, without compromising the economic growth of the country.

Given this backdrop, the study proposes two contrasting scenarios, prepared according to the government of India’s ambitions on the electricity generation mix.

- ❖ **LOW COAL SCENARIO:** According to the Ministry of Power’s notification, the coal power generation is expected to be reduced by 58,000 gWh by 2026-27 (GOI, 2022). The gap in coal power generation is assumed to be substituted by Solar and Wind energy according to their share in the electricity generation mix presented in different projections by 2030.
- ❖ **OPTIMAL MIX SCENARIO:** For different baseline projections, it was observed that the highest Solar+Wind energy mix was for the Central Electricity Authority-National Electricity Plan (CEA NEP) 2030. For this study, the Solar (23%) and Wind (12%) in the CEA NEP case is considered to be optimal mix to be achieved by 2030. The ‘Other energy sources’ with Coal at the forefront will accommodate the power supply balance to meet the energy demand.

In the Low coal scenario, 58,000 gWh of thermal power will be curtailed and substituted by solar and wind in each of the 2030 projections provided in Table 4.12. The composition of solar and wind energy differs in different projections, based on their share of Solar and Wind mix. This is presented in Figure 4.3.

Figure 4.3: Low-coal scenario: Solar and Wind mix in different baseline projections

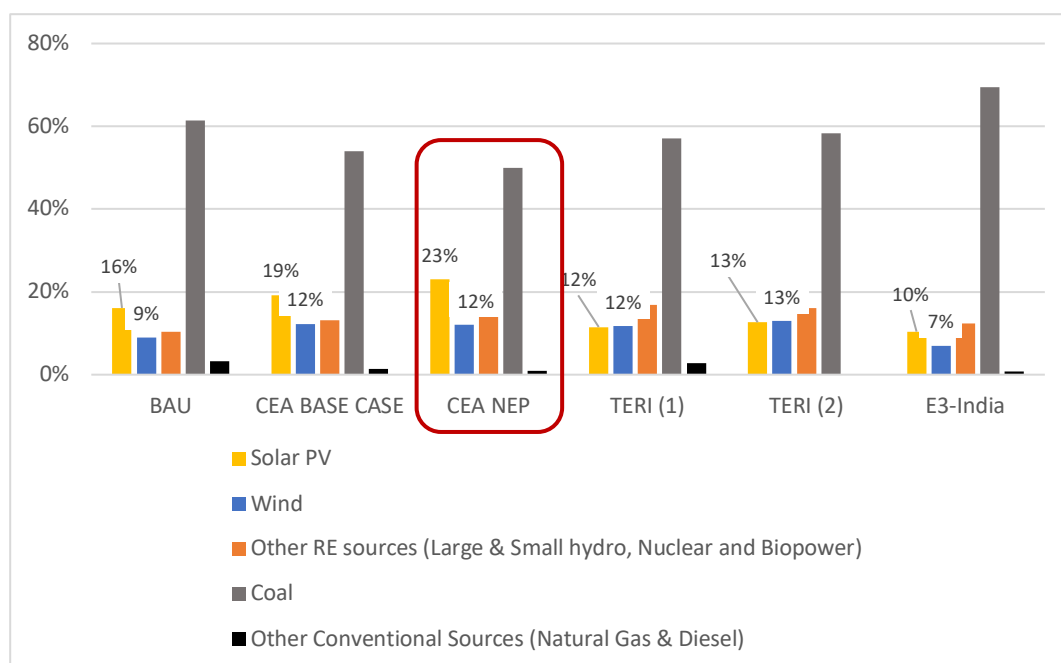


Source: Authors' calculations

To this end, the composition of Solar and wind energy that is expected to substitute thermal power will also follow the given shares in Figure 4.3.

In the Optimal Mix scenario, the solar and wind energy shares in different projections are presented in Figure 4.4.

Figure 4.4: Optimal Mix Scenario: Electricity mix in different baseline projections



Source: Authors' calculations

The key assumption in this scenario is based on the CEA NEP constitutes the optimal solar + Wind mix of 23% and 12% respective share in the total energy mix, in combination with the

rest of the energy sources as well. The 2030 projections also are targeted to reach the same solar and wind shares in the combined electricity portfolio and the resulting changes through the IO model over the BAU scenario are studied.

Given this brief background of the two scenarios, the change in the composition in the two scenarios also depends on the power producing capacity per GW of coal, solar and wind power generation. This is presented in Table 4.13.

Table 4.13: gWh per GW conversion rate for coal, solar and wind power

Sr. no.	Power projections	gWh power generation per GW installed capacity			GW capacity of Solar and Wind required to produce equivalent amount of power from 1 GW coal-TPPs	
		Coal	Solar	Wind	Solar	Wind
1.	BAU 2030	6034	1423	1824	4.2	3.3
2.	CEA Base case 2030	5087	1614	2208	3.2	2.3
3.	CEA NEP (2030)	5557	2582	3021	2.2	1.8
4.	TERI Current Policy Scenario (2030)	5733	1447	2121	4.0	2.7
5.	TERI Base Case 2030	5008	1513	2264	3.3	2.2
6.	E3 India 2030	4765	1310	1692	3.6	2.8

Source: CEA (2020); CEA (2022a); Spencer et al., (2020); Pachouri, Spencer, & Renjith, (2019); Mukhopadhyay (2021)

Using these ratios of solar and wind capacities, with the coal power capacity, the modifications in the electricity portfolios in both the scenarios are conducted to observe the changes over and above the Business As Usual (BAU) scenario.

Given this comprehensive discussion on the ALCA and CLCA methodologies with the application of the SEEA framework in this chapter, the results of the study are discussed in the forthcoming chapters. The ALCA results for solar and wind energy are discussed in Chapters 5 and 6, respectively and given the waste generation and cost of recycling estimates from these chapters, the CLCA and SEEA application results, using the IO 2018-19 is presented in Chapter 7.

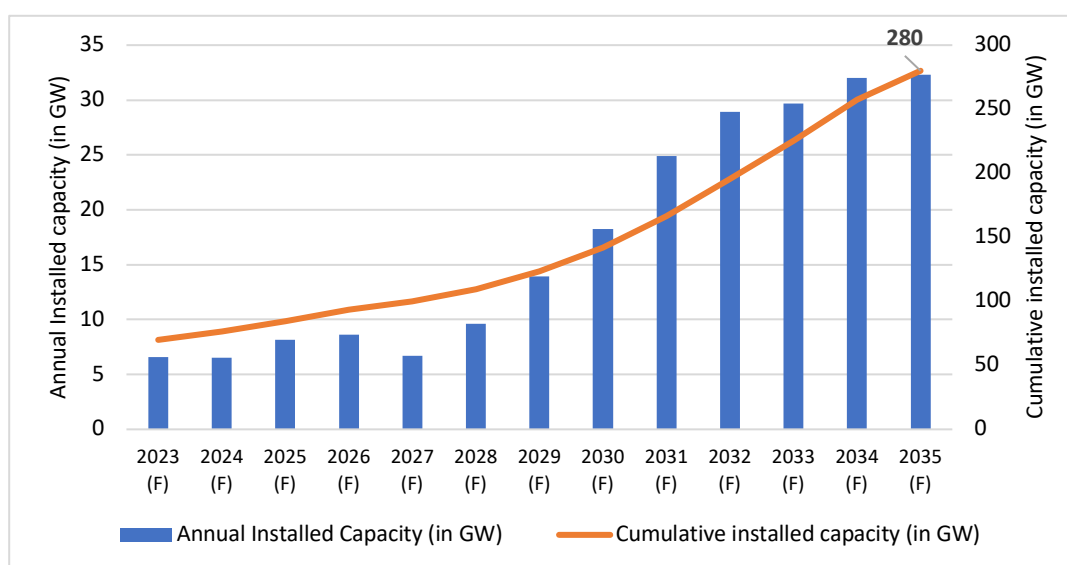
CHAPTER 5 SOLAR PHOTOVOLTAICS LIFE CYCLE ASSESSMENT

This chapter focuses on the Life Cycle Impact Assessment of the ground-mounted and rooftop Solar PV in India. The long-term solar PV capacity installation forecasts are provided using the E3-India model. Given the Life Cycle Inventory of Ground-mounted and Rooftop Solar PV modules discussed in chapter three, the direct Energy and Environmental burden along with the cost-benefit analysis of adopting Solar PV recycling technology has been presented. The recycling of Solar PV in the End-of-Life (EoL) phase and the potential of a Circular Economy in Solar Energy has been elaborated.

5.1 Estimation of Solar PV installation timeline

The solar PV capacity installation was forecasted using the E3-India model. (The model details are discussed in chapter 3). In this regard, the uniqueness of E3-India lies in its non-linear forecasts derived from its exclusive Future Technology Transition (FTT) module (Pollitt, 2021). These estimates are on the basis of economies of scale in terms of capital costs and the increasing market share estimates of solar energy (Pollitt, 2021). Thus, over time, the realization of the Solar PV potential in the country is translated into faster solar PV capacity installation. The projected timeframe for the completion of the intended solar PV capacity target along with the annual capacity addition, as suggested by the BAU baseline of the E3-India model, is presented in Figure 5.1.

Figure 5.1: Solar PV installed capacity forecast (in GW)



Source: Authors' calculations

Given the technology frontier, the model estimates show that the 280 GW target can be achieved only by 2035. In Figure 5.1, it is observed that the rate of annual solar PV module capacity installation grows multi-fold post-2028. The E3-India model prediction does not take into consideration the market slowdown that resulted from the COVID-19 impact during mid-2020s and 2021. The globalization of the pandemic led to disruptions in the solar PV industry supply-chain as well. Prior to the pandemic, India was importing approximately 80% of its solar cells and modules from China along with other solar PV equipment such as inverters, pre-fabricated structures and raw materials (Pimpalkhare, 2020). This resulted in disruption of approximately 3 GW solar PV projects worth Rs. 160 billion in the country with the Indian government declaring a ‘force majeure’ situation⁸. The Ministry of New and Renewable Energy (MNRE) also directed the State Distribution Companies (DISCOMs) to continue to purchase and scheduling power from RE sources on a ‘must-run’ status, thus ensuring cash flow for RE generation companies (Deshwal, Sangwan, & Dahiya, 2021). Furthermore, in the Union budget 2020-21, the Central government announced key provisions directed towards supporting the solar energy industry. These include i) lowering corporate tax for new energy companies to attract fresh investments, ii) Extension of PM-KUSUM scheme that allows farmers to utilize their barren land for RE generation and providing two million farmers with solar agriculture pumps and 1.5 million farmers with grid-connected pumps and iii) Solar PV capacity installation along railway tracks. Given these incentives along with the solar Projects which were already in the pipeline since 2020, India installed a record 13 GW capacity (11.3 GW ground-mounted PV and 1.7 GW solar rooftop PV) in the Calendar Year (CY) 2022 which was the highest in the country thus far on an annual basis (MERCOS, 2023). Furthermore, by the end of 2022 approximately 51 GW worth of solar projects were tendered, pending auction. Post-COVID, as a step towards promoting indigenous solar PV module manufacturing, India had announced 40% solar panel import duty and 25% on solar cells to avoid Chinese imports (Saurabh, 2021).

Given these short-term fluctuations in the solar PV industry, the long-run solar PV forecasts proposed by the E3-India model are expected to remain consistent. With the lifetime of 30 and 25 years, respectively for mono-Si and multi-Si crystalline technology (Rajput, et al., 2016; Patel, 2018), it is estimated that the Solar PV module waste accumulation will be generated

⁸ The project developers were granted relief in terms of meeting deadlines and avoiding financial penalties.

between 2034-65. This is discussed further in detail in the End-of-life phase section later in this chapter.

5.2 Life Cycle Impact Assessment

5.2.1 Embodied energy requirement and emissions from Solar PV

Based on the Life Cycle Inventory presented in Table 4.1 in Chapter 4, the LCIA results are categorized into Embodied energy consumption and the consequent GHG emissions in each of the phases of the solar PV modules' lifecycle. As the study is for the year 2018-19, the results are presented for the 28.2 GW solar PV capacity installed as of March 2019 and also the 280 GW capacity expected to be completed by 2035 (Figure 4.1). First, the phase-wise embodied energy consumption results are presented in Tables 5.1 and 5.2.

Table 5.1: Embodied energy resource consumption from installed Solar PV ground-mounted and rooftop PV capacity of 28.2 GW in 2018-19 (in gWhs)

Sr. no.	Stages	Ground-mounted PV		Rooftop PV		Total
		m-Si	p-Si	m-Si	p-Si	
1.	Raw material acquisition phase	3.1	20.8	0.2	1.4	25.5
	Glass	0.6914	4.6271	0.0471	0.3150	5.6806
	Aluminium	1.8401	12.3143	0.1253	0.8384	15.1181
	Copper	0.0001	0.0004	0.0000	0.0000	0.0005
	Polymer based adhesive	0.2102	1.4069	0.0143	0.0958	1.7272
	Polyvinyl fluoride	0.3136	2.0987	0.0214	0.1429	2.5766
	Silver	0.0524	0.3509	0.0036	0.0239	0.4308
2.	Production Phase	37146.5	191898.3	2529.1	13065.3	244639.1
	Silicon Feedstock	11730.5	78044.8	798.7	5313.6	95887.5
	Czochralski Process	13685.5	0.0	931.8	0.0	14617.3
	Wafer Process	2915.5	42006.4	198.5	2860.0	47980.4
	Cell production	2949.8	21577.1	200.8	1469.1	26196.7
	Module Assembly	5865.2	50270.0	399.3	3422.6	59957.2
3.	Construction Phase	18281.7	122346.6	544.1	3641.4	144813.8
	Foundation and Support structure	17149.8	114771.7	467.1	3125.7	135514.2
	Inverter	1131.9	7574.9	77.1	515.7	9299.6
4.	Operational Phase	5316.4	35579.2	291.9	1953.5	43141.1
	Overall Operation & Maintenance, electronic components, cables and miscellaneous, etc.	5316.4	35579.2	291.9	1953.5	43141.1
5.	End-of-life Phase	0.0270	0.1804	0.0018	0.0123	0.2215
6.	Total	60747.7	349845.1	3365.3	18661.7	432619.8

Source: Authors' calculations

Note: The break-up of 28.2 GW cumulative capacity into Ground-mounted and Rooftop PV and between m-Si and p-Si technology PV modules is provided in Chapter 4, Section 4.1

Table 5.2: Embodied energy resource consumption from installed Solar PV ground-mounted and rooftop PV capacity of 280 GW in 2035 (in gWhs)

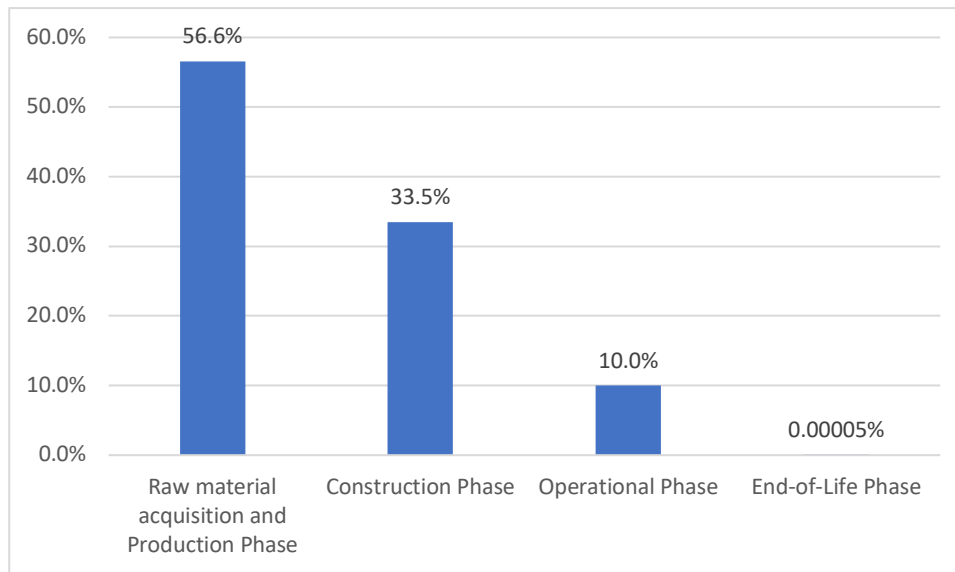
Sr. no.	Stages	Ground-mounted PV		Rooftop PV		Total
		m-Si	p-Si	m-Si	p-Si	
1.	Raw material acquisition phase	19.79	132.43	13.19	88.29	253.70
	Glass	4.4024	29.4625	2.9350	19.6417	56.4417
	Aluminium	11.7165	78.4106	7.8110	52.2738	150.2120
	Copper	0.0004	0.0027	0.0003	0.0018	0.0052
	Polymer based adhesive	1.3386	8.9583	0.8924	5.9722	17.1614
	Polyvinyl fluoride	1.9969	13.3636	1.3312	8.9091	25.6008
	Silver	0.3339	2.2343	0.2226	1.4895	4.2803
2.	Production Phase	236527.2	1221897.6	157684.8	814598.4	2430708.0
	Silicon Feedstock	74692.8	496944.0	49795.2	331296.0	952728.0
	Czochralski Process	87141.6	0.0	58094.4	0.0	145236.0
	Wafer Process	18564.0	267472.8	12376.0	178315.2	476728.0
	Cell production	18782.4	137390.4	12521.6	91593.6	260288.0
	Module Assembly	37346.4	320090.4	24897.6	213393.6	595728.0
3.	Construction Phase	116407.2	779032.8	33924.8	227035.2	1156400.0
	Foundation and Support structure	109200.0	730800.0	29120.0	194880.0	1064000.0
	Inverter	7207.2	48232.8	4804.8	32155.2	92400.0
4.	Operational Phase	33852.0	226548.0	18200.0	121800.0	400400.0
	Overall Operation & Maintenance, electronic components, cables and miscellaneous, etc.	33852.0	226548.0	18200.0	121800.0	400400.0
5.	End-of-life Phase	0.1	0.7	0.1	0.5	1.3
6.	Total	386806.3	2227611.5	209822.9	1163522.4	3987763.0

Source: Authors' calculations

Note: The break-up of 28.2 GW cumulative capacity into Ground-mounted and Rooftop PV and between m-Si and p-Si technology PV modules is provided in Chapter 4, Section 4.1

The phase-wise embodied energy consumption results in Table 5.1 and 5.2 for the existing installed capacity (28.2 GW) and the target capacity (280) in 2035 shows that the raw-material acquisition and production phases constitute the highest share of the lifetime energy requirement. The phase-wise share of total energy consumption is presented in Figure 5.2.

Figure 5.2: Solar PV phase-wise share of total lifetime energy requirement (As percentage of total)



Source: Authors' calculations

Manufacturing phase constituting the acquisition of key raw materials and the production process of the Solar PV modules constitutes the highest share of embodied energy consumption (Figure 5.2) This has also been proven elaborately in the literature where the manufacturing phase constitutes the highest share (Hsu et al., 2012; Aristizabal, Sierra and Hernandez 2016; Prabhu, Shrivastava & Mukhopadhyay, 2022). This is a result of the consumption of energy-intensive non-ferrous metals such as aluminium and copper as well as polymer-based materials. Unlike ferrous metals such as iron and steel which require significant direct raw coal combustion and heat generation contributing towards high GHG emissions, non-ferrous metals' significant energy input is electricity (Paltsev, et al., 2021). Thus, the greening of the electricity sector itself will directly contribute towards the decarbonization of the aluminium and copper manufacturing processes as well. The decarbonization of the polymer and polyvinyl-based materials, which are both plastics, is based on two key pillars – Bio-based polymers and recycling (Titone, Mistretta, Botta, & La Mantia, 2022). However, the recycling of plastics is considered to be a highly sophisticated task, since there are different types of polymers used in plastics that cannot be recycled altogether, while the production of new plastics from non-RE sources is cheaper in the current scenario (DeWeerd, 2022). Finally, glass which constitutes 70% of the total material composition of Solar PV modules is attributed with the least share of total energy requirement, since relative to other materials, it is not highly energy intensive.

The Construction and Operation phases constitute significantly lower share of energy requirement, compared to the manufacturing phase while the EoL phase requires negligible energy (Figure 5.2).

The lifetime energy consumption by Solar PV modules leads to the release of GHG emissions. As discussed in the LCI section 4.1 in Chapter 3, the energy demand in the solar PV industry is assumed to be met through the coal-fired TPPs since it constitutes 74% of the existing national electricity mix. The results are presented in Tables 5.3 and 5.4.

Table 5.3: Embodied GHG emissions from installed Solar ground-mounted PV and rooftop PV capacity of 28.2 GW in 2018-19 (in thousand tCO₂eq.)

Sr. no.	Stages	Ground-mounted PV (million tCO ₂)		Rooftop PV (million tCO ₂)		Total
		m-Si	p-Si	m-Si	p-Si	
1.	Raw material acquisition phase	0.00297	0.01990	0.00020	0.00136	0.02444
	Glass	0.66167	4.42811	0.04505	0.30149	5.43632
	Aluminium	1.76095	11.78483	0.11989	0.80236	14.46804
	Copper	0.00006	0.00041	0.00002	0.0003	0.00050
	Polymer based adhesive	0.20119	1.34639	0.01370	0.09167	1.65295
	Polyvinyl fluoride	0.30012	2.00850	0.02043	0.13675	2.46581
	Silver	0.05018	0.33581	0.00342	0.02286	0.41227
2.	Production Phase	35.55	183.65	2.42	12.50	234.12
	Silicon Feedstock	11.23	74.69	0.76	5.09	91.76
	Czochralski Process	13.10	-	0.89	-	13.99
	Wafer Process	2.79	40.20	0.19	2.74	45.92
	Cell production	2.82	20.65	0.19	1.41	25.07
	Module Assembly	5.61	48.11	0.38	3.28	57.38
3.	Construction Phase	17.50	117.09	0.52	3.48	138.59
	Foundation and Support structure	16.41	109.84	0.45	2.99	129.69
	Inverter	1.08	7.25	0.07	0.49	8.90
4.	Operational Phase	5.09	34.05	0.28	1.87	41.29
	Overall Operation & Maintenance, electronic components, cables and miscellaneous, etc.	5.09	34.05	0.28	1.87	41.29
5.	End-of-life Phase	0.00003	0.00017	0.0000018	0.00001	0.00021
6.	Total	58.14	334.80	3.22	17.86	414.02

Source: Authors' calculations

Table 5.4: Embodied GHG emissions from installed Solar PV ground-mounted and rooftop PV capacity of 280 GW in 2030 (in million tCO₂eq.)

Sr. no.	Stages	Ground-mounted PV		Rooftop PV		Total
		m-Si	p-Si	m-Si	p-Si	
1.	Raw material acquisition phase	0.01894	0.12674	0.01263	0.08449	0.24279
	Glass	0.00421	0.02820	0.00281	0.01880	0.05401
	Aluminium	0.01121	0.07504	0.00748	0.05003	0.14375
	Copper	0.00000	0.00000	0.00000	0.00000	0.00001
	Polymer based adhesive	0.00128	0.00857	0.00085	0.00572	0.01642
	Polyvinyl fluoride	0.00191	0.01279	0.00127	0.00853	0.02450
	Silver	0.00032	0.00214	0.00021	0.00143	0.00410
2.	Production Phase	226.4	1169.4	150.9	779.6	2326.2
	Silicon Feedstock	71.5	475.6	47.7	317.1	911.8
	Czochralski Process	83.4	0.0	55.6	0.0	139.0
	Wafer Process	17.8	256.0	11.8	170.6	456.2
	Cell production	18.0	131.5	12.0	87.7	249.1
	Module Assembly	35.7	306.3	23.8	204.2	570.1
3.	Construction Phase	111.4	745.5	32.5	217.3	1106.7
	Foundation and Support structure	104.5	699.4	27.9	186.5	1018.2
	Inverter	6.9	46.2	4.6	30.8	88.4
4.	Operational Phase	32.4	216.8	17.4	116.6	383.2
	Overall Operation & Maintenance, electronic components, cables and miscellaneous, etc.	32.4	216.8	17.4	116.6	383.2
5.	End-of-life Phase	0.000100	0.000670	0.000067	0.000447	0.0013
6.	Total	370.2	2131.8	200.8	1113.5	3448.1

Source: Authors' calculations

With the energy requirement being the highest for the raw material acquisition and production phases, naturally, it constitutes the highest share of GHG emissions as well (Tables 5.3 and 5.4). It has been well-established in the literature that the m-Si PV modules are more efficient, while also being more energy and emission intensive alternatives (Alsema and Scholten, 2005; Baharwani et al., 2014; Ludin et al., 2018). The Electronic Grade Silicon (EG-Si) undergoes highly energy-intensive combustion at temperatures of 1100-1200°C, contributing towards GHG emissions as well (Nawaz and Tiwari, 2006). On the other hand, the p-Si PV does not require the Cz process, hence its energy requirement is always lower than m-Si PV. The operations and construction phase requires minimal energy consumption, which is largely restricted to electricity consumption for mounting supporting structures, preparing the foundation, land levelling and fencing.

The energy and environmental burden generated through the manufacturing phase varies on the efficiency of the production process adopted. The embodied energy consumption across different lifecycle phases discussed earlier with reference to Figure 5.2, electricity is the key input in the manufacturing phase used for different production activities. Thus, the decarbonization of the power sector itself will contribute towards reducing GHG emissions. Studies have shown the CO₂ emissions from Solar PV production vary with the type of technology adopted among different regions. Liu & van den Bergh, (2020) studied the GHG emissions from Solar PV technologies across the European Union (EU), USA and China. The carbon intensity from electricity as input to the lifecycle of solar PV modules is the lowest in the European Union (0.354 kgCO₂/kWh), followed by the USA (0.478 kgCO₂/kWh) and China (0.679 kgCO₂/kWh). The contribution of 50% of EU's power demand through Renewable energy and Nuclear power contributes significantly to the greening of the power sector in the region. On the other hand, in China, the share of coal power in the national electricity mix has been higher than 50% since 1949 while the share of RE in the US electricity mix is very low, 50% of its fossil power is generated from gas-based power plants which is less carbon-intensive compared to coal (Liu & van den Bergh, 2020).

On the other hand, India's share of coal power which was 74% during pre-COVID times (2018-19) has increased to 76% in 2022-23, while the coal-fired TPPs' Plant Load Factor has also increased from 56.5% to 66.9% during the same period (PTI, 2023). Thus, with the assumption of coal power as the sole source of power for solar PV module manufacturing, the carbon intensity is expected to be 0.957 kgCO₂/kWh (GOI, 2019), which is almost 30% higher than China (0.679 kgCO₂/kWh). In order to achieve the carbon intensity levels of China (679 kgCO₂/kWh) and relaxing the assumption of 100% coal power supply to Solar PV module's lifetime energy input requirement, the share of Renewable energy needs to be increased.

5.2.2 LCA Parameters

The key LCA parameters of Capacity Utilization Factor (CUF), Energy Payback Time (EPBT) and Energy Return on Investment (EROI) are discussed here⁹.

As has been discussed in Chapter 4, the CUF for Solar PV technology depends on the type of technology used (which is Mono-Si and Multi-Si crystalline technology for this study) and whether it is Ground-mounted PV or Rooftop PV. The separate electricity generation data by type of technology and type of Solar PV installation is not available, but only the cumulative Solar PV power generation from the installed capacity in 2018-19. Based on the LCI data

⁹ The detailed notes and definitions of these LCA parameters is discussed in Chapter 4.

compiled for Solar PV in Chapter 4, the CUF for Solar PV is estimated to be 18% in 2018-19. This is comparable with scientific publications such as Kumar, et al., (2020) who study the on-grid solar PV systems in India under warm and temperate climate, present across most of the Indian landmass. The study shows that in 2018, the Solar PV CUF ranged as low as 9.4% to 19.3%. Yadav & Bajpai, (2018) study the performance of rooftop PV systems in Northern India with results indicating CUF varies between 16% to 20%.

With the Cumulative Energy Demand compiled for the two PV technologies as well as for ground-mounted PV and Rooftop PVs, the results for the EPBT and EROI are presented in Tables 5.5 and 5.6, respectively.

Table 5.5: EPBT for Ground-mounted and Rooftop PV systems for different PV technologies

Sr. no.	PV system	PV Technology	EPBT (in years)
1.	Ground-mounted PV	mono-Si	2.2
		multi-Si	1.9
2.	Rooftop PV	mono-Si	1.7
		multi-Si	1.4

Source: Authors' calculations

Table 5.6: EROI for Ground-mounted PV and Rooftop PV systems for different PV technologies

Sr. no.	PV system	PV Technology	EROI (in years)
1.	Ground-mounted PV	mono-Si	13.6
		multi-Si	13.4
2.	Rooftop PV	mono-Si	17.4
		multi-Si	17.9

Source: Authors' calculations

As has been discussed thoroughly in the literature, the mono-Si PV technologies are the most productive in terms of conversion efficiency (heat-to-electricity), while at the same time, it is the least efficient in terms of energy consumption, especially in the production process (Alsema and Scholten, 2005; Baharwani et al., 2014; Ludin et al., 2018). Thus, the EPBT for mono-Si PV modules is higher than that for multi-Si. Complementarily, the EROI on mono-Si is higher, owing to its higher conversion efficiency levels as discussed earlier. The results also depend on external factors such as module efficiency, solar irradiation levels, lifetime and the performance ratio of solar PVs. These parameters vary across different studies and across different regions. To the best knowledge of the authors, there are no comparative LCA studies across different Solar PV technologies in the Indian context where the EPBT and EROI from this study can be compared. Secondly, the Cumulative Energy demand (CED) by incorporating the EoL phase

has been considered while almost all studies undertaken in the literature review in Chapter 2 restrict the EPBT and EROI calculations to the first three phases of manufacturing, construction and operational phases (Pacca, Sivaraman & Keoleian 2007; Baharwani et al., 2014; Espinosa, Hosel, Angmo, & Krebs, 2012).

Liu & van den Bergh, (2020) state that the EPBT and EROI parameters are significant determinants for estimating the electricity intensity of the grid. The EPBT is based on the CED throughout the lifetime and EROI is the inverse of EPBT multiplied by the lifetime of Solar PV technology. Thus, the CED plays a significant role in determining the values of the two LCA parameters. Given the discussion in section 5.2.1 on the need to use energy efficient materials in the manufacturing phase to reduce the energy and carbon intensity, it will contribute towards the reduction in CED as well.

5.3 Full Recovery End-of-Life Photovoltaics (FREL P) Analysis

The Full Recovery End-of-Life Photovoltaic (FREL P) method is considered to be the most advanced PV recycling system till date, expected to decrease lifetime environmental impact by 10-15% compared to other recycling methods (Latunussa, Mancini, Blengini, Ardente, & Pennington, 2016)¹⁰. The step-by-step procedure for recycling PVs using the FREL P method has been applied in the case of PV waste expected to be generated between 2034-65 in India as has been discussed earlier in section 5.1.

The 280 GW worth of c-Si PV modules will generate approximately 19,382 tonnes of waste in its EoL phase. With a lifetime of 30 and 25 years for m-Si and p-Si modules respectively, PV waste will start accumulating annually once the solar modules reach the EoL phase. Given that the solar PV capacity installation started as early as 2009, this waste accumulation timeframe ranges between 2034 and 2065 for the 280 GW capacity installed until 2035. The cumulative waste accumulation from the existing installed capacity in 2018-19 (28.2 GW) and by 2035 (280 GW) is presented in Table 5.7.

¹⁰ This has been discussed in detail in Chapter 3.

Table 5.7: Crystalline silicon-based PV panel composition for installed solar PV capacity of 28.2 GW (2018-19) and 280 GW (2035)

Sr. no.	Materials	28.2 GW	280 GW	Recycling rates
1.	Glass	1,365	13,568	90%
2.	Aluminium frame	351	3,489	76%
3.	Copper connector	20	194	43.8%
4.	Polymer-based adhesive (EVA) encapsulation layer (from cables)	99	989	
5.	Back-sheet layer (based on polyvinyl fluoride)	29	291	
6.	Silicon metal solar cell	71	707	
7.	Silver	1	10	94.3%
8.	Aluminium, internal conductor	10	103	76%
9.	Copper, internal conductor	2	22	43.8%
10.	Various metal (tin, lead)	1	10	
	Total	1,951	19,382	

Source: Authors' calculations

The cumulative waste accumulation and type of metallic and non-metallic minerals that can be recycled and recovered have been presented in Table 5.7. Given the recycling rates, the potential recovered materials are presented in Table 5.8.

Table 5.8: Materials recovered and energy saved from recycling 1,951 (28.2 GW) and 19,382 (280 GW) tonnes of PV waste

Sr. no.	Primary materials recovered		28.2 GW	280 GW	Unit
1.	Primary aluminium		275.3	2735.7	tonnes
2.	Raw materials for the production of primary white glass for packaging		1221.5	12136.6	tonnes
3.	Primary copper		8.5	84.9	tonnes
4.	Primary Metallurgical-grade silicon metals (MG-Si)		67.7	672.2	tonnes
5.	Primary Silver		1.0	9.7	tonnes
			Energy content/tonne		
6.	Produced by the incineration of PV encapsulation, back-sheet layer and polymers	Electricity	134,832.7	1,339,714.3	mWh
		Thermal Energy	272,454.8	2,707,145.4	mWh

Source: Latunussa, Mancini, Blengini, Ardente, & Pennington, (2016) and Authors' calculations

From Table 5.7, it is observed that the cumulative recovery of glass is the highest amongst all the panel components. This is not only because of a high recycling rate of 90% but also due to glass constituting more than 70% of the total panel composition (Table 4.2 in Chapter 4). The other materials such as polymer-based encapsulation layers which are made of plastic compounds are unrecyclable with the current available technologies and hence would have to be incinerated (DeWeerd, 2022). However, theoretically, the electricity that can be generated from the heat due to incineration can be reused for other purposes while saving electricity consumption from the grid. This has also been quantified in Table 5.8.

The resale and reuse of recovered materials such as glass and aluminium are expected to replace their virgin manufacturing by producers, thus resulting in embodied energy and emission savings. According to Somvanshi, (2013), the embodied energy requirement from virgin manufacturing of glass and aluminium is expected to be 155 MJ/kg and 15 MJ/kg, respectively and the resulting embodied emissions are 8.24 kgCO₂/kg and 0.85 kgCO₂/kg, respectively. Given the quantity of recovered materials, presented in Table 5.8, the cumulative embodied energy and emission savings of 185 gWh and 36 thousand tonnes CO₂ is expected in the economy.

Given this significant amount of material, energy and emission savings, a cost-benefit analysis is also conducted of the entire recycling process in the EoL phase of Solar PV modules. The net monetary cost of PV recycling or EoL treatment using the FRELP method can be estimated as the difference between the total cost incurred during recycling, transportation, and disposal and the benefit gained from the materials and energy recovered during the process. The total cost can further be divided into private costs (investment, processing, and transportation fuel costs) and external costs (air, water, and land pollution) (Markert, Celik, & Apul, 2020). With the help of the cost-benefit analysis presented by Markert, Celik & Apul (2020) (see Table A7 in the Appendix), the total private and external costs of recycling of c-Si PV waste and the commercial value of recovered materials (aluminium, glass, silver, silicon, copper) are calculated and presented in Table 5.9. Private costs include the cost of investment, processing, transportation and disposal while the external costs are from CED, Global Warming Potential, acidification, freshwater toxicity, particulate matter etc.

Table 5.9: Cost Benefit Analysis of Solar PV recycling (in USD million)

Sr. no.	Particulars	28.2 GW (2018-19)	280 GW (2035)
1.	Private Costs	1,894	18,816
2.	External Costs	1,609	15,988
3.	Commercial/Economic value of recovered materials (Aluminium, glass, silver, silicon, copper)	3,487	34,627
4.	Net Benefit (Sr. no. 3 - 1 - 2)	-15	-177

Source: Latunussa, Mancini, Blengini, Ardente, & Pennington, (2016) and Authors' calculations

Note: The monetary values were converted from USD to INR at the Purchasing Power Parity of 1 USD = 21.073 INR

The cost-benefit analysis of the EoL treatment with the given recycling rates presented in the study reports a loss of USD 15 million for recycling 28.2 GW installed PV capacity as of March 2019 and USD 177 million for recycling the cumulative 280 GW capacity, expected to be installed by 2035. However, when viewed as a proportion of the total cost, this loss amounts to less than 1% of the total cost. On the other hand, the monetary gains from the resale of recovered materials can be reused to install new solar PV capacity. According to the IRENA report, the cost of utility-scale solar PV was the lowest in India amongst G20 countries at USD 618/KW (IRENA, 2019). Given the solar PV cost, it is estimated that approximately 5.64 GW and 56 GW of solar PV capacity can be reinstalled using the 3R strategy of recycling, resale and reuse of recovered materials from the decommissioned 28.2 GW installed capacity as of 2018-19 and the cumulative 280 GW capacity, respectively.

5.4 Discussion

The LCA study of solar energy shows that the manufacturing phase is the most energy and carbon-intensive phase, owing to the significant energy requirement in raw material acquisition and production processes of solar PV modules. The energy supply to meet the energy demand across different phases is assumed to be from coal-fired power plants since it constitutes almost 3/4th of the total electricity generated in the country as of 2018-19 (CEA, 2023). Given the slow and steady rate of capacity installation of clean energy sources such as solar PV, the electricity supply with a mix of fossil and non-fossil fuel sources can also be implemented which is also expected to make the manufacturing phase more energy efficient.

5.4.1 Incorporating recycling cost in electricity tariff determination

Currently in India, the electricity tariff that the consumer pays is determined based on the cost of 'generation, transmission and distribution' per kWh for power generation from any energy

source (Kumar et al., 2022). From the producer’s point of view, the Levelized cost of Electricity (LCOE), defined as the price at which the electricity generated should be sold to break even at the End of its lifetime for that particular system under consideration (Papapetrou & Kosmadakis, 2022). In other words, LCOE measures the average cost of generating one kilowatt-hour (kWh) of electricity over the system’s lifetime. In order to estimate the per unit lifetime generation cost, LCOE considers three key variables – a) Capital cost, b) Operation and maintenance costs and c) Fuel costs (USDOE, 2015). While the electricity tariff indicates the price the consumer pays, the LCOE determines the investment the producer has to incur in order to achieve the breakeven point. However, in both parameters, the recycling costs are not considered.

According to Kumar et al., (2022) the LCOE for solar energy is estimated to be \$ 0.038/kWh, compared to \$0.039/kWh for wind energy. Since this estimate takes into consideration only the capital, fuel and O&M costs, this study tries to quantify the contribution of the recycling costs of solar energy in the LCOE.

In the previous section, the CUF for solar energy was estimated to be 18%, based on the actual power generation (39,298.2 gWh) and installed capacity (28.18 GW) in 2018-19. Assuming the CUF to remain constant, the electricity generated from 280 GW capacity throughout its lifetime (30 years) is calculated which is 4,41,504 gWh/year which is equivalent to 1,32,45,120 gWh throughout its lifetime. Given the cost of recycling 280 GW Solar PV modules in EoL phase to be USD 3,503 million (Table 5.9), The recycling cost per kWh is estimated to be \$0.0026/kWh. Provided that the cost of Recycling is to be included in the LCOE, we estimate the ‘LCOE + Cost of recycling’.

This is presented below:

$$\begin{aligned} \text{Cost of Recycling (LCOR) (280 GW)} &= \frac{\text{Recycling cost}}{\text{Lifetime electricity generation}} \\ &= \frac{\$ 34,604 \text{ million}}{1,32,45,120 \text{ GWh}} = \mathbf{\$ 0.0026/kWh} \end{aligned}$$

Through the inclusion of the cost of recycling along with LCOE, the revised cost, including recycling costs is provided below:

$$\text{LCOE} + \text{Cost of recycling} = \frac{\$0.038}{\text{Kwh}} + \frac{\$0.0026}{\text{Kwh}} = \mathbf{\$0.041/kWh}$$

The result above indicates that, with the promotion of the Extended Producers’ Responsibility (EPR), it is observed to be the investment the producer has to incur, including the recycling costs is \$0.041/kWh.

Given that a net loss of USD 177 million will be incurred from recycling the cumulative 280 GW of solar PV modules, one option for the government is to subsidize the recycling process. In FY2019, the government of India provided subsidies of USD 1.03 billion for the RE sector (Balasubramanian, et al., 2021). These are largely directed towards capital incentives to encourage solar PV module manufacturing within the country. Along similar lines, the subsidization of PV module recycling in the EoL phase can support the producers' investment in recycling technology. This study shows that the subsidization of \$1.3/KW is required in order to negate the losses that will be incurred by the producer who will undertake the recycling.

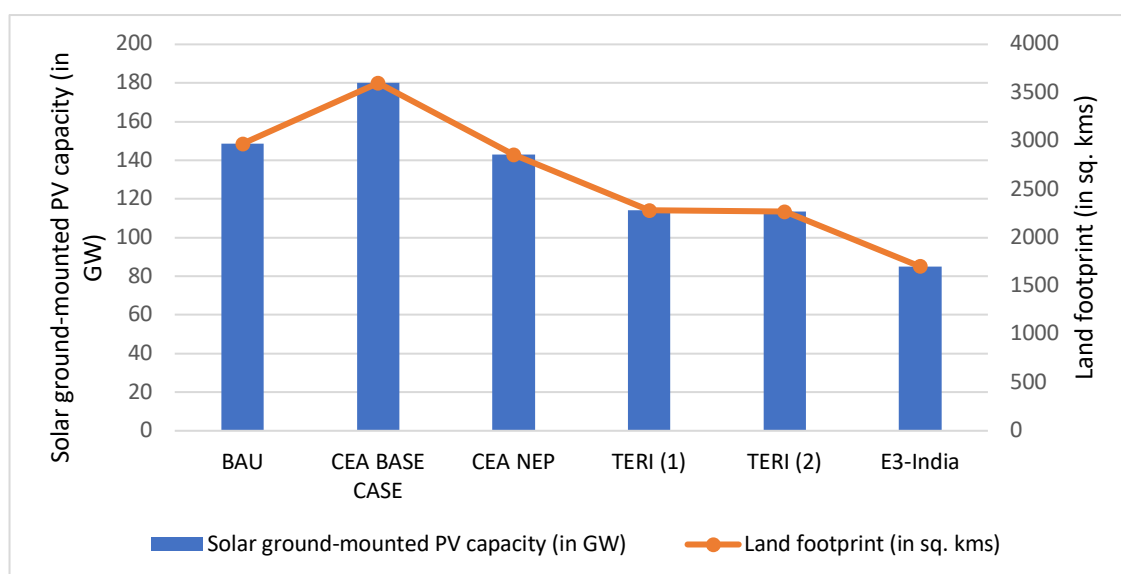
Another alternative for compensating the producers under the Extended Producer Responsibility (EPR) is through carbon credits. For incentivising recycling in the EoL phase, Carbon credits may be one of the tools that can encourage solar PV manufacturers for yielding gains from the Circular Economy framework. Furthermore, the carbon credits can be attributed in two ways – Through the usage of energy efficient raw materials in the manufacturing phase as well as through GHG emissions saved through the EoL phase by substituting virgin material manufacturing. To this end, it was only in May 2023, the government announced the plans for developing an Indian Carbon Market (ICM) for the pricing of GHGs such that a carbon credit trading platform can be developed. Nevertheless, India still has a long way to go in finalizing the market, provided the first emphasis is on decarbonizing harder-to-abate sectors such as coal and steel. On the other hand, the linkage between Carbon credits and Renewable energy sources such as solar energy from a life cycle perspective may take longer to materialize.

It is expected that solar tariffs are expected to fall further from \$0.039/kWh in 2018-19 to \$0.023/kWh in 2030 (RBI, 2021). This is expected to make solar energy an attractive alternative to coal power. However, recently the Ministry of Power has declared that the coal power generation is expected to meet 76% of total power demand in 2023-24, which is two percentage points higher than the pre-COVID share of 74% in 2018-19 (PTI, 2023). Furthermore, the Plant Load Factor (PLF) has also increased from 56% in 2018-19 to 66.9% in 2023-24. Given this backdrop, the share of solar energy in the total electricity mix may either remain or may decrease through crowding out by coal power generation. Given the exclusion of recycling costs in the existing RE tariff structure and the recent developments of expanding coal power generation, the deflationary impact on solar tariffs by 2030 might not hold.

5.4.2 Land and water footprint from solar PV capacity installation

With increasing solar PV capacity installation, the demand for land is also expected to increase for utility-scale ground-mounted PV projects. In India, solar PV projects per sq. km can accommodate 50 MW of PV panels (50 MW/sq. km) (Chakravarty & Somanathan, 2020). In Chapter 3, the different scenario assumptions that are considered for this study provide the expected installed solar PV capacity by 2030. Assuming that 60% of the total solar PV capacity will be ground-mounted PV projects (which was the share for the national 100 GW solar target for 2022), the land footprint is presented in Figure 5.3.

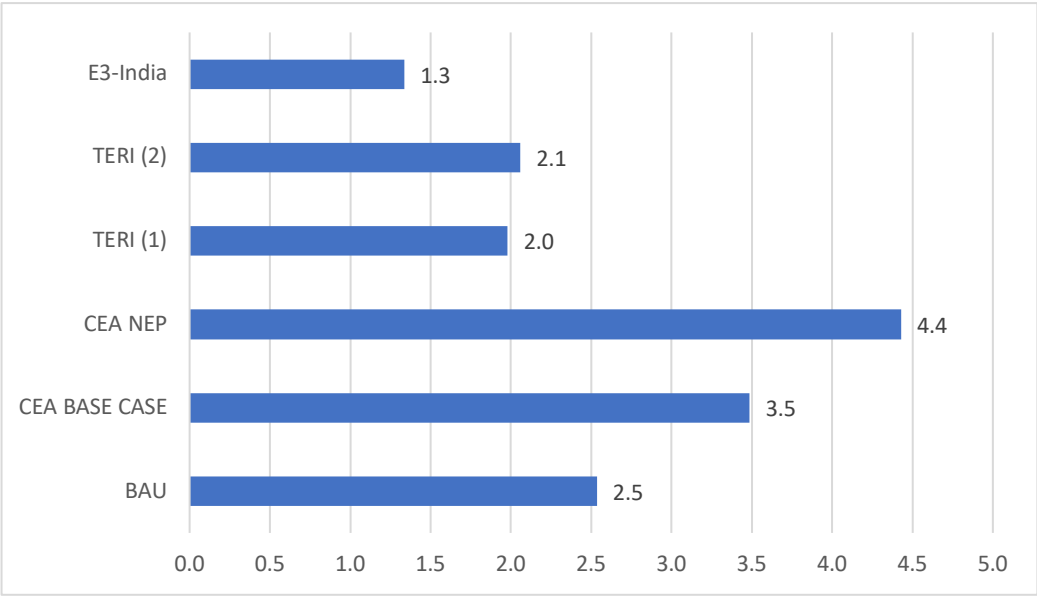
Figure 5.3: Land footprint of ground-mounted Solar PV projects



Source: Authors' calculations

Given the land requirement in different scenarios, the share of total arable land in India that needs to be dedicated for ground-mounted solar PV projects is expected to be on an average 0.168% of the total arable land area (15,53,691 sq. km). Encroachment on cropland and commercial forests to achieve the solar PV capacity targets can lead to Land Use Change (LUC) emissions related to increasing global land competition, emissions related to vegetation losses, carbon release from soil and vegetation directly below the installed panels where sunlight is much reduced (van de Ven, et al., 2021). According to this study, in India the LUC emissions per kWh are below 12g of CO₂. Given the emission factor, the scenario-wise LUC emissions resulting from utility-scale ground-mounted PV installations are presented in Figure 5.4.

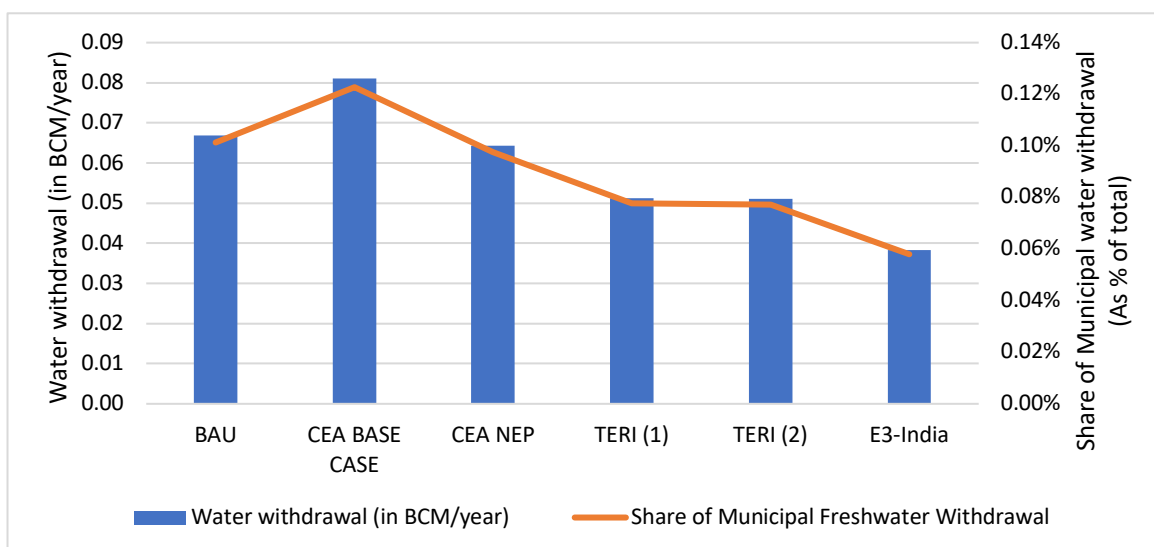
Figure 5.4: Scenario-wise LUC emissions from ground-mounted PV installations (in million tonnes CO₂eq.)



Source: Authors’ calculations

Furthermore, solar PV also incurs water footprint in the operational phase which is a result of washing of PV modules in order to maintain module efficiency and ensure its longevity (Segev, 2022). The frequent washing can demand water requirements between 7,000 to 20,000 litres per MW per wash (Segev, 2022). Provided that the water will be sourced from local water bodies which are largely under the jurisdiction of the local municipal corporations, a proportion of the water management activities need to be allocated for solar module washing purposes. In 2019, municipal water withdrawal for India was 56 Billion Cubic Meters (BCM) per year which has increased from 42 BCM per year in 2000 to 56 BCM per year in 2019, growing at a CAGR of 1.54% (KNOEMA, 2020). Assuming the rate to remain constant by 2030, approximately 66 BCM of municipal water is expected to be withdrawn for various purposes. To this end, the scenario-wise water footprint and its share in the municipal water withdrawal is presented in Figure 5.5.

Figure 5.5: Scenario-wise Water footprint and its share in the municipal water withdrawal



Source: Authors' calculations

Figure 5.5 represents the burden on water supply that is expected to be generated by 2030, which ranges between 0.06% to 0.1% of total municipal water withdrawal. Given that India is already a water scarce nation and with rapid urbanization and a growing population, it is expected to lead to sub-optimal outcomes in terms of maintaining solar module efficiency levels without proper water management solutions.

5.5 Concluding remarks

The Government of India has set an ambitious long-term target of achieving 280 GW of solar PV capacity by 2030 in its efforts to tackle climate change. This chapter evaluates the energy and environmental ramifications of incremental solar PV capacity installation throughout its lifetime using the attributional LCA methodology. The study finds that India will achieve the target only by the year 2035 in the Business-as-usual scenario.

With the current electricity market share of only 4.1% and CUF of 18%, compared to the 66% Plant Load Factor (PLF) of coal-fired power plants, solar energy in the given scenario cannot substitute TPPs for power generation in the short to medium run. In terms of energy efficiency, the manufacturing phase is attributed the most energy and consequently, the most emission intensive phase. With the adoption of viable PV module recycling technology, the energy intensity in Solar PV module manufacturing can be reduced through the reuse of recycled materials such as glass, copper and aluminium in the EoL phase. Another strategy is to utilize energy efficient raw materials which can be implemented through the decarbonization strategy for carbon-intensive sectors such as aluminium and copper.

The cost of recycling 280 GW of decommissioned solar PV modules is expected to reach USD 34.6 billion. Through the resale of recovered materials, an approximate revenue of USD 34.4 billion still leads to a net loss of USD 177 million. Nevertheless, a further 19 GW of PV modules can be installed through the resale of recovered materials. The recycling costs can be further reimbursed through proper government subsidization strategies and complemented with the Extended Producer Responsibility¹¹ (EPR). Through incentivizing EPR, the producer undertakes partial or full responsibility for the recycling of PV modules in the EoL phase, which has the potential to yield economic benefits. The inclusion of the recycling cost in the LCOE provides financial leverage for the producer, which is essential for undertaking the recycling process, without incurring economic losses. However, this is only a theoretical estimation provided here, since the PV module recycling is still not practiced on a large scale in India. With further developments through scientific innovations, the Circular Economy framework presented in this study can be further adopted through the implementation of the 3R strategy.

The main purpose of conducting an Attributional LCA study for solar energy is to estimate and quantify the GHG emissions through embodied energy consumption and the waste abatement costs through recycling technologies. Furthermore, the land footprint in the installation phase and the water footprint in the operational phase have also been quantified here in order to address the issue of clean energy transition from a holistic perspective. This study is complementary and the first step towards conducting the Economy-Energy-Environmental impact at the Macro level using the Input Output-Consequential LCA framework that has been undertaken later in Chapter 7. The next chapter deals with the A-LCA study undertaken for the onshore wind energy.

¹¹The solar module manufacturer will be obligated to undertake the decommissioning and recycling of PV modules at the end-of-life stage.

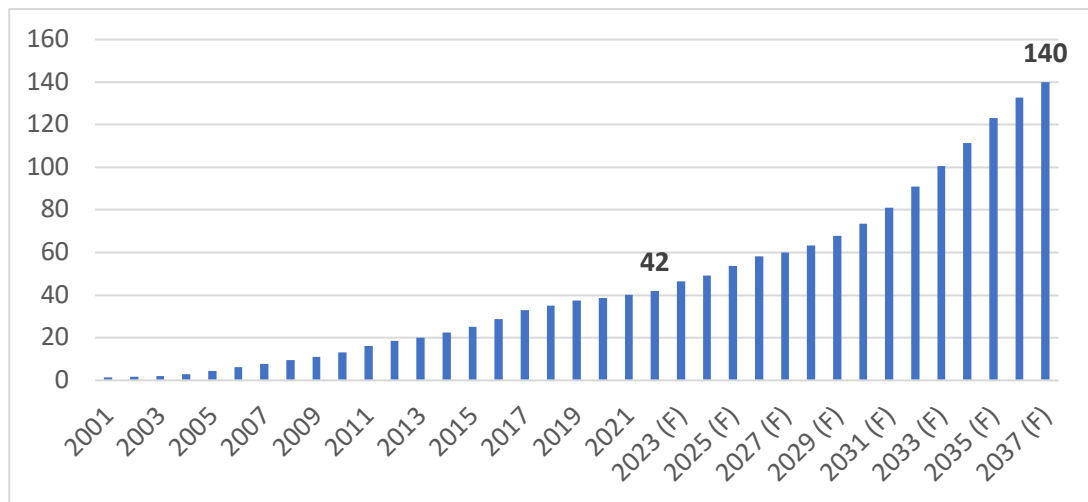
CHAPTER 6 ONSHORE WIND LIFE CYCLE ASSESSMENT

In this chapter, the Life Cycle Impact Assessment of the onshore wind energy is presented. The long-term forecast of onshore wind capacity installation is provided that is referred to estimate the timeline of wind turbine waste expected to be generated in the EoL phase. Using the Life Cycle Inventory presented in the third chapter, the direct energy and environmental consequences of wind energy over its lifetime and the economic impact and circular economy prospects of decommissioned wind turbines in the End-of-life phase through recycling have been elaborated.

6.1 Estimation of the onshore wind installation timeline

Based on the estimates from the E3-India model applied for forecasting the annual wind capacity installation as described in Chapter 3, the 140 GW target will not be achievable by 2030 and will surpass even 2035 in the Business-as-Usual Scenario. This has been shown in Figure 6.1.

Figure 6.1: Onshore wind capacity installation forecast (in GW)



Source: Author's calculations

The E3-India model provides estimates until 2035 and the results indicate that 89% of the target will be achieved until that time. Nevertheless, given the increasing growth trajectory, it can be observed that the target should be achievable by 2037. With a lifetime of 20 years for wind turbines (Vestas, 2006; Mali & Garrett, 2022), the wind turbine waste is expected to accumulate between 2021 and 2057. This has been discussed further in the End-of-life phase sub-section later in the chapter.

Using the E3-India model, the 'growth rate' of annual wind capacity installation post-2022 over the existing installed capacity as of December 2022 is considered for forecasting and not the

‘level’ of annual wind capacity installation (in MW terms). Since the negative impact of the COVID-19 induced lockdowns is not embedded in the model, there will be a mismatch in the actual decline in capacity installation post-2020 and the forecasted capacity from the model. This limitation is partially overcome by considering only the growth rates over the existing wind capacity in 2022. Nevertheless, the slowdown in the wind industry post-2020 has carried forward in the succeeding years. With a halt to transport, industry and construction sectors during the lockdowns, the existing project timelines in 2020 were extended to 2021 (GWEC, 2020). On the other hand, supply-chain disruptions continued even in 2022 with the ongoing Russia-Ukraine war leading to a rise in cost-push inflation in the wind industry, through rising prices of raw materials such as steel and nickel along with soaring logistics costs (GWEC, 2022). This led to India missing the 60 GW onshore wind energy target in 2022 by a margin of 40.8% (or 17.4 GW) (CEA, 2022).

Nevertheless, the central and state governments have been keen on intervening in the wind energy market, with a pipeline of 13.4 GW capacity that is expected to drive installations until 2024 (GWEC 2022). Furthermore, private players have found hybrid solar-wind technology projects more attractive since they provide leverage to the market risks. Such hybrid projects are expected to push for wind capacity installations post-2024. Another major catalyst is the amendments made to the Renewable Purchase Obligations (RPO) by the Ministry of Power; wherein, not only State DISCOMs, but also the existing operational coal and lignite power plants need to procure or generate green energy which is 40% of its existing capacity (PTI, 2023). Given the ongoing dynamic changes in the wind industry in the short run, wherein the effects of slowdowns have been attempted to be countered through innovations in wind capacity tenders put forth by the central and state governments. To this end, the long-run forecasts provided by E3-India model of the target being achieved by year 2037 seems practical since the short-run tailwinds are not considered to be extreme events with the potential to disrupt the long-run targets.

6.2 Life Cycle Impact Assessment

6.2.1 Embodied energy requirement and by-products from onshore wind

The Life Cycle Impact Assessment (LCIA) results are provided here which has been categorized into the lifetime embodied energy consumption and by-products across different phases.

India's current electricity mix is dominated by coal-fired TPPs, constituting 74% of total electricity generation in 2020-21 while solar and wind energy constitute a share of only 7.6% (Niti Aayog, 2021). Thus, the electricity supply in various stages of onshore wind is also assumed to be supplied by fossil-fuel sources in the current scenario.

Since this study is for the year 2018-19, the results are presented for the 35.6 GW wind capacity installed as of March 2019 and also the 140 GW capacity expected to be completed by 2037. The lifecycle phase-wise embodied energy consumption is presented in Table 6.1.

Table 6.1: Embodied energy resource consumption from installed onshore wind capacity of 35.6 GW in 2018-19 and 140 GW in 2037 (in gWhs)

Sr. no.	Life-cycle phases	2018-19 (35.6 GW)	2037 (140 GW)
1.	Raw materials acquisition and manufacturing, (including nacelle, rotor tower)	52,319	2,05,748.1
2.	Transportation and Installation	8,069	31,732.6
3.	Operation and Maintenance	9,801	38,541.6
4.	End-of-life	2,997	11,787.3
5.	Total	73,186	2,87,809.6

Source: Author's calculations

It has been well-established in the literature that, turbine manufacturing is the most energy-intensive phase (Haapala & Prempreeda, 2014; Gomaa et al., 2019; Li et al., 2020). In this study as well, the manufacturing phase constitutes 71.5% of the lifetime energy consumption of onshore wind turbines. Majority of the raw materials being processed in the manufacturing phase are for the production of the nacelle and tower which are the most significant components of the wind turbine. Of the total raw materials, 25% is being constituted by steel and iron materials, whereas 70% is Cement as presented in the Life Cycle Inventory in Chapter 4. Both these materials constitute highly energy-intensive manufacturing processes, thus, contributing significantly to the cumulative energy requirement and in turn, towards cumulative emissions. As of December 2022, India was the world's second-largest producer of crude steel. India also has the highest CO₂ emissions intensity in Electric Arc Furnace (EAF) steel production (GOI, 2022). This difference is due to two reasons, the first is that the primary energy source used in EAFs is electricity which is highly carbon intensive. Further, in India a significant amount of energy-intensive Direct Reduced Iron (DRI) is used as feedstock in EAFs. According to the Indian government, the energy consumption in the Indian steel plants is 6-6.5 Giga Calorie/tonne compared to 4.5-5 GigaCalorie/tonne in Western countries (GOI, 2021). Naturally, the emissions from the Indian steel sector, combined with being one the largest producers of steel India accounts for over 6.6% of the total global carbon emission from the

Iron and steel sector (Hasanbeigi, 2022). The government itself acknowledges the inefficient energy consumption in the steel industry is a result of the adoption of obsolete technologies, outdated operational practices and poor-quality raw materials with high fly ash coal/coke, high alumina etc. (GOI, 2021). To this end, there is significant scope for energy efficiency in the Indian steel sector, which in turn will contribute towards reduction in the energy consumption in the manufacturing phase of wind turbines as well.

Cement is another sector which is considered to be a hard-to-abate sector. In wind turbines, approximately 70% of the total material composition is made of concrete and cement (Mali & Garrett, 2022). It is essential to form the foundation structure on which the wind turbines are installed. Cement constitutes 2-3% of global energy demand (ETEnergyworld, 2023). The carbon intensity of India's cement sector is 3.1 GJ/tonne which is lower than the global average of 3.5 GJ/tonne. Nevertheless, India being the second largest cement producer in the world after China, the cumulative energy consumption and the subsequent GHG emissions are significant. In the production of cement, raw materials (mainly limestone and clay) are quarried and crushed and then fed into the cement kilns (Norster, 2023). In this chemical and thermal process, CO₂ emissions are unavoidable. Efficiency measures such as thermal efficiency of cement-making equipment, fuel switching, Carbon Capture and Sequestration (CCS) provide scope for steady decarbonization of the cement sector.

This is followed by the Operation and Maintenance Phase (13.4%) and the Transport and Installation phase (11%). The energy consumption and other related activities across different phases in onshore wind leads to release of pollutants in the form of air, water and solid waste. The phase-wise attribution of pollution has been shown in Table 6.2 and Table 6.3.

Table 6.2: Air, water and solid waste generation from 35.6 GW (in million tonnes)

Sr. no.	Particulars	Turbine Manufacturing	Construction			Operation	Total
			Foundations	Site parts	Set up		
I	Stockpile goods	3631.20	1149.88	216.09	7.69	416.52	5421.4
1	Slag (deposited)	0.40	0.00	0.48	0.00	0.00	0.9
2	Spoil (deposited)	-0.21	356.0	3.74	5.23	1.78	366.5
3	Waste (deposited)	97.19	96.8	21.00	1.17	-2.34	213.9
II	Emissions to air	23638.40	3666.8	1505.88	354.93	1651.84	30817.9
II(i)	Inorganic emissions to air	18120.40	3136.36	1235.32	351.73	1274.48	24118.3
1	Carbon dioxide	2979.72	615.88	107.51	21.86	131.36	3856.3
2	Carbon dioxide (biotic)	91.85	28.73	1.09	0.16	8.54	130.4
3	Carbon dioxide (land use change)	3.36	0.58	0.05	0.31	0.16	4.5
4	Carbon monoxide	16.34	3.45	0.28	0.13	0.89	21.1
5	Nitrogen (atmospheric nitrogen)	74.40	0.07	0.11	0.00	0.78	75.4
6	Nitrogen oxides	7.65	1.06	0.19	0.22	0.19	9.3
7	Oxygen	9.72	0.86	0.10	0.01	0.57	11.3
8	Sulphur dioxide	6.19	0.89	0.34	0.03	0.14	7.6
9	Water (evapotranspiration)	8971.20	1747.96	100.39	325.74	818.80	11964.2
10	Water vapour	5980.80	733.36	1021.72	3.47	315.77	8055.1
II(ii)	Organic emissions to air (group VOC)	8.86	0.93	0.52	0.11	0.37	10.8
III	Emissions to fresh water	2662880.00	167320.00	922040.00	1345.68	117480.00	3871065.7

III(i)	Heavy metals to water	0.50	0.08	0.01	0.00	0.03	0.6
1	Iron	0.49	0.08	0.01	0.00	0.03	0.6
2	Lead	0.00037736	0.00003809	0.00002093	0.00001007	0.00003809	0.00048454
3	Manganese	0.00112140	0.00016091	0.00003225	0.00000021	0.00005376	0.00136853
4	Molybdenum	0.00033713	0.00003321	0.00000790	0.00000011	0.00002036	0.00039871
5	Nickel	0.00045924	0.00006408	0.00001324	0.00001563	0.00003314	0.00058533
IV(iii)	Inorganic emissions to fresh water	55.54	3.23	1.20	0.96	2.06	63.0
1	Acid (calculated as H ⁺)	0.01	0.00	0.01	0.00	0.00	0.02
2	Aluminium	0.00	0.00	0.00	0.00	0.00	0
3	Ammonia	0.00	0.00	0.00	0.00	0.00	0
4	Barium	0.00	0.00	0.00	0.00	0.00	0
5	Carbonate	0.34	0.00	0.01	0.01	0.00	0.36

Source: Mali & Garrett, (2022) and Author's calculations

Table 6.3: Air, water and solid waste generation from 140 GW (in million tonnes)

Sr. no.	Particulars	Turbine Manufacturing	Construction			Operation	Total
			<i>Foundations</i>	<i>Site parts</i>	<i>Set up</i>		
I	Stockpile goods	4111.35	1301.93	244.67	8.71	471.60	6138.3
1	Slag (deposited)	0.45	0.00	0.55	0.00	0.00	1
2	Spoil (deposited)	-0.24	403.07	4.23	5.93	2.01	415
3	Waste (deposited)	110.04	109.64	23.78	1.33	-2.65	242.14
II	Emissions to air	26764.08	4151.66	1705.00	401.86	1870.26	34892.9
II(i)	Inorganic emissions to air	20516.44	3551.08	1398.66	398.24	1443.00	27307.4
1	Carbon dioxide	3373.72	697.32	121.73	24.75	148.73	4366.25
2	Carbon dioxide (biotic)	103.99	32.53	1.24	0.18	9.67	147.61
3	Carbon dioxide (land use change)	3.81	0.66	0.06	0.35	0.18	5.06
4	Carbon monoxide	18.50	3.91	0.32	0.15	1.01	23.89
5	Nitrogen (atmospheric nitrogen)	84.24	0.08	0.12	0.00	0.88	85.32
6	Nitrogen oxides	8.67	1.20	0.21	0.25	0.21	10.54
7	Oxygen	11.00	0.98	0.12	0.01	0.65	12.76
8	Sulphur dioxide	7.01	1.01	0.39	0.03	0.16	8.6
9	Water (evapotranspiration)	10157.45	1979.09	113.67	368.81	927.07	13546.09
10	Water vapour	6771.63	830.33	1156.82	3.93	357.53	9120.24
II(ii)	Organic emissions to air (group VOC)	10.04	1.05	0.58	0.13	0.42	12.2
III	Emissions to fresh water	3014989.33	189444.52	1043960.21	1523.62	133014.24	4382931.9

III(i)	Heavy metals to water	0.57	0.09	0.01	0.00	0.03	0.7
1	Iron	0.56	0.09	0.01	0.00	0.03	0.69
2	Lead	0.000427	0.000043	0.000024	0.000011	0.000043	0.000548
3	Manganese	0.001270	0.000182	0.000037	0.000000	0.000061	0.00155
4	Molybdenum	0.000382	0.000038	0.000009	0.000000	0.000023	0.000452
5	Nickel	0.000520	0.000073	0.000015	0.000018	0.000038	0.000664
IV	Inorganic emissions to fresh water	62.88	3.66	1.36	1.09	2.33	71.3
1	Acid (calculated as H ⁺)	0.00971	0.00015	0.00726	0.00019	0.00012	0.01743
2	Aluminium	0.00376	0.00030	0.00031	0.00000	0.00021	0.00458
3	Ammonia	0.00168	0.00010	0.00008	0.00000	0.00007	0.00193
4	Barium	0.00357	0.00049	0.00013	0.00021	0.00027	0.00467
5	Carbonate	0.38735	0.00103	0.00943	0.01358	0.00194	0.41333

Source: Mali & Garrett, (2022) and Author's calculation

The pollution by-products across all phases shown in Tables 6.2 and 6.3 indicate that the turbine manufacturing phase constitutes the highest share of air, water and solid waste pollution. The EoL phase demonstrates the potential to offset several of the hazardous by-products emitted in the environment across different phases. Heavy metal particles such as iron which constitute the highest share of turbine materials composition can also enter freshwater bodies if left untreated.

6.2.2 LCA Parameters

In this section, the key LCA parameters, namely Capacity Utilization Factor (CUF), EPBT and EROI are discussed. The results are presented below in Table 6.4.

Table 6.4: LCA Parameter results

Sr. no.	Parameters	Value
1	Capacity Utilization Factor	18.6%
2.	Energy Payback Time	1.26
3.	Energy Return on Investment	15.8

Source: Author's calculations

The CUF of 18.6% for onshore wind in comparison to 56.5% Plant Load Factor (PLF) for coal-fired TPPs (ETEnergyWorld, 2020) shows the gap that onshore wind power generation needs to cover in order to be in a position to substitute fossil fuels sources without jeopardizing India's energy security. EPBT result shows that of the lifetime of 20 years for a wind turbine, 1.26 years will be the break-even point where the electricity generated by onshore wind will be equal to the energy consumed through its lifetime. The results are comparable to Das & Banerjee, (2018) showing EPBT results of 0.5 to 1.6 years in scenario with recycling technology for different onshore wind manufacturers in India. In the case of EROI which helps in evaluating the long-term viability of onshore wind, the results can be compared to Kubiszewski, Cleveland, & Endres, (2009) which shows a range of EROI results of 4.7 – 18.9 for a range of developed and developing countries, excluding India. Since the EROI is towards the higher end, it would imply that the onshore wind technology is more efficient over its lifetime in terms of energy generated, compared to energy consumed.

6.2.3 End-of-life phase

Post-decommissioning in the EoL phase, the expected waste generation from the existing (35.6 GW) and the target (140 GW) onshore wind turbines is estimated to be 24.2 Million Tonnes (MT) and 95.2 MT, respectively. This is presented in Table 6.5.

Table 6.5: Wind turbines material composition 2018-19 (35.6 GW) and 2037 (140 GW)

Sr. no.	Material classification	35.6 GW	140 GW	Recycling Rate (in %)
I	Steel and iron materials	6,084,752	23,928,798	52%
II	Lights alloys, cast and wrought alloys	1,17,836	463,400	76%
III	Non-ferrous heavy metals, cast and wrought alloys	49,840	196,000	45%
IV	Polymer materials	2,83,020	1,113,000	
V	Other materials and material compounds (concrete, ceramic/glass)	17,565,752	69,078,793	
VI	Electronics / electrics	32,396	127,400	
VII	Lubricants and liquids	17,444	68,600	
VIII	Not specified	67,810	266,667	
IX	Total mass	24,218,850	95,242,657	

Source: Mali & Garret, (2022); IAI, (2023); UNEP, (2011) & Authors' calculations

It can be observed that there are three components of wind turbines constituting steel, copper and aluminium that can be recovered, recycled and reused in the economy. On the other hand, polymer materials which constitute plastic and chemical compounds may have to be incinerated, while concrete/ceramic may have to be landfilled, since they cannot be reused. Electronic components at a disaggregated level are highly complex and the recycling rates are different for different components, hence are not quantified here. Given the recycling procedure discussed in Chapter 3, the total cost of recycling is given in Table 6.6.

Table 6.6: Onshore wind turbine recycling costs (in USD million)

Sr. no.	Particulars	35.6 GW (2018-19)	140 GW (2037)
1.	Labour	1,511	5,943
2.	Electricity	482	1,895
3.	Maintenance	523	2,056
4.	Overheads	637	2,506
5.	Depreciation	874	3,437
6.	Admin	1,413	5,558
7.	Total cost	5,440.3	21,395.1

Source: Fonte & Xydis, (2021) and author's calculations

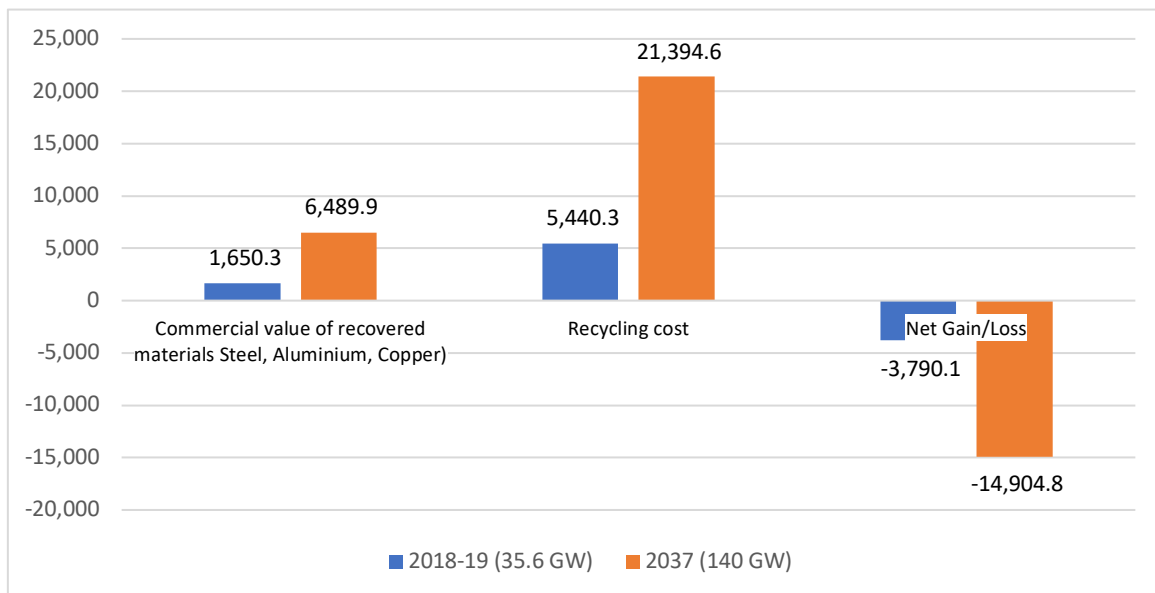
The results show that labour and administrative costs constitute the highest share of 28% and 26%, respectively. Simultaneously the economic gains from the resale of recovered materials is expected to be USD 9.6 billion (Table 6.7).

Table 6.7: Resale value of recovered materials from onshore wind turbines (in USD million)

Sr. no.	Materials recovered	35.6 GW (2018-19)	140 GW (2037)
1.	Steel	1,356	5,332
2.	Aluminium	160	628
3.	Copper	135	530
4.	Total	1,650	6,490

Source: Government of India, (2019) and Scrap Register, (2022) and Author’s calculations
 Steel which constitutes more than 82% of the total material composition of onshore wind turbines is attributed with 97% of the total resale value of recovered materials. However, it is observed that considering the cost of recycling wind turbines, there is a net loss in the entire process. This is shown in Figure 6.2.

Figure 6.2: Net benefits/loss from EoL phase with viable recycling technology (in USD million)



Source: Author’s calculations

From Figure 5.2, it is observed that the total commercial value of recovered steel, aluminium and copper constitutes only 30.3% of the total recycling cost in the EoL phase. At the current recycling rates and the economic value of the respective materials, there is a net loss in the entire recycling activity. Nevertheless, with the commercial gains of recycling 140 GW wind turbines of USD 6,489 billion, and an approximate cost of USD 1,350/KW of wind turbines, the recovered steel, aluminium and copper can potentially contribute to the commissioning of 4.8 GW additional turbines through the circular economy framework. On the other hand, there are simultaneous energy and GHG emission savings from substituting virgin material manufacturing of these materials.

This is also expected to lead to significant air, water and solid waste pollution savings. This has been shown in a tabular format in Table 6.8.

Table 6.8: Total pollution savings from recycling 140 GW onshore wind

Sr. no.	Particulars	35.6 GW	140 GW	Unit
1.	Energy savings	7,767.4	30,545.8	gWhs
2.	Solid waste (avoided landfilling/incineration)	3.3	12.9	Million Tonnes
3.	GHG emission savings	3.0	11.8	Million Tonnes

Source: Mali & Garrett, (2022) and author's calculations

The embodied energy and pollution savings arise from the substitution of virgin material manufacturing by the recovered Steel, Copper and Aluminium which can be reused in turbine manufacturing. Despite the significant positive environmental benefits from the circular economy prospects in the wind industry, a net loss in the recycling activity implies penalizing the producers for undertaking such an exercise in the current scenario.

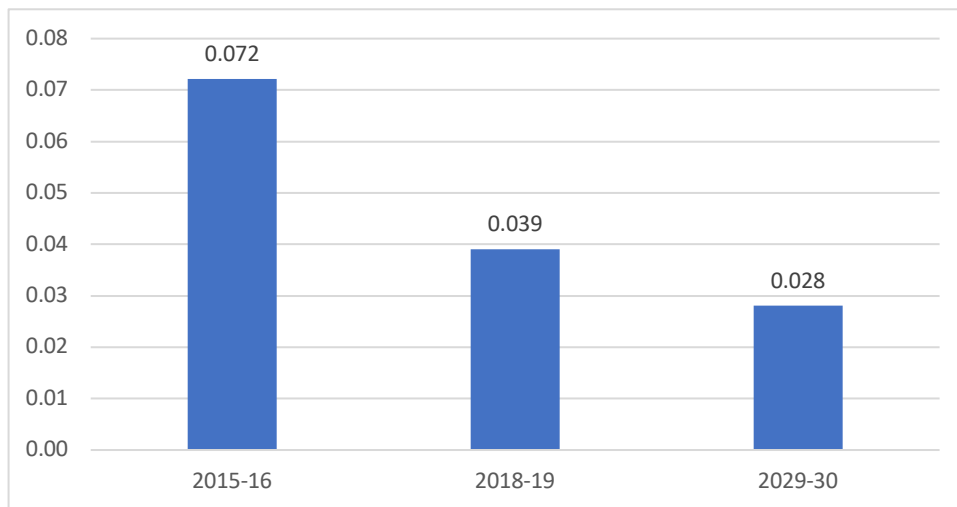
6.3 Discussion

The Onshore Wind LCA results indicate two key results. Firstly, the usage of energy efficient raw materials in the manufacturing phase will contribute significantly towards reducing the embodied energy requirement of Onshore wind energy. An alternative is the altogether replacement of virgin material manufacturing attributed to wind turbine manufacturing of inputs such as steel, copper and aluminium, through the 3R strategy of Recycle, Reduce and Reuse in the End-of-Life phase of wind turbines. The resulting energy, GHG emissions savings and the avoided solid waste landfilling/incineration through the 3R strategy are presented in Table 7. However, given the current recycling scenario in terms of the expected recycling cost and commercial value from the resale of recovered materials, it is observed that the producer will incur a 'net loss' from undertaking the recycling initiative. Despite environmental benefits from the Circular Economy initiative, the producer is expected to undertake the 3R strategy only if it yields economic gains.

6.3.1 Incorporating recycling cost in electricity tariff

Wind power continues to remain an attractive source of power generation due to windfall gains from declining tariff rates over the years (Figure 6.3).

Figure 6.3: Wind tariff trends in India (\$/kWh)



Source: RBI, (2021); Niti Aayog, (2021)

The steep decline in wind tariffs has been witnessed post 2017-18, which is attributed to the switch from the feed-in tariff system to competitive bidding (Sharma & Sinha, 2019). However, the current power generation tariff rates exclude the cost of recycling in the EoL phase, thus showing a deflationary trend over time. With the incorporation of the recycling costs, the wind tariffs may see a small increase, thus making it competitive with other energy sources in the power market.

There are several studies estimating the LCOE for wind and other energy sources in India. According to Kumar, Pal, Kar., Mishkra, & Bansal, (2022), the LCOE for wind energy is estimated to be \$ 0.039/kWh. However, this constitutes only the capital and operational cost that is expected to be incurred by the producer. In our study, the recycling costs are estimated based on the tonnes of waste generation for 140 GW worth of wind turbines in the EoL phase, post-decommissioning. However, we further estimate the recycling cost in per kWh terms.

In the previous section, the CUF estimated to be 18.6% indicates the actual electricity generated per year from installed wind capacity in 2018-19 (35.6 GW). Assuming the CUF to remain constant, the electricity generated from 140 GW capacity throughout its lifetime (20 years) is calculated which is 2,28,110 gWh/year which is equivalent to 45,62,208 gWh for 20 years. Given the cost of recycling 140 GW wind turbines in the EoL phase to be USD 21,395 million (Table 5), The recycling cost per kWh is estimated to be \$ 0.0046/kWh. Provided that the cost of Recycling is to be included in the LCOE, we estimate the ‘Levelized Cost of Recycling of Wind turbines’.

This is presented below:

$$\begin{aligned} \text{Cost of Recycling (LCOR) (140 GW)} &= \frac{\text{Recycling cost}}{\text{Lifetime electricity generation}} \\ &= \frac{\$ 21,395 \text{ million}}{45,62,208 \text{ gWh}} = \$ \mathbf{0.0046/kWh} \end{aligned}$$

Through the inclusion of the Levelized cost of recycling along with LCOE, the revised cost, including recycling costs is provided below.

$$\text{LCOE} + \text{Cost of recycling} = \frac{\$0.039}{\text{kWh}} + \frac{\$0.0046}{\text{kWh}} = \$\mathbf{0.045/kWh}$$

The result above indicates that with the promotion of the Extended Producers' Responsibility (EPR), the investment the producer has to incur including the recycling costs is \$0.045/kWh.

In Figure 5.2, it is observed that through the recycling and resale of recovered materials from 140 GW wind turbines, a net loss of USD 14,904 million is incurred. This implies the subsidization of approximately **\$106/KW** equivalent to the cumulative losses from 140 GW will contribute towards achieving the break-even point.

Further advancements in recycling technology, increasing the resale value of recovered materials economies of scale with further expansion of cumulative capacity installed is expected. The net economic gains are expected to be higher than the break-even point that has been theoretically determined here, given the current resale prices and assumption of recycling technology.

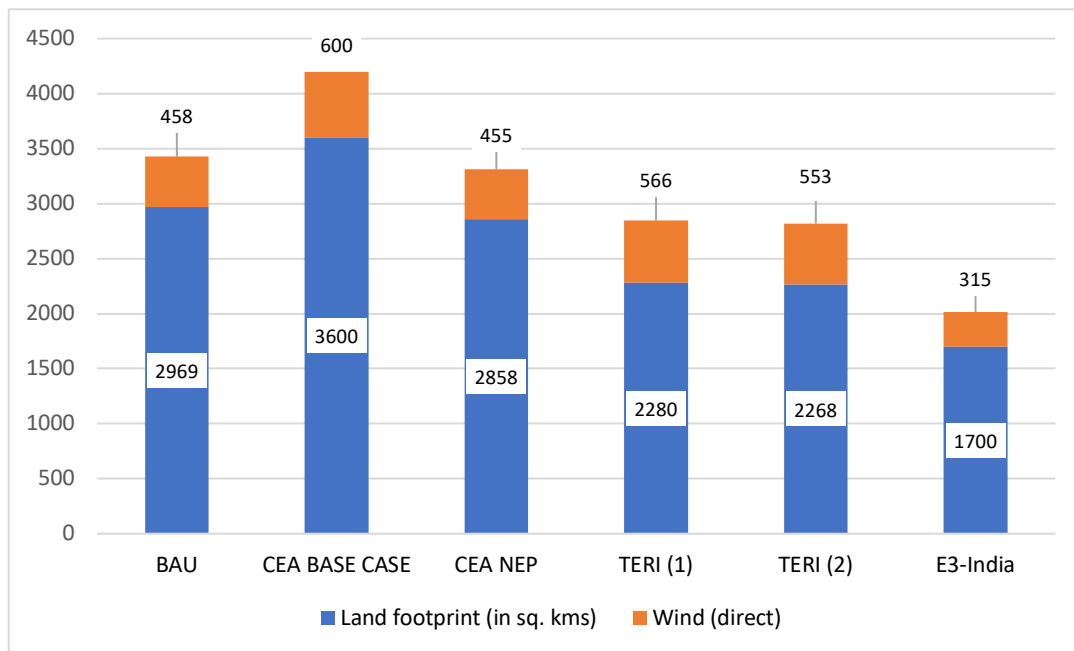
The rise of carbon credits also provides an interesting alternative to subsidization by the government, for incentivising the producers to recycle wind turbines in the EoL phase. The carbon credit certificates imply the monetary value of the quantity of GHGs that have been abated by the country/organization (Blaufelder, Levy, Mannion, & Pinner, 2021). Through the abatement of GHGs by recycling in the EoL phase, the producers can be rewarded with monetary compensation such that both, economic and environmental gains can be achieved.

6.3.2 Land footprint of onshore wind capacity installation

With increasing onshore wind capacity installation, the demand for land is also expected to increase for installed wind turbines and supporting equipment. The land requirement for wind farms is estimated to be 5-9 MW/sq. kms of which 3% is a direct requirement (Chakravart & Somanathan, 2020). This implies that the actual land required to install only the tower of the wind turbine is 3% of the total land requirement, while the rest of the area is for the supporting structures such as transformers, wires and cables, concrete foundation etc.

Based on the different projections of installed wind capacity as presented in different scenarios in Chapter 3, the land footprint is presented in Figure 6.4.

Figure 6.4: Land footprint of installed wind capacity 2030 (in sq. kms)



Source: Authors' calculations

Note: The installed GW capacity by 2030 measured in different scenarios is discussed in Chapter 3.

Figure 6.4 shows the installed wind capacity in different scenarios resulting in, on average 0.2% requirement of total arable land in India (1553690.8 sq. km). Given that onshore wind turbines are generally installed away from urban areas and largely on agricultural and livestock grazing land, any social, or local conflicts need to be avoided from such wind projects.

6.4 Concluding remarks

The Government of India has set an ambitious long-term target of achieving 140 GW onshore wind capacity by 2030 in its efforts to tackle climate change. To this end, this chapter evaluates the energy and environmental ramifications of incremental onshore wind capacity installation throughout its lifetime using attributional LCA methodology. The study finds that India will achieve the target only by the year 2037 in the Business-as-usual scenario. With the current electricity market share of only 10.3%, wind energy cannot substitute TPPs for power generation in the short to medium run. Nevertheless, a robust indigenous turbine manufacturing ecosystem (more than 90% market share) remains one of the key strengths of the wind turbine industry, providing scope for accelerating the annual wind capacity installations in the country. In terms of energy efficiency, the manufacturing phase is attributed to the highest share of energy requirement and simultaneously, the most emission intensive phase of onshore wind turbines. With the adoption of viable turbine recycling technology, the energy intensity in

turbine manufacturing can be reduced through the reuse of recycled materials such as steel, copper and aluminium in the EoL phase. Another strategy is to utilize energy efficient raw materials which can be implemented through the decarbonization strategy for carbon-intensive sectors such as steel and cement. Even though it is beyond the scope of the current study, it is important to note the practical alternative options available at the behest of the producer.

The cost of recycling 140 GW of decommissioned onshore wind turbines is expected to reach USD 21.4 billion. The resale of recovered materials generates an approximate revenue of USD 6.4 billion still leads to a net loss of USD 14.9 billion. Nevertheless, a further 6.8 GW of wind turbines can be installed through the generated revenue. The recycling costs can be further reimbursed through proper government subsidization strategies and complemented with the Extended Producer Responsibility¹² (EPR). Through incentivizing EPR, the producer undertakes partial or full responsibility for the recycling of wind turbines in the EoL phase, which has the potential to yield economic benefits. The inclusion of the recycling cost in the LCOE provides the financial leverage for the producer, essential for undertaking the recycling of wind turbines in the EoL phase, without incurring economic losses. However, this is only a theoretical estimation provided here, since the availability of turbine recycling technology is still scarce as has been discussed earlier. With further developments through scientific innovations, the Circular Economy framework presented in this study can be further adopted through the implementation of the 3R strategy.

The main purpose of conducting an Attributional LCA study for Onshore wind energy is to estimate and quantify the GHG emissions through embodied energy consumption and the waste abatement costs through recycling technologies. Through this estimation, the Economy-Energy-Environmental impact at the Macro level using the Input-Output-Consequential LCA framework can be conducted and has been discussed in the next chapter.

¹²The wind turbine manufacturer will be obligated to undertake the decommissioning and recycling of wind turbines at the end-of-life stage.

CHAPTER 7 CONSEQUENTIAL LCA EXERCISE

In this chapter, the total macroeconomic impact of Solar and Wind capacity installation is studied using the Indian Input-Output Table 2018-19 and the cost of waste abatement in the End-of-life (EoL) phase (estimated and presented in the Attributional LCA studies in Chapters 4 and 5) is accounted in the System of Economic and Environmental Accounting (SEEA) framework to calculate the Green-GDP.

The forecasts of solar and wind capacity installations presented in chapters 4 and 5 have indicated that the government determined 280 GW solar and 140 GW wind capacity targets will be achieved by 2035 and 2037, respectively. There are several baseline projections discussed in Chapter 3 that indicate that the targets will be achieved only post-2030. In section 7.1, the six different baseline projections considered in this study (and elaborated in detail in Chapter 3, section 3.3) have been evaluated in comparison to the Business-As-Usual scenario prepared uniquely for this study, to highlight the variations in results across the two scenarios using the I-O model. Section 7.2 provides the macroeconomic and inter-industry impact results from the two scenarios across all the baseline projections.

The GHG emission savings by substituting coal power in different scenarios and the incremental waste generation from additional solar and wind capacity installations is presented in Section 7.3. Using the calculated waste abatement cost from chapters 5 and 6 for solar PV modules and wind turbines, respectively, Section 7.4 presented the resulting environmental and health cost benefits from recycling in the EoL phase are accounted for and the Environmentally-adjusted GDP is estimated using the SEEA framework.

7.1 Comparison between different baseline projections

The macroeconomic impact of solar and wind energy on Total output, GDP and Employment across different baseline projections has been studied. In order to pursue this objective, the existing Indian Supply Use Table 2018-19, in which the electricity sector is not differentiated by energy source, was split into ‘Solar energy’, ‘Wind energy’ and ‘Other electricity sources’¹³.

In Chapters 5 and 6, the Attributional LCA exercise for solar PV and wind energy was undertaken in which the raw materials acquisition for the production phase and the solar PV modules and wind turbines was identified and their direct energy and environmental burden was estimated. In this chapter, the monetary cost of producing and installing solar PV modules

¹³ The methodological framework is discussed in Chapter 3, section 3.2 and data construction and sources is presented in Chapter 4, Section 4.2.

and wind turbines, using the inputs identified in the preceding chapters is estimated. For solar energy, the lifetime energy and environmental burden from rooftop and ground-mounted PV was different, owing to the differences arising in the construction and operational phases of these two types. However, the inputs used in both forms of solar PV installations are the same, thus, the input cost structure, which is attributed to the production phase will also be identical in per unit terms. Thus, the cumulative input cost of solar industry constructed in the modified I-O framework is inclusive of both types of solar PV installations. For wind energy the monetary cost of raw material acquisition for wind turbine manufacturing identified in Chapter 4 has been estimated which forms the input cost structure of wind energy industry in the I-O framework.

The significance of treating solar and wind energy industries separately from the rest of the energy sources is to identify their unique input cost structures. For instance, the input cost structure of coal-fired thermal power plants which will constitute the largest share of the 'Other electricity sources' industry in the I-O table will be vastly different in terms of the type of inputs as well as the degree of monetary valuation, since it constitutes 2/3rd of the total installed capacity in India as of March 2019 (CEA, 2019). The output flow of solar, wind and other electricity sources, that is the electricity being consumed by different industries within the processing sector and the Final demand components of the I-O table is also determined based on their share of electricity generation in the year 2018-19 (This has been discussed in detail in Chapter 3).

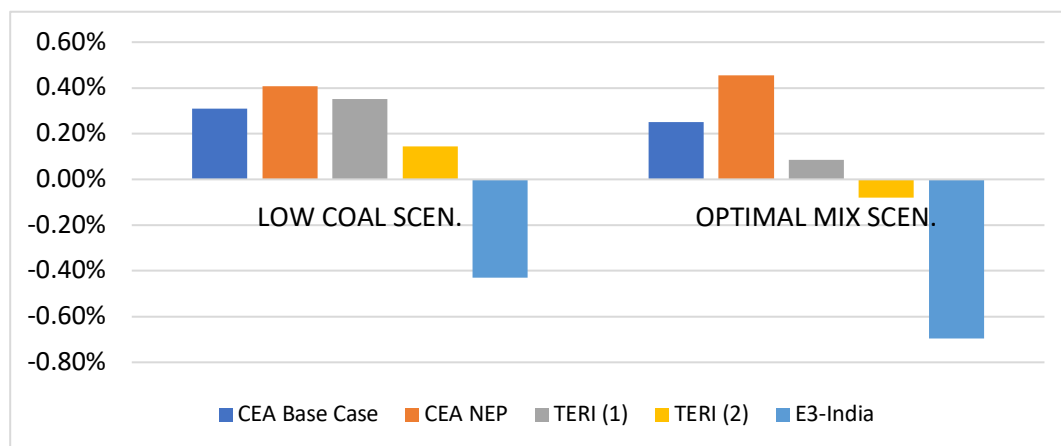
With solar and wind energy being treated separately from other electricity sources within the I-O model, the electricity consumption by other industries based on the type of energy source has also been captured (discussed in detail in Chapter 3). Thus, the exclusive backward and forward linkages arising from their inter-connectedness with rest of the sectors can be identified within the I-O framework and the resulting aggregate impact on the economy can be captured. These include our own unique BAU 2030 forecasts, two Central Electricity Authority (CEA), the Government of India's baseline forecasts and three internationally recognized model forecasts constituting two by TERI and one from the E3-India model (presented in Table 4.10 in Chapter 4). This exercise is conducted for the comparison of the baseline projections provided by different government bodies and other international/national organizations with our unique BAU scenario such that the variations in results are highlighted across the two scenarios using the I-O model.

The two scenarios considered for this study focus on the promotion of solar and wind energy sources in India's electricity mix portfolio with the aim of a steady reduction in the reliance on coal for power generation. In the 'Low Coal scenario' (Scenario 1), the coal power generation is expected to be reduced by 58,000 gWh by 2030 according to the Ministry of Power, Government of India (GOI, 2022). However, they do not provide a strategy on how the reduced coal power will be balanced by other electricity sources within India. As discussed in Chapter 1, coal plays a significant role in ensuring India's energy security with a current share of 74% in the total electricity mix (CEA, 2022). Thus, the strategy of curtailing coal power generation without proper grid balancing strategy is a serious flaw in India's clean energy transition. In this study, the 58,000 gWh of curtailed annual coal power is expected to be met by solar and wind energy sources by 2030 according to their projected combined shares (Figure 4.11 in Chapter 4). It is observed that, except TERI (2) baseline, all the scenarios provide a higher emphasis on solar power, compared to wind energy. This is also aligned with the national government's 450 GW RE target in which solar power is attributed with a higher share (280 GW), compared to wind energy (140 GW). Thus, it is expected that solar power will undertake a larger burden of grid balancing to support the curtailment of coal power in the near to long-term future. Given the different shares of the combined solar and wind energy mix, the macroeconomic impact over the BAU scenario using the I-O framework is studied.

In the 'Optimal mix scenario' (Scenario 2) as well, the aim of a greener electricity mix is pursued but the approach is different from the Low coal scenario. In this scenario, the share of solar and wind energy in the total electricity mix portfolio is targeted to be increased, rather than focusing on how coal power is to be reduced. In different 2030 baseline projections, coal power is also expected to increase compared to 2022 to meet the rising demand and the ever-increasing population in the country. Simultaneously, solar and wind energy generation is targeted to increase at a higher rate such that it will constitute a higher share in 2030 compared to 2022 where currently it is 2.53% and 4.7%, respectively. Amongst all the baseline projections discussed in Section 4.3 in Chapter 4, it was observed that the Central Electricity Authority's National Electricity Plan 2030 (CEA NEP 2030) provided the highest combined share of solar and wind energy, of 23% and 12%, respectively (Figure 4.3 in Chapter 4). This is considered to be the optimal solar energy mix compared to other baseline scenarios. Thus, the baseline projections are modified such that the solar and wind energy achieve the optimal shares and consequently, the macroeconomic impact compared to our BAU scenario is studied.

The change in total output in both scenarios compared to the BAU scenario is presented in Figure 7.1.

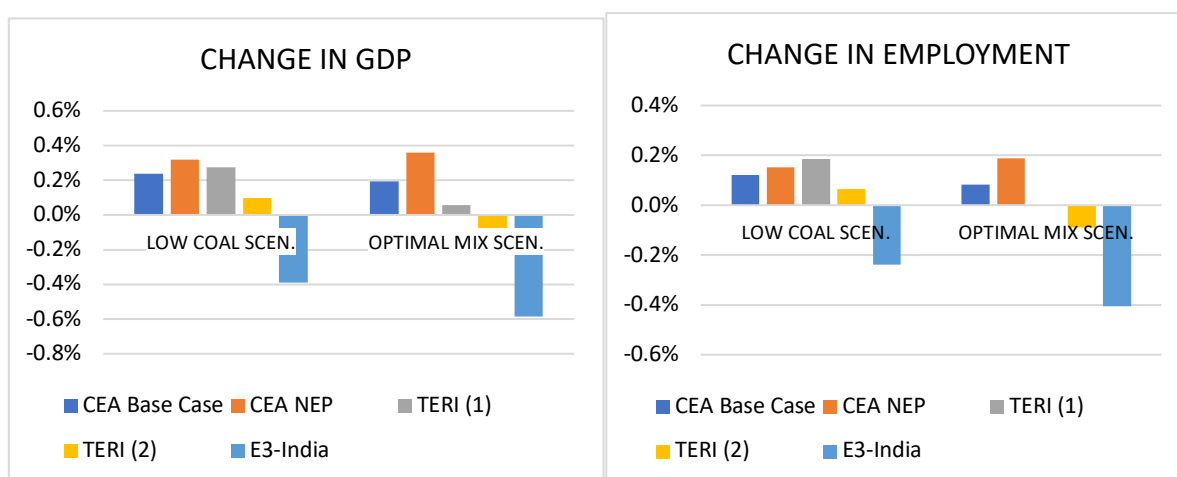
Figure 7.1: Change in total output over BAU scenario (in percentage)



Source: Authors' calculations

The results indicate that four out of five baseline projections' total output increase is higher than the BAU forecasts, resulting in positive output impact. The E3-India results show the solar and wind energy impact on total output to be lesser than BAU. This indicates that the majority of baseline forecasts provide an optimistic outlook regarding the economic impact of greening of the electricity grid through incremental solar and wind energy.

Figure 7.2: Change in GDP and Employment over BAU scenario (in percentage)



Source: Authors' calculations

Similarly, the results from the two scenarios also indicate a positive, but minimal impact on the GDP and Employment over BAU across most of the projections. In the case of employment, the negative, yet minimal impact is seen in three out of five cases in the optimal mix scenario.

This implies that a steady increase in solar PV and wind energy investments to increase the power generation share in the electricity mix while reducing the share of coal power leads to a net employment/GDP loss, compared to the BAU scenario.

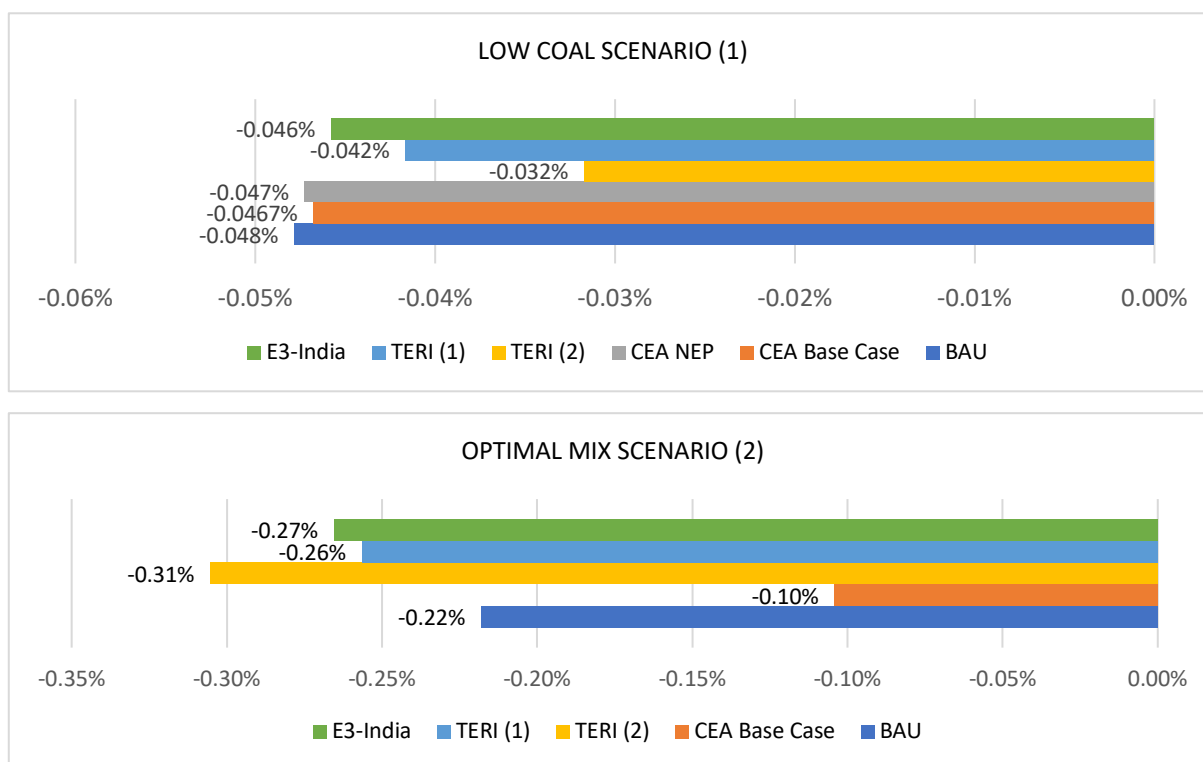
7.2 Macroeconomic and Inter-industry impact from different scenarios

In the previous sub-section, the different baseline projections were compared with the BAU forecasts that were constructed for this study. In this sub-section, the impact of both scenarios is compared with the respective baseline forecasts and the range of net macroeconomic and inter-industry impact across different cases. As presented in the previous sub-section, there are six baselines considered for this study (Presented in Table 3.11 in Chapter 3). The novelty of considering different projections is to highlight the convergence of similar results such that it provides more weightage toward policy prescriptions.

In Chapter 3, the discussion on the substitutability of coal by solar/wind was discussed (Table 3.15) in which it was presented that 1 GW of coal is not equivalent to 1 GW of solar/wind that has been observed for different baseline projections. This implies that the per unit (GW) power generation from coal TPPs (gWh) is much higher compared to Solar/Wind energy. Thus, a uniform 58,000 gWh coal power reduction in coal (Low Coal scenario) and an increase in the share of solar and wind energy mix to 23% and 12%, respectively by reducing the equivalent amount of coal power in different baseline projections (in Optimal Mix scenario) have a disproportional negative impact on the economy.

Using the I-O model the macroeconomic impact across total output, GDP and employment is presented. Figure 7.3 presents the impact on total output in both scenarios. Figure 7.4 represents the similar impact on GDP and Employment in both scenarios.

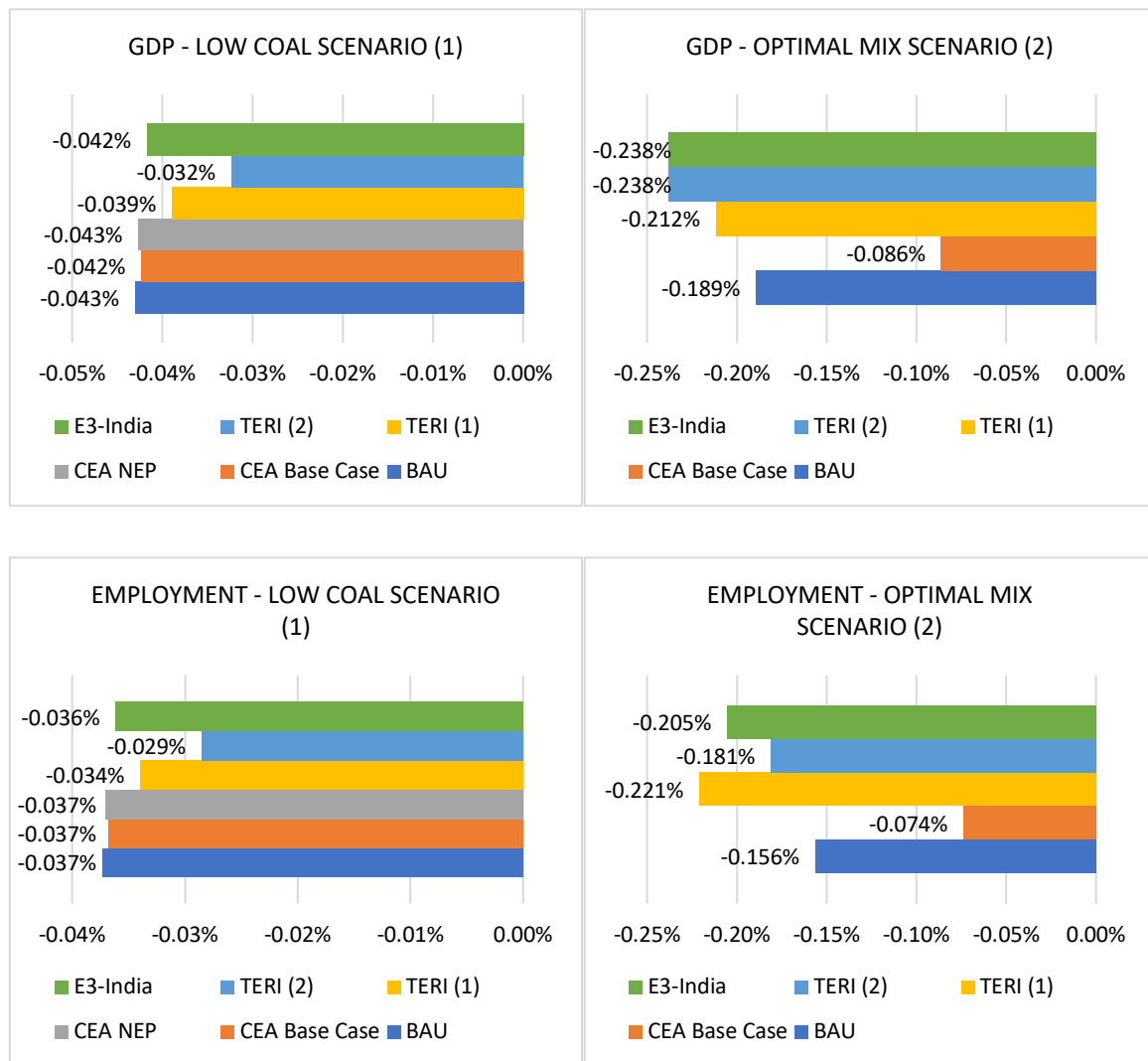
Figure 7.3: Change in total output in both the scenarios (in percentage terms)



Source: Author's calculations

In both scenarios, a decrease in total output is witnessed, resulting from the curtailment of thermal power generation. Despite an increase in solar and wind sector manufacturing and across its supply-chain, the overall decrease in output is attributed to the relatively stronger backward linkages of the coal sector with rest of the Indian economy. The coal is majorly consumed by the electricity sector in India, (about 64%), followed by steel (8%) and cement sectors (5%) (GOI, 2022). For the supply of coal, there is a monopoly of the government-owned Coal India Limited (CIL) which produces almost 84% of total coal production in the country and is also the single biggest coal producing company in the world (Srivastava, 2017). It also has several coal producing subsidiary companies across different states in India. Thus, it is the single largest driver of coal production and supply in the country and any reduction in its production and supply to its largest buyer, that is the Thermal power plants will lead to a negative impact. However, the negative impact is marginal, since it is partially subsided by the incremental production of solar and wind power generation. The solar and wind industries are at a very nascent stage in their development and its positive contribution is not enough to compensate for the negative impact of curtailing thermal power generation.

Figure 7.4: Change in GDP and Employment in both scenarios (in percentage terms)



Source: Author's calculations

India produces 700-800 Million Metric Tonnes (MMT) of coal annually, contributes 0.7% to the national income (Spencer, Pachouri, Renjith, & Vohra, 2018), and accounts for 23% of the Gross Value Addition of the Mining and Quarrying industry (GOI, 2019). The coal sector is one of the largest employers in the country. Approximately 1.2 million people are directly dependent on the coal sector while indirect employment especially through coal logistics and transportation is significantly higher. (Lahiri-Dutt, 2016). About 40% of India's districts have coal dependency of varying degrees (Aggarwal, 2021). It is expected that additional 0.5 million jobs will be created in the transportation sector (Spencer et al., 2018). Approximately 44% revenue of the Indian Railways (also one of the largest employers in the country) is generated from coal freight transport (Kamboj & Tongia, 2018). The Indian coal mining sector has also

been subject to gradual mechanization (Jacobs et al., 2019), however, compared to the advanced nations, India is still far off and the coal sector remains a highly labour-intensive industry and is a source of livelihood for millions. As a result, reducing reliance on thermal power generation in the power sector without proper policy intervention for covering the economic downside can have significant negative consequences.

The inter-industry impact across both the scenarios is discussed in which first, the sectors which are positively impacted by the changes in the electricity mix in both scenarios are presented in Table 7.1 and the sectors which will incur a decrease in demand are presented in Table 7.2. The range of results across different baseline projections are presented here.

Table 7.1: The economic sectors positively impacted from the scenarios (in percentage terms)

Sr. no	Sector	LOW COAL SCENARIO (1)					OPTIMAL MIX SCENARIO (2)				
		BAU	CEA Base	CEA NEP	TERI (1)	TERI (2)	E3-India	BAU	CEA Base	TERI (1)	TERI (2)
1.	Inorganic chemicals	0.42% to 0.48%					0.78% to 2.5%				
2.	Cement	0.3% to 0.64%					0.54% to 1.57%				
3.	Iron and steel foundries	0.19% to 0.45%					0.27% to 0.97%				
4.	Iron ore	0.15% to 0.41%					0.14% to 0.77%				
5.	Iron and steel Ferro alloys	0.12% to 0.33%					0.1% to 0.61%				

Source: Authors' calculations

The usage of Cement is for the concrete support structures that form the foundation of wind turbines, constituting 72% of the total material composition (Mali & Garrett, (2022)). It is essential to form the foundation structure on which the wind turbines are installed. Apart from the foundation, the wind turbines which are installed over the cement structure are predominantly made of Iron and steel materials, constituting 87% of total material composition (Mali & Garrett). Most of the steel is used in the production of the tower which can be 100 meters long. Apart from that the nacelle, gearbox and the generators also constitute steel in varying proportions. Given its high degree of usage, the results show a significant impact on the iron ore and its ancillary industries, arising from incremental wind turbine installations.

The inorganic chemicals sector has the highest impact arising from the solar PV industry. Due to variations in weather, the PV modules are subject to stability issues, resulting in poor

performance over a period of time. The Encapsulation layer of PV module, which uses these polymer-based materials is one of the multiple ways in which these stability issues can be mitigated (Gaddam, Pothu, & Boddula, 2021). It is expected to provide higher stability for conversion efficiency.

Table 7.2: The economic sectors negatively impacted from the scenarios (in percentage terms)

Sr. no	Sector	LOW COAL SCENARIO (1)						OPTIMAL MIX SCENARIO (2)				
		BAU	CEA Base Case	CEA NEP	TERI (1)	TERI (2)	E3-India	BAU	CEA Base Case	TERI (1)	TERI (2)	E3-India
1.	Copper ore	– 1.4% to – 2%						– 5.66% to – 15.33%				
2.	Coal and Lignite	– 0.6% to – 0.82%						– 1.5% to – 4.49%				
3.	Coal tar products	– 0.46% to – 0.57%						– 1% to – 3.10%				
4.	Crude petroleum	– 0.43% to – 0.47%						– 0.76% to – 2.56%				
5.	Electric cables, wires	– 0.18% to – 0.38%						– 0.94% to – 2.66%				

Source: Author’s calculations

Currently in India, approximately 65% of coal consumption is attributed to thermal power plants, followed by Iron and Steel (8.4%), Construction (0.9%) chemical and chemical products (0.2%) etc. (GOI, 2021). With a reduction in Thermal power generation, naturally, the demand for coal will go down significantly. Similarly, coal tar is also used for heating purposes or to fire boilers (Speight, 2015). Copper ore which is used primarily in power cables, grounding networks, transformers and generators that are linked with thermal power plants will also witness a reduction in demand with the curtailment of electric cables and wires. The thermal power generation involves heat transfer processes, steam generators, heat exchangers, coolers, condensers, tanks, pipework and valves aid fittings. The application of copper alloys is well-suited for this purpose due to its good corrosion resistance with heat transfer properties (CDA, 2023). As coal-fired TPPs constitute 51% of India’s installed power capacity (CEA, 2022), a reduction in its capacity will have a significant impact on copper demand in the country.

Sections 7.1 and 7.2 discussed above provide a more comprehensive understanding of the results after considering different baseline projections. While Section 7.1 evaluated the results

being provided by different baseline projections, Section 7.2 highlights the variations as well as convergence of results across both the scenarios developed for this study. It was observed that the incremental solar and wind power capacity by substituting coal power leads to a minimal, yet negative impact on the economy. The convergence of similar trends across different baselines provides further weightage from a policy perspective, since the impact on the economy is observed to be similar.

Given the reduction in coal power in both the scenarios, the total GHG and non-GHG emission savings is discussed in the next sub-section.

7.3 Environmental Impact: GHG and non-GHG emission savings

While in the previous sub-sections it is observed that an increase in the solar and wind energy with a simultaneous reduction in the electricity mix will lead to a net loss to the economy, there are nevertheless, environmental benefits arising from reduced coal power generation. With a high threshold of coal usage in TPPs, the share of power sector in environmental pollution is also high, accounting for 51% of SO₂, 43% of CO₂, 20% of Nitrogen Oxides (NO_x) and 7% of PM_{2.5} emissions (Pachouri & Saxena, 2020). Given the emission factors presented in Table 4.8 for different GHG and non-GHG emissions in Chapter 4, the emission savings have been quantified in both scenarios.

In ‘Low coal scenario (Scenario 1)’ a 58,000 gWh coal power reduction is proposed in all baseline projections (discussed in detail in chapter 3). Given that the macroeconomic and inter-industry impact will be different in different cases since the capacity of solar and wind energy to substitution coal-TPPs is varying, the environmental impact of 58,000 gWh reduction is the same across all baseline projections. To this end, the GHG and non-GHG emission savings are presented in Table 7.3.

Table 7.3: GHG and non-GHG emission savings in the Low Coal scenario

Sr. no.	Emissions	Quantity	Unit
GHG emission savings			
1.	CO ₂	55.2	Million tonnes
2.	NO _x	0.3	Million tonnes
3.	CH ₄		Million tonnes
Non-GHG emission savings			
3.	Hg	0.0058	Thousand tonnes
4.	PM ₁₀	56.8	Thousand tonnes
5.	SO _x	423.4	Thousand tonnes
6.	Fly Ash	13,579	Thousand tonnes

Source: Author’s calculations

Similarly, the GHG and non-GHG emission savings in the ‘Optimal Mix scenario’ in which the optimal combined share of 23% and 12% of solar and wind energy, respectively in the electricity mix portfolio is pursued in each case (discussed at length in Chapter 4). This has been presented in Table 7.4.

Table 7.4: GHG and non-GHG emission savings in the Optimal Mix scenario

Sr. no.	Emissions	BAU	CEA Base Case	TERI (1)	TERI (2)	E3-India	Unit
GHG emission savings							
1.	CO ₂	208.1	84.1	269.1	203.8	301.2	In million tonnes
2.	NO _x	1.0	0.4	1.3	1.0	1.5	In million tonnes
3.	CH ₄	139.8	56.5	180.7	136.9	202.3	In million tonnes
Non-GHG emission savings							
4.	Hg	0.022	0.009	0.028	0.021	0.032	In thousand tonnes
5.	PM ₁₀	0.213	0.086	0.276	0.209	0.308	In thousand tonnes
6.	SO _x	1.696	0.685	2.193	1.661	2.455	In thousand tonnes
7.	Fly ash	50,940.0	20,577.4	65,847.3	49,886.1	73,711.0	In thousand tonnes

Source: Author’s calculations

The different GHG emission sources that are saved in different scenarios ranges between 1.6 – 5.8 Billion tonnes of CO₂eq. saved by 2030. In 2023, India was the third largest global GHG emitter with 3.9 Billion Tonnes (BT) CO₂eq.¹⁴, behind the US (6 BT CO₂eq.) and China (15.7 BT CO₂eq.) (Tiseo, 2023). While the data or studies on the cumulative GHG emissions estimated in India by 2030 in the base case is not available, the optimal mix scenario exceeds the target of achieving 1 billion tonnes of carbon reduction by 2030.

These emissions apart from generating negative environmental consequences which are well-documented in literature, can also have significant health impacts as well. The emission-related health impacts that can be saved have been documented in Table 7.5.

Table 7.5: The Health impacts of GHGs and non-GHGs

Sr. no.	Emissions	Impacts
GHG emission savings		
1.	CO ₂	It is the primary greenhouse gas produced from burning fossil fuels which leads to respiratory illnesses
2.	NO _x	It contributes to Smog and respiratory illnesses
3.	CH ₄	It can cause cancer, affect neurological and reproductive defects.
Non-GHG emission savings		

¹⁴ 1 kg NO_x = 298 kg CO₂eq. and 1 kg CH₄ = 25 kg CO₂eq. (CBS, 2024).

3.	Hg	Mercury and other heavy metals have been linked to neurological and developmental damage to humans and other animals
4.	PM ₁₀	It contributes to smog, haze and respiratory and lung illnesses
5.	SO _x	It contributes to acid rain and respiratory illnesses
6.	Fly Ash	It creates residues created when power plants burn coal

Source: (EIA, 2022; ALA, 2022)

Given these negative environmental and human-health impacts, India has also periodically updated its legislations, related to the Emission standards from the Thermal Power Plants (TPPs). This has been presented in Table 7.6.

Table 7.6: Chronology of emission standards for TPPs

Sr. no.	Date of TPP installation	PM	SO ₂	NO _x	Mercury (Hg)
1.	Before December 2003	100 mg/Nm ³	600 mg/Nm ³ < 500 MW 200 mg/Nm ³ ≥ 500 MW	600 mg/Nm ³	0.03 mg/Nm ³ for ≥ 500 MW
2.	January 2004 to December 2016	50 mg/Nm ³	600 mg/Nm ³ < 500 MW 200 mg/Nm ³ ≥ 500 MW	300 mg/Nm ³	0.03 mg/Nm ³
3.	January 2017 onwards*	30 mg/Nm ³	100 mg/Nm ³	100 mg/Nm ³	0.03 mg/Nm ³

Source: (GOI, 2015)

Note: *The latest amendment to the Environment (Protection) Rules, 1986

The latest amendments which are deemed to be on par with the standards set in the US, EU and China (WRI, 2012), have made it mandatory to implement Emission Control Systems (ECS) within 2 years from the date of notification, that is January 2017 (GOI, 2015). However, the deadline was pushed to December 2022 due to the incapability of upgrading all TPPs with ECS in such a short period (Pachouri & Saxena, 2020). There are several Pollution Control Technologies (PCTs) which can be installed in coal-fired TPPs at different stages of operation – pre-combustion, in-combustion and post-combustion for control of three main GHG emissions, namely, SO_x, NO_x and PM. These emissions have the potential to be dispersed as far as 200 kms away from the power plant site (Guttikunda & Jawahar, 2014) with life threatening impacts on human health (Cropper, et al., 2021). Several studies have shown that GHG emission factors differ based on coal composition and power plant characteristics (Garg, Kapshe, Shukla, & Ghosh, 2002; Chakraborty, et al., 2008; Mittal, Sharma, & Singh, 2014). The GHG composition also varies between domestic coal and imported coal, with the former

constituting high PM emissions due to higher ash content (30-40%), while the latter constitutes higher sulphur content (>0.5%) (CSTEP, 2018). In general terms, the curtailment of coal power does lead to GHG and non-GHG emission savings that also contribute towards cost savings through reduced negative environmental and human health impact. This has been captured using the System of Economic and Environmental Accounting (SEEA) framework that has been discussed in the next sub-section.

On the other hand, the waste generation from incremental solar PV and wind capacity installation is also presented in Table 7.7.

Table 7.7: Scenario-wise Solar PV module and wind turbine waste accumulation (in tonnes)

Sr. no.	Particulars	Solar PV modules		Wind turbines	
		Scenario 1	Scenario 2	Scenario 1	Scenario 2
1	BAU	1970.0	7315.7	6514184.1	24978096.7
2	CEA Base (2020)	1730.6	4067.9	5431538.8	2036827.05
3	CEA NEP (2022)	899.9	-	6110481.2	-
4	TERI (2018)	1661.3	13126.9	7468365.9	2138086.45
5	TERI (2020)	1107.6	23778.2	10184135.3	81344734
6	E3 2030	2007.5	11877.1	8147308.2	36088143.4

Source: Authors' calculations

Based on the incremental capacity addition in the respective scenarios to substitute coal power in the electricity mix, additional waste is also expected to be generated in the economy post-decommissioning in the End-of-life phase (The material-wise waste generation in each scenario is presented in Tables A8 to A11 in the Appendix). The toxic compounds in untreated waste such as cadmium, indium, and molybdenum pose maximum human health risks via soil-dermal contact, followed by soil-ingestion pathways. Lead also poses significant cancer risk through all pathways. Suresh et al., (2019) highlight that while glass and aluminium, constituting more than 80% of PV weight are non-hazardous in nature, other materials such as polymers, lead, cadmium telluride, silicon and metallic compounds are classified as potentially hazardous. The monetary impact of untreated and unrecycled waste is discussed in the next section.

7.4 Environmentally-adjusted GDP estimate

This study aims to estimate the Environmentally-adjusted GDP or 'Green GDP', which is a modified GDP figure adjusted for the environmental costs of economic activities, using the SEEA framework (Chakraborty & Mukhopadhyay, 2014) that has been discussed at length in Chapter 4. Two components are considered simultaneously: First, the environmental and health cost savings resulting from the curtailment of coal power generation while being substituted

by solar and wind energy is quantified. The estimates have been compiled from TERI (2013) for Mining, Chakravarty & Somanathan (2021) for Agriculture and Gupta & Somanathan (2017) for Health/Mortality and have been presented in Chapter 4, Table 4.9. Second, the environmental and health costs incurred from solar PV module and wind turbine waste expected to be generated in the End-of-Life phase and presented in the ALCA results in Chapters 5 and 6, respectively has been considered. The defensive expenditure constitutes the expenditure incurred for adopting the recycling technologies for solar PV modules and wind turbine in the EoL phase, such that the Circular Economy potential can be realized. Given the time period considered for the study is 2018-19, the Environmentally adjusted GDP for the year 2018-19 is presented in Table 7.8.

Table 7.8: Environmentally adjusted GDP in SEEA framework (2018-19) (in Rs. Million)

Sr. no.		Domestic production	Final cons. (households, govt.)	Capital formation	Rest of the world
1.	Supply of products	i) 363,123,643			45,172,559
	408,296,203	ii) 623,859			
2.	Use of products	175,402,830	139,546,218	55,684,220	37,662,939
	408,296,203	5,154,834	109,035		
3.	Use of fixed capital	19,842,840		19,842,840	
4.	Value added (VA/NDP)	213,050,532			
5.	Defensive expenditure	690,466	176,609	1,030,260	
	Agriculture impact due to reduced insolation	20,999			
	Environmental cost of mining	242,016			
	Solar PV waste environmental impact	21,086			
	Wind PV waste environmental impact	26,619			
	Environmental value addition	212,020,272			
	Environmentally adjusted domestic product	211,843,663			
	<i>% loss in terms of GDP</i>	-0.570%			

Note: Authors' calculation

In Table 6.7, it is observed that the Total Use¹⁵ (Rs. 408,296,203 million) is equal to the Total Supply. By including the Solar and Wind sectors the total supply changes to Rs. 408,920,061 million. The Environmental Value addition (Rs. 212,020,272 million) is calculated by subtracting the Natural Capital consumption (Rs. 1,030,260 million) from the Net Value Addition (Rs. 213,050,532 million). This implies the value addition to the economy after deducting the monetary impact on the environment from coal power generation, the solar PV modules and wind turbine waste generation and the defensive expenditures incurred. The GHG emission attribution to coal-fired power plants is not only through the operational phase where the coal-burning takes place but also through the extraction, transport and handling process which affects the workers and local communities (Rovira, Schumacher, Nadal, & Domingo, 2018). With a high threshold of coal usage in TPPs, the share of power sector in environmental pollution is also high, accounting for 51% of SO₂, 43% of CO₂, 20% of Nitrogen Oxides (NO_x) and 7% of PM_{2.5} emissions (Pachouri & Saxena, 2020). Thus, per unit environment cost derived from Table 4.9 in Chapter 4 is used to estimate significant impact on the economy. Secondly, the environmental impact from PV and turbine waste accumulation is also a result of three different segments – 1) the external costs from the actual recycling of waste where air and water pollution will be incurred as by-products 2) the external transportation costs for transferring the decommissioned PV modules and wind turbines from the place of installation to the recycling plants and 3) the external landfilling costs which arises from materials which can be neither recycled nor incinerated (The external cost estimation is presented in the Tables A4 to A6 in in the Appendix). The defensive expenditure, which is defined as the expenditure incurred by households and/or governments to reduce the effects of pollution (Chakraborty & Mukhopadhyay, 2014) includes the 1) cost of solar and wind power capacity installation for substituting more GHG-intensive coal power. This was calculated while constructing the new solar and wind energy industries in the I-O table discussed in Chapter 3. 2) The capital cost for recycling solar PV modules and wind turbines post-decommissioning in the End-of-life phase which was calculated in the A-LCA exercises conducted for respective energy sources in Chapters 5 and 6, respectively. The cumulative defensive expenditure is estimated to be (Rs. 690,666 million).

Finally, the environmentally-adjusted domestic product (Rs. 211,843,663 million) is estimated by subtracting the environmental cost to households (Rs. 176,609 million) from the Environmental Value Addition. The health impact on households arising from coal-power

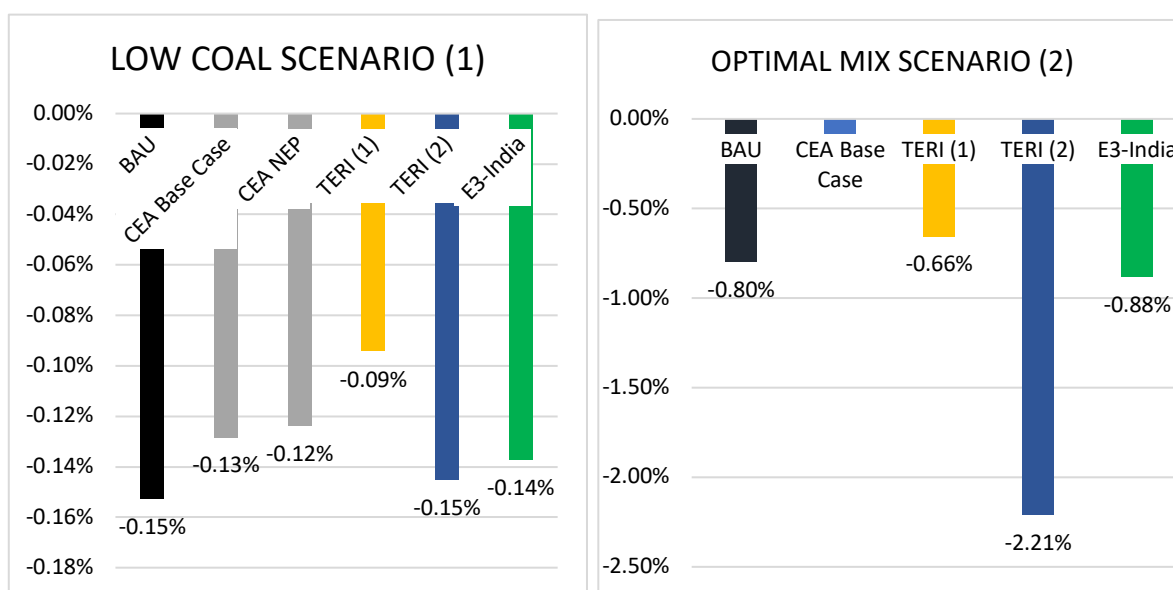
¹⁵ It is the sum of intermediate consumption, final consumption, capital formation and exports

generation as well as solar PV and wind turbine waste generation has been calculated here. The xenobiotic effects from the inhalation of aerosols from coal on lungs, immune system, heart, reproductive system, brain and DNA have been well documented (Gasparotto & Marinello, 2021). These emissions have the potential to be dispersed as far as 200 kms away from the power plant site (Guttikunda & Jawahar, 2014). Cropper, et al., (2021) estimate that coal-fired power plants in India were responsible for 78,000 annual premature deaths in 2018 and is expected to rise to 112,000 deaths per year with further coal power expansion. Thus, significant health benefits are expected to be realized through RE deployment. On the other hand, the human health impact from solar PV and turbine waste is also determined in a similar pattern as the environmental cost, arising from the recycling, transportation and landfilling of waste. As has been reiterated in the literature, the Solar PV modules and wind turbine waste if left unrecycled can also lead to significant health related complications through direct or indirect contact with toxic substances. The metal leaching effects post-decommissioning occur in four ways – i) dermal contact with contaminated soil due to solar PV leachate, ii) dermal contact with contaminated groundwater, iii) accidental ingestion of contaminated soil and iv) ingestion of contaminated groundwater (Nain & Kumar, 2020). If left untreated or unrecycled, heavy metals such as Zinc, Nickel and Copper will be released in the surrounding environment once the protective layers are broken and exposed to acidic conditions (Su, Ruan, Ballantine, Lee, & Cai, 2019).

The net loss to GDP arising from the changes in the composition of solar, wind and thermal power in India's electricity mix in 2018-19 is only 0.57%. It can be observed that the environmental and agricultural impact of coal mining is significantly higher than impact from solar PV and wind turbine waste. This is owing to the fact that the installed capacity in 2018-19 of solar and wind energy was 28.2 GW and 35.6 GW, respectively which is only 7.9% and 10%, of the total electricity capacity portfolio (CEA, 2019). In comparison, the power generated from 200 GW of coal & lignite fired TPPs will have a relatively higher impact on the economy.

While Table 7.7 provided the application of the SEEA framework over the existing RE and coal mix status in the country in 2018-19, this study focuses on accounting for India’s long-term solar and wind energy targets while balancing with reduced thermal power generation. Considering the two scenarios and their impact on different baseline projections studied, the loss/gain to GDP arising from the net changes in the environmental and health impact from reduced thermal power generation and solar PV module and wind turbine waste generation in the EoL phase is presented in Figure 7.5.

Figure 7.5: Environmentally-adjusted GDP 2030 estimates over the respective baseline projections in different scenarios (in percentage)



Source: Author’s calculations

Results from Figure 6.5 indicate the effect on the environmentally adjusted domestic product arising from environmental and human health impact from incremental solar PV modules and wind turbine waste in the EoL phase. The results have been presented in the SEEA framework along with the calculations in tables A12 to A22 in the Appendix for the respective baselines. The results for the respective scenario over each baseline projection also indicate the environmental and human health cost savings from reduced coal power generation (indicated with a minus sign and presented in Tables A12 to A22 in the Appendix). Nevertheless, the negative impact of the increased waste generation in the EoL phase exceeds the monetary savings from reduced coal power generation. However, it can be observed from Figure 7.5 that the negative impact is very minimal and it should not discourage the pursuit of the long-term 280 GW solar and 140 GW wind capacity targets already set forth by the Indian government. The ‘Economic Injury’ arising from the waste accumulation and the cost incurred is negligible. By combining these results with the cost-benefit analysis that was undertaken in Chapters 5

and 6, where the commercial gains from recycling and resale of recovered materials also contribute towards substituting virgin material manufacturing which will curb the release of additional environmental by-products, the pursuit of clean energy transition from a life-cycle perspective shows an overall optimistic outlook.

However, this is with the key implicit assumption that the PV modules and wind turbine recycling technologies are well-established and functioning within the economy. Currently, there is no legal or regulatory framework to deal with the impending RE solid waste that is expected to be generated in the near future. Only recently, the Government of India mandated the inclusion of Solar PV waste under the E-waste (Management) Rules, 2022 through the Extended Producer Responsibility where each producer shall store and process the modules or solar cells waste expected to be generated and comply with the standard operating procedure and guidelines laid down by the Central Pollution Control Board (CPCB, 2023). However, the notification did not mention about PV module waste abatement technologies being currently promoted or incentivized by the government for this purpose while on the other hand, wind turbine waste accumulation has not received any accumulation yet. In order to reap the lifetime benefits of solar and wind energy technologies, all stakeholders including the government (subsidizing and promoting RE waste abatement technologies), private players (RE technology manufacturers who will also procure and recycle waste in the EoL phase), electricity generators (increase solar and wind power generation to substitute coal power in the long run), distribution companies (DISCOMs) (procure higher share of RE power through the Renewable Purchase Obligations for its distribution to different consumers) need to execute their respective responsibilities.

7.5 Concluding Remarks

This study which was linked with the direct economic and environmental impact results from the Attributional LCA studies on solar and wind energy presented in Chapters 5 and 6, respectively, provided a more holistic, macro perspective of the intended clean energy transition trajectory for India. In this Chapter, the analysis of the macroeconomic as well as the environmental/human health consequences in an integrated framework using I-O modelling and the SEEA framework has been undertaken. The results indicate that overall, there is minimal, yet negative impact on the economy through the substitution of coal power generation by solar and wind energy across Total output, GDP and employment. While certain industries within the value chain of solar and wind energy, namely, iron and steel foundries, cement and

inorganic chemicals will benefit through this transition, the losses incurred through reduced demand for coal & lignite, coal tar products, copper ore etc. essential for thermal power generation is higher, leading to a net loss to the economy. This common trend was observed across multiple baseline projections considered for this study for evaluating the scenarios, thus providing additional credibility and significance to our results.

Secondly, the environmental benefits from reduced coal power generation in terms of GHG and non-GHG emission savings have been quantified and the monetary environmental and human health savings have been computed and presented in the SEEA framework across different baseline projections. It is observed that the incremental environmental and human health impact of solar PV modules and wind turbines in the EoL phase has been quantified in Chapters 5 and 6 show a net loss to GDP, though at a very minimal rate.

Considering the economic, environmental and human health impact together, it is found that while the clean energy transition roadmap with higher emphasis on solar and wind energy does not yield a significant positive impact on the economy or the environment from a life cycle perspective, the negative impact or the ‘Economic Injury’ is also at a very minimal or negligible rate. Considering that the I-O model is for the year 2018-19 wherein the solar PV and wind turbine industry is at a very nascent stage in its development, strong backward linkages with the rest of the economy need to be developed that can be comparable with the coal sector in terms of Total Output, GDP and employment impacts. This is expected to materialize over a period, since any structural changes introduced through the introduction of new industries take time to build strong economic foundations. Secondly, the negative, yet negligible impact arising from the Green-GDP estimation through decommissioned solar PV and wind turbine waste is an indication of the developing legal and economic framework by the central government in consultation with the states for dealing with this eventuality of waste accumulation. With higher capacity installation targets, significant waste accumulation is inevitable in the near future. As a result, the emphasis towards not only tackling the negative consequences of waste management is important, but also reaping the benefits through the circular economy concept provides a significant opportunity. This has been the key motivation and outcome of the study, where, considering the life-cycle perspective the positives as well as the drawbacks of India’s clean energy transition in response to climate change-related disasters were comprehensively presented.

While the policymakers across the world are focusing on the Net Zero targets for different countries in the coming decades, the greener technologies are largely being promoted in relative terms, that is RE technologies being relatively cleaner compared to fossil-fuel source technologies. This implies that the focus is only on the ‘Operational phase’ of the energy technologies, where the GHG emission factors of RE sources such as solar and wind are significantly lower compared to that of gas or coal-fired TPPs. It is in this context where this study fills the gap in the literature, with a more inclusive and detailed analysis can be carried out using the integrated IO-LCA analysis wherein it provides an overview of the positives as well as the prospective downside of India’s pursuit of long-term net-zero 2070 ambitions. In the next Chapter, the current status and impact of India’s long-term solar and wind capacity addition at the regional level has been discussed in detail.

CHAPTER 8 SUB-NATIONAL LEVEL DECARBONIZATION TRAJECTORY

In Chapters 5, 6 and 7, the energy and environmental accounting of solar and wind energy transition in India and its economic ramifications were studied using the attributional and consequential LCA exercise with the application of the Indian Input-Output framework. Given that the national 450 GW RE capacity installation target (of which 280 GW is solar energy and 140 GW is wind energy) was set forth by the central government, the contribution of regional states towards the national goal will vary depending upon its current status and future potential in several energy transition indicators. This chapter evaluates the energy transition status of the regional Indian states by preparing a sub-national level index. The categorization of states in terms of their potential contribution towards the national RE target based on the index scores is undertaken while evaluating its influence on clean energy transition policies.

8.1 A decentralized decarbonization strategy

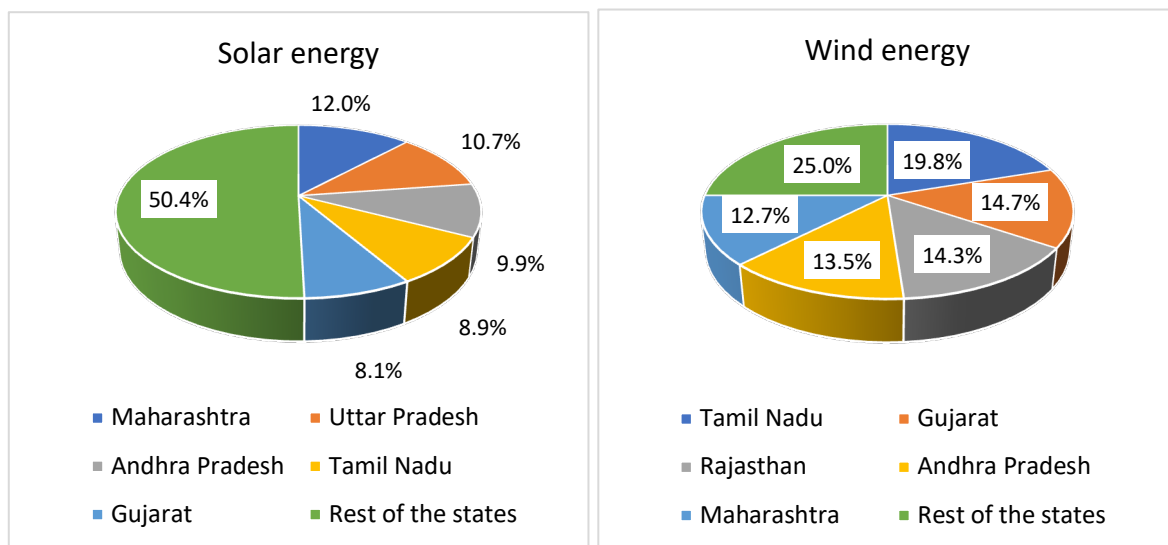
India constitutes a geographical landmass of 32,87,263 sq. kms, encompassing 28 States and 8 Union Territories (UTs) (GOI, 2023). Being the seventh largest country in the world geographically along with an array of responsibilities delegated across the central, state and concurrent list prepared under the Indian constitution, a centralized approach towards certain policy priorities may not be feasible and could be even counterproductive. Furthermore, different states are in different growth trajectories with varying economic, geographic and demographic endowments.

In terms of a strategic roadmap for India's decarbonization trajectory, it is observed that the central government has adopted a more decentralized approach. In 2010, the Indian government announced the grid-connect solar PV capacity installation target of 22 GW by 2022 under the Jawaharlal Nehru National Solar Mission (JNNSM) (Kapoor, Pandey, Jain, & Nandan, 2014). This was the first-of-its-kind national-level solar capacity installation program pursued by the Indian government. Subsequently, with the arrival of a new central government in 2015, this target was upgraded from 22 GW to 100 GW solar capacity by the year 2022 of which 60 GW was attributed to ground-mounted PV and 40 GW rooftop-PV (Niti Aayog, 2015). Furthermore, 60 GW was allocated to wind energy. Niti Aayog, the central government's apex public policy think tank allocated different capacity targets to different states, cumulatively amounting to the 100 GW national solar PV target. In determining the state-wise capacity installation shares, the following factors were taken into consideration:

- i) The potential of RES is not equally distributed across different states.
- ii) Solar is observed to have varying potential in all states, while wind energy constituting abundant potential is concentrated in only a few coastal states in southern and western India.
- iii) Land availability for solar ground-mounted PV might be a concern in a few states (discussed in Chapter 5).
- iv) State utilities have limited orientation to manage the variability of wind and solar power.

Given these factors, the allocation of 100 GW solar and 60 wind energy targets amongst different states by the Ministry of New and Renewable Energy, Government of India is shown in Figure 8.1.

Figure 8.1: State-wise share of Solar (100 GW) and Wind (60 GW) targets to be achieved by 2022 (As percentage of total)

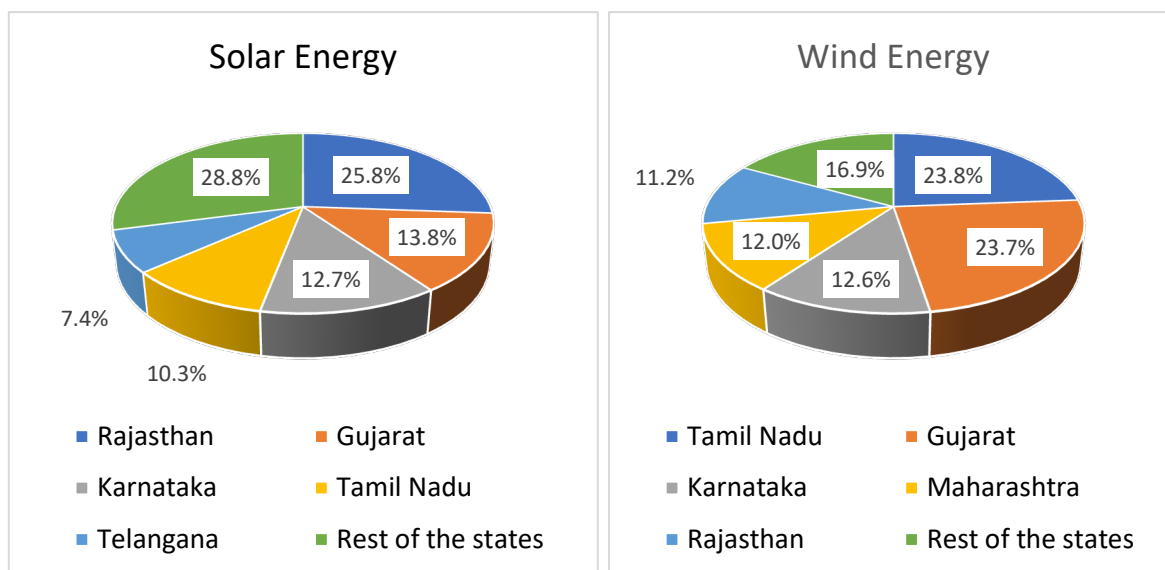


Source: Niti Aayog (2015) and Author’s calculations

For Solar energy, the highest allocation was for Maharashtra (11.9 GW) followed by Uttar Pradesh (10.7 GW) and Andhra Pradesh (9.8 GW) while for wind energy, Tamil Nadu constitutes the highest share (11.9 GW) followed by Gujarat (8.8 GW) and Rajasthan (8.6 GW).

However, the actual installed capacity that was achieved as of December 2022 at the sub-national level presented a different picture (Figure 8.2).

Figure 8.2: State-wise share of Solar and Wind installed capacities as of December 2022 (As percentage of total)



Source: Niti Aayog (2015) and Author's calculations

It was observed that in the solar PV installations, the top three states, namely Rajasthan (16.4 GW), Gujarat (8.7 GW) and Karnataka (8 GW), together constituted 52% of the total cumulative solar PV capacity installed in the country. These three states were ranked sixth, fifth and seventh, respectively in terms of the capacity targets that were allocated by Niti Aayog (Figure 7.1). While few states surpassed their allocated targets to be achieved by 2022, there were other states such as Maharashtra, Uttar Pradesh and Andhra Pradesh which lagged behind, and were ranked top three by Niti Aayog. For the wind capacity installations, Andhra Pradesh falls out of the top five in terms of actual capacity installed compared to its share in the allocated wind capacity targets. While the determination of the allocation was done considering the factors discussed above, the methodology or weightages allocated to each factor was not published by the central government. Furthermore, the state-wise allocation was done for the 2022 175 GW RE target. A similar exercise for the 450 GW 2030 target has not yet been undertaken by the government. A roadmap for state-wise contribution towards the long-term RE goal is pivotal in ensuring equitable distribution of the burden for solar and wind capacity installation at the sub-national level. In this study, the states are evaluated based on key decarbonization-related indicators and categorized in terms of their contribution towards the national RE target 2030.

8.2 State index construction and scoring

This study adopts the index scoring method from Sachdeva, Lolla, & Garg, (2023) in which the progressive and regressive indicators can be analysed. To develop a neutral foundation for analysis across parameters with different metrics and units, the indices are normalized to a standard scale of 0 – 10. The formula is as follows:

i) Progressive indicators

$$Index\ score = \left[\frac{(Actual\ value - Lowest\ value)}{(Highest\ value - Lowest\ value)} \right] * 10$$

Source: Sachdeva, Lolla, & Garg, (2023)

Where the higher value on the metric implies better performance.

ii) Regressive indicators

$$Index\ score = \left[\frac{(Highest\ value - Actual\ value)}{(Highest\ value - Lowest\ value)} \right] * 10$$

Source: Sachdeva, Lolla, & Garg, (2023)

Where the lower values on the metric imply better performance.

The progressive and regressive indicators considered for this study are presented in Table 8.1.

Table 8.1: Progressive and Regressive decarbonization-related indicators

Sr. no.	Indicators	Sources
1	Current Solar/Wind Power mix	Accessed from Central Electricity Authority (CEA, 2022)
2.	2030 Solar+Wind RE Mix	2030 Solar and Wind mix forecasted from state-level power demand published by the 20th Periodic Power Survey report (CEA, 2022)
3.	2022 Solar/Wind targets	The 2022 state-level RE capacity installation targets were published by Niti Aayog (2015).
4.	2022 Actual Solar/Wind capacity installed	The actual capacity installed as of December 2022, is published by the Central Electricity Authority, CEA, (2022).
5.	Solar/Wind Actual vs Potential	The potential of RE capacity is published by the Ministry of New and Renewable Energy (GOI, 2021)
6.	Solar/Wind Financing	The financing for solar and wind capacity installations at the sub-national level is estimated by the authors and discussed in detail later.
7.	Solar/Wind generation waste	Waste Generation as per the per unit assumptions from Latunussa et al., (2016) and Mali & Garrett, (2022)

8.	Electricity intensity	Electricity consumption data accessed from CEA, (2022) and GSDP data from RBI, (2022)
9.	GHG Emission intensity	The source-wise GHG emission actors were accessed from the 42nd Standing Committee on Energy Report (GOI, 2021)

Note: The indicators highlighted in green are progressive indicators and those highlighted in red are regressive indicators; The details regarding calculations of each of the parameters are presented in the tables A23 to A32 in the Appendix.

A combination of progressive and regressive indicators is considered in this study, which are the inherent factors in determining the overall energy transition trajectory of the states. The progressive indicators are:

- 1) Current Solar/Wind power mix in the respective states' electricity portfolio (2021-22)
- 2) The status of the Solar/Wind capacity targets to be achieved by 2022. The states which have achieved and exceeded their respective 2022 targets are expected to be more optimistic to contribute positively towards the 2030 target as well. On the other hand, states that lag by a big margin should be approached with caution, in terms of their long-term contribution.
- 3) The actual and potential Solar/Wind capacity in respective states. Given the solar and wind potential at the sub-national level as identified by the Ministry of New and Renewable Energy (MNRE, 2022), the gap between actual and potential capacity signifies the scope for further capacity in the present and future.
- 4) The combined solar and wind energy mix in the 2030 RE portfolio in respective states. The 20th Electric Periodic Survey conducted by the Central Electricity Authority provided the electricity demand in each state by 2029-30. The share of Solar and Wind energy of the total RE portfolio to meet the electricity demand is evaluated along with other RE sources.
- 5) Solar/Wind Financing is another important parameter that significantly influences the indicators mentioned above. The state-wise breakdown of RE financing and more specifically, Solar and Wind energy financing is currently not available. For this study, we have used the per unit solar PV and wind turbine industry costs using the modified I-O model 2018-19 in which solar and wind energy industries were added into the model, splitting from the homogenous electricity utility in the Supply Use Table published by Government of India (This has been discussed in detail in section 3.1.2,

Chapter 3). Using the model, the per unit or per GW costs of solar PV and wind energy capacity is presented in Table 8.2.

Table 8.2: Per unit Cost of solar and wind capacity installation

Sr. no.	Industry	Cost (in INR million/GW)	Cost (in USD million/GW)
1.	Solar	6,270.5	297.5
2.	Wind	15,837.4	751.5

Source: Authors' calculations

Note: The INR to USD conversion was based on the PPP of 1 USD = INR 21.073 in 2019 (OECD, 2023)

Given these per-unit costs, the cumulative financing that has already taken place based on the actual installed capacity as of December 2022 has been estimated.

An upward trend in the indicators directly or indirectly contributes positively towards the green energy transition. The progressive indicators' state-wise calculations are presented in Tables A23 to A28 in the Appendix.

Regressive indicators considered for this study are those which may be a direct or indirect unintended consequence of variations in different variables. These are:

- 1) Electricity intensity: The electricity intensity is determined based on the ratio of total electricity consumption to the Gross State Domestic Product of the respective state. Higher electricity intensity implies that the electricity consumption per unit of GDP is very high and, hence will be attributed to a lower index score.
- 2) GHG emission intensity: It is determined based on the ratio of total GHG emissions to the Gross State Domestic Product of the respective states. High GHG emission intensity would imply that the GHG emissions per unit of GSDP are high and, hence will be attributed with a lower index score.
- 3) Solar PV and Wind turbine waste generation: The third parameter is directly taken from the Attributional LCA studies on solar and wind energy, presented in Chapters 4 and 5. While higher waste generation in the future is directly related to a higher rate of wind capacity installation, the latter cannot be discouraged to reduce the solar PV modules and wind turbine waste accumulation. It is considered to be a regressive indicator in this study, owing to the fact that currently there is no regulation for managing decommissioned solar PV modules and wind turbines in India as has been reiterated in

preceding chapters. Thus, higher waste accumulation in the absence of management rules will have a negative impact.

The regressive indicators' state-wise calculations are presented in Tables A29 to A31 in the Appendix.

As discussed earlier, the scores for each indicator across states is normalized between 0 to 10. In order to rank the performance of the states by considering all the parameters combined, the individual parameter index value was further categorized into three groups. Following the method adopted by Jain, Gangopadhyay & Mukhopadhyay (2022), the state-level index scores for different indicators were categorized into three groups and scores were assigned based on their performance (Table 8.3):

Table 8.3: Categorization of index scores

Sr. no.	Categories	Index score range	Scorecard
1.	Category I	7 – 10	3
2.	Category II	3.5 – 6.99	2
3.	Category III	0 – 3.49	1

Source: Jain, Gangopadhyay & Mukhopadhyay, (2022)

Using this categorization presented in Table 8.2, the states are ranked based on their final scorecard which is a cumulative score of each state across all seven parameters.

8.3 State Index results

Based on the methodology discussed in the previous sub-section, the parameter-wise index score is presented in Table 8.4.

Table 8.4: Parameter-wise index score

Sr. no.	State Name	Solar/Wind Power Mix 2022	2022 Solar/Wind capacity targets	2022 Solar/Wind actual installed	Green Financing	Solar wind actual vis-a-vis potential	Solar+Wind RE mix 2030	Electricity intensity	GHG emission intensity	Waste generation
1	Andhra Pradesh	7.2	8.5	4.1	4.4	5.1	4.0	2.4	5.4	3.1
2	Bihar	0.1	0.4	0.0	0.0	0.7	0.04	0.0	3.7	9.9
3	Chhattisgarh	0.1	0.0	0.4	0.3	1.2	0.04	0.0	0.0	9.95
4	Gujarat	9.9	7.9	8.9	10.0	7.5	10.0	8.7	7.7	2.7
5	Haryana	0.8	1.2	0.4	0.3	0.1	0.4	6.1	9.8	10.0
6	Karnataka	9.9	5.3	6.31	6.29	4.8	4.4	8.8	7.9	4.9
7	Madhya Pradesh	2.1	5.3	2.6	2.9	4.6	1.4	6.6	7.9	4.8
8	Maharashtra	2.5	9.3	4.1	4.8	7.2	2.9	9.7	6.3	3.6
9	Orissa	0.3	0.3	0.2	0.1	0.3	0.1	5.5	0.0	9.97
10	Punjab	2.3	1.6	0.5	0.3	0.0	1.0	6.5	6.4	9.9
11	Rajasthan	10.0	6.6	10.0	8.3	10.0	7.1	8.4	5.0	2.8
12	Tamil Nadu	5.0	10.0	7.8	9.4	2.3	3.8	10.0	6.3	0.0
13	Telangana	3.7	0.1	2.2	1.4	1.2	1.8	9.1	4.8	8.3

14	Uttar Pradesh	0.7	4.7	1.1	0.7	1.4	0.7	10.0	2.7	9.9
15	West Bengal	0.1	1.9	0.041	0.03	0.3	0.03	9.7	3.9	10.0
16	Kerala	2.3	0.0	0.283	0.18	0.3	0.4	9.3	10.0	10.0
17	Jharkhand	0.0	0.1	0.0	0.00	1.2	0.0	8.6	3.1	10
16	INDIA	3.4	3.7	2.9	2.9	2.8	2.2	7.0	5.4	7.0

Source: Authors' calculations

Note: Categories for preparation of the scorecard are represented as follows: Category I: Green; Category II: Yellow; Category III: Red

The parameter-wise index score presented in Table 8.4 highlights two distinct features. First, there are two states, namely Gujarat and Rajasthan which fall under Category I in almost all the parameters. Since the index results are relative in terms, it would imply that these two states are performing better than all the other states that represent the Indian energy transition trajectory. Both states have already exceeded the 2022 solar PV target set forth by the central government (Table A24 in the Appendix). Gujarat has exceeded its 2022 wind target, while Rajasthan missed its wind capacity target by 3.6 GW. The solar and wind energy contribution to their respective total power mix was also the highest amongst all states and by 2030, only Gujarat and Rajasthan fall under Category I in terms of solar and wind energy share in the total RE mix. Similarly, for Solar and Wind financing estimated to achieve their respective capacities installed by December 2022, only these two states along with Rajasthan fall under Category I in terms of the index score.

The second feature of these results highlights how regional variations in terms of their performance across different parameters have a subsequent influence on the All-India level index score. It is observed that apart from Gujarat and Rajasthan, there are other states which are also attributed with Category I index scores in a select few parameters. Despite these results, the All-India level index scores do not fall in Category I in any of the parameters. This is because only a select few states undertake a higher burden of performing better across different parameters while there are many other states which are relatively worse off. The waste generation parameter shows that many states fall under the Category I index score. However, it is only because these states have currently lower installed solar and wind capacity, hence the burden of waste accumulation will also be lower in these states.

Given these index scores, the final state-wise rankings are presented in Table 8.5.

Table 8.5: State-wise performance ranking

Sr. no.	States	Scorecard
1.	Gujarat	25
2.	Rajasthan	23
3.	Karnataka	21
4.	Tamil Nadu	20
5.	Maharashtra	19
6.	Andhra Pradesh	18
7.	Telangana	15
8.	Madhya Pradesh	15
9.	Kerala	15
10.	Haryana	14
11.	West Bengal	14
12.	Uttar Pradesh	14
13.	Punjab	13
14.	Jharkhand	13
15.	Orissa	12
16.	Bihar	12
17.	Chhattisgarh	11

Source: Authors' calculations

Table 7.5 represents the cumulative scorecard for all parameters for each state. The parameter-wise scores are presented in Table A32 in the Appendix. The all-India average is calculated to be 15. In Table 8.6, the classification of states in comparison to the All-India level performance has been presented.

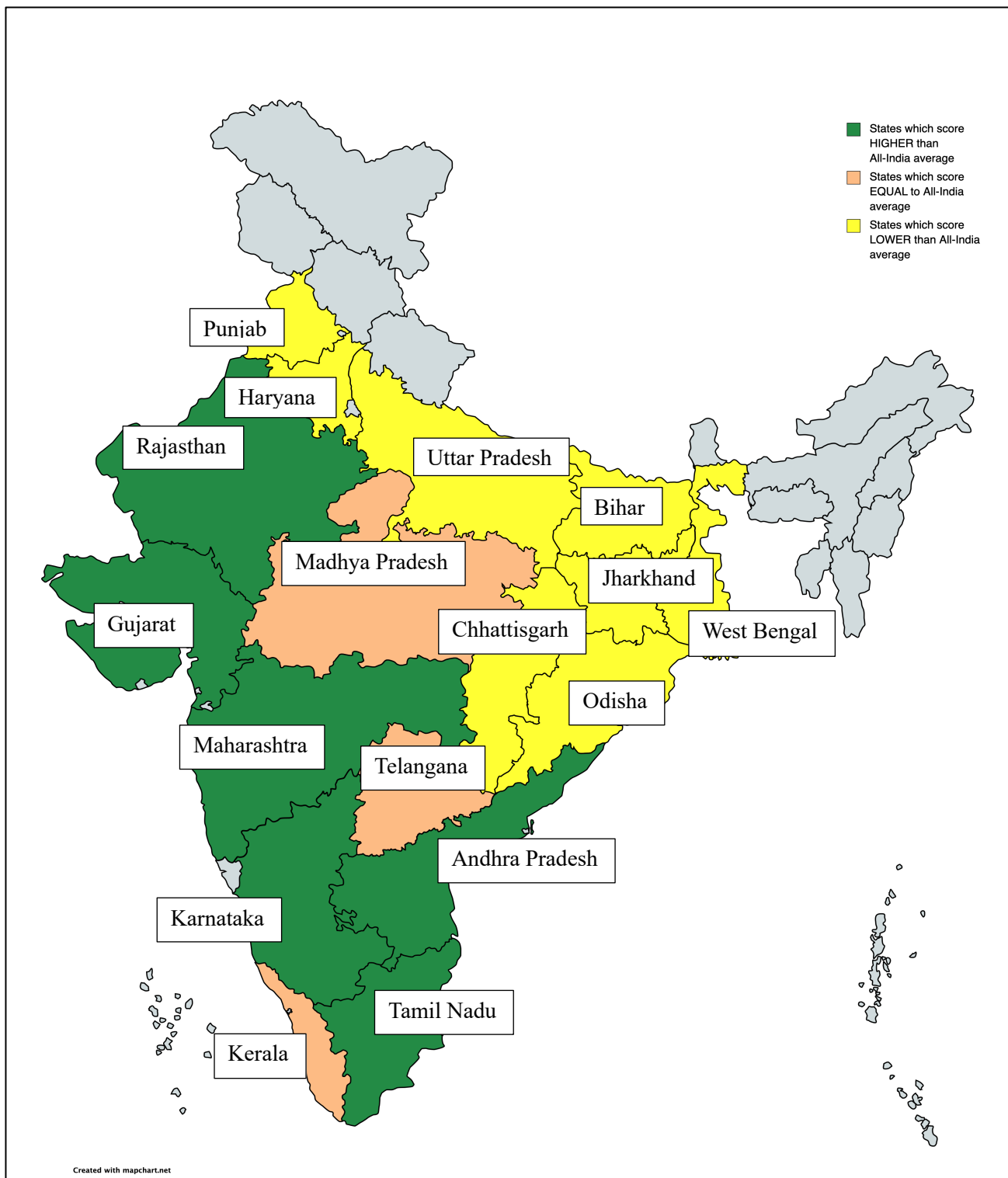
Table 8.6: Classification of states based on index score

Sr. no.	Classification	States
1.	States which score HIGHER than the All-India average	Gujarat, Rajasthan, Karnataka, Tamil Nadu, Maharashtra and Andhra Pradesh
2.	States which score EQUAL to the All-India average	Telangana, Madhya Pradesh and Kerala

3.	States which score LOWER than the All-India average	Haryana, West Bengal, Orissa, Bihar, Uttar Pradesh, Jharkhand, Punjab and Chhattisgarh
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This has been presented geographically in Figure 8.3.

Figure 8.3: Geographic representation of state-wise scorecards

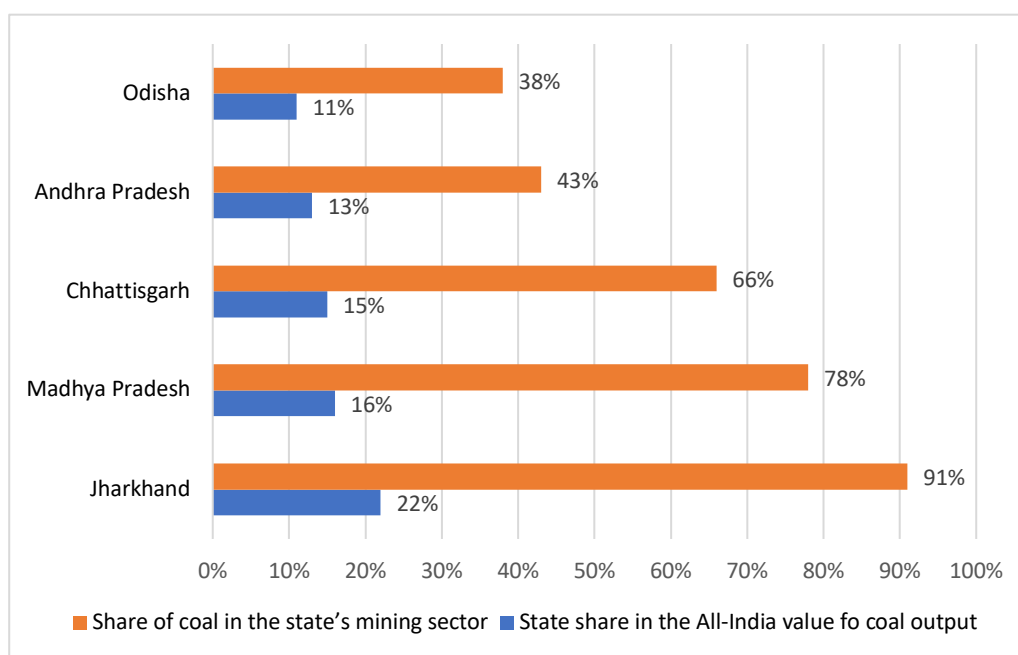


Source: Created by author

The states highlighted in green, lying on the western belt of the country are also relatively more economically developed states, with all of them being ranked higher than the other group of states in terms of the Gross State Domestic Product (RBI, 2020). The state of Rajasthan is attributed with the largest solar power potential in the country, while Gujarat and Tamil Nadu are attributed with the largest wind power potential (MNRE, 2022). Currently, in India, there are no offshore wind turbines being installed, with complete focus being on onshore wind capacity installation. Recently, a feasibility study of harnessing offshore wind energy over the seacoast of Gujarat and Tamil Nadu was conducted, thus indicating the possibility of expanding the RE portfolio in these states (GWEC, 2018).

According to the Indian Bureau of Mines, all the states highlighted in yellow in Figure 7.2 are ranked amongst the top six (except Punjab) of seven states in terms of annual coal production in the country (IBM, 2019). The coal mining is a key source of revenue for several states. As reported by Coal India Limited, which is a public body having almost monopoly over coal production in India, the combined revenue for major coal mining states, namely Madhya Pradesh, Chhattisgarh, West Bengal, Jharkhand, Uttar Pradesh, Odisha Assam and Maharashtra was INR 430 billion of which Jharkhand, Chhattisgarh and Odisha had received 60% of total royalties and 70% of total GST compensation cess (Spencer, Pachouri, Renjith, & Vohra, 2018). The significance of the coal sector in the economies of these states is presented in Figure 8.4.

Figure 8.4: Contribution of coal in the state and All-India level (2018)



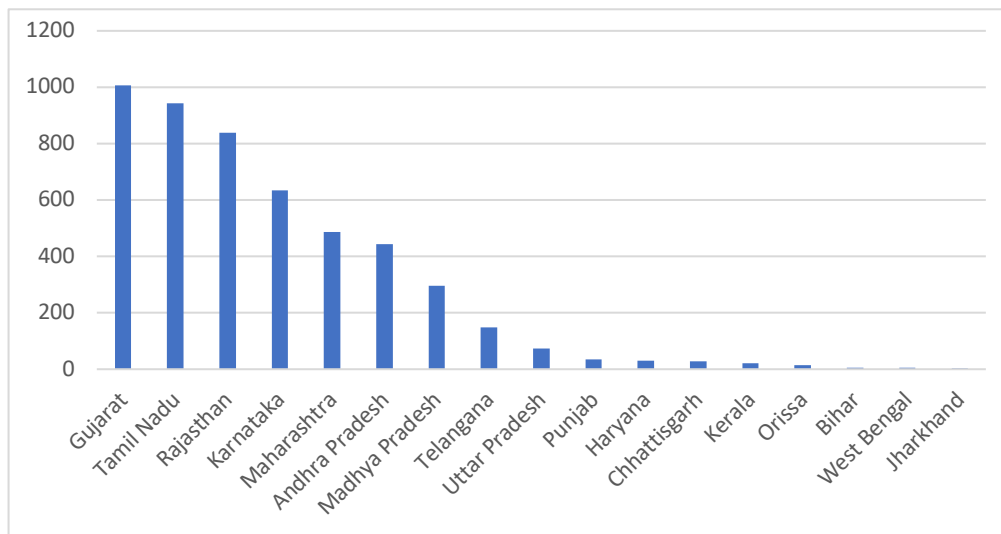
Source: (Spencer, Pachouri, Renjith, & Vohra, 2018)

It can be observed that four out of the top five states in terms of the contribution of coal at the state and national level are the eastern and central states, highlighted in yellow in Figure 8.2, while Andhra Pradesh is the only southern state in this list.

As discussed in Chapter 6, the coal sector with its strong backward linkages in the economy and being the largest employer in the country, plays a pivotal role in these states in ensuring the livelihoods of millions. Furthermore, owing to the fact that the production of coal is concentrated in a few Indian states, the transportation of coal to the rest of the states, largely for Thermal Power Plants is also significant. Approximately 44% revenue of the Indian Railways (also one of the largest employers in the country) is generated from coal freight transport (Kamboj & Tongia, 2018). Given the pivotal role that thermal power generation plays in ensuring energy security in the country as discussed in Chapter 6, the transportation of coal from the east to the more developed western states is also expected to be very high.

While this study evaluated the sub-national performance based on energy and decarbonization-related indicators, another important parameter that significantly influences these indicators is 'Green Financing'. Green Financing has been formally defined as 'to increase the level of financial flows (from banking, micro-credit, insurance and investment) from the public, private and not-for-profit sectors to sustainable development priorities' (UNEP, 2023). As discussed earlier it has been observed that only two states, namely Gujarat Rajasthan and Tamil Nadu fall under Category I in the scorecard for the Solar/Wind financing parameter. This also indicates that the more economically developed states are more conducive to RE financing. The state-wise Solar/Wind financing is presented in Figure 8.5.

Figure 8.5: State-wise solar and wind energy financing (combined) (in USD million)



Source: Authors' calculations

Note: The INR to USD conversion was based on the PPP of 1 USD = INR 21.073 in 2019 (OECD, 2023)

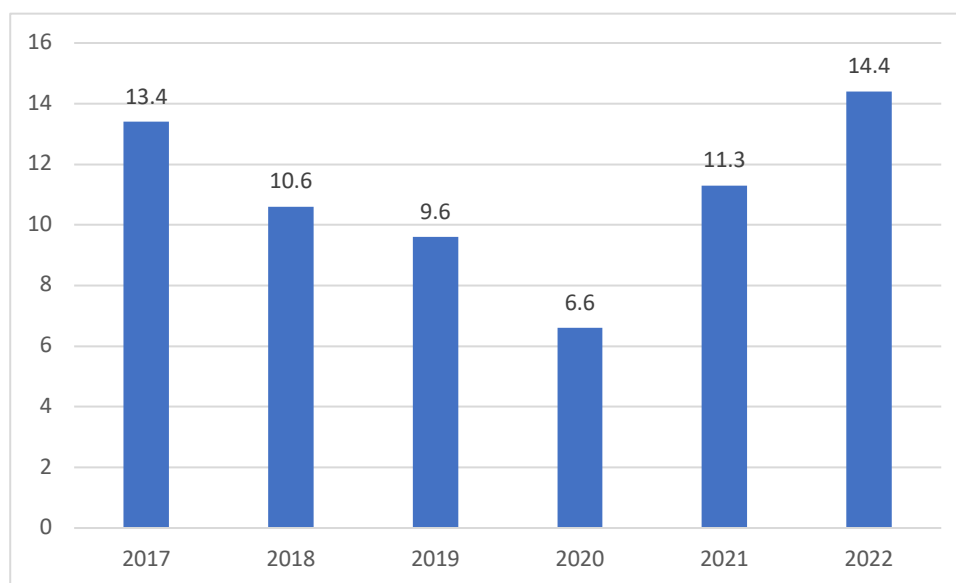
It can be observed that the top six states are all composed of economically developed states ranking higher than the All-India average as presented in Table 8.6. The geographical endowments in the form of solar irradiation levels and wind velocity which directly determine the solar and wind capacity potential need to be complemented with a conducive investment environment which can attract private players in the regional market. However, this is also partially because these two states have significantly high solar as well as wind potential whereas many other states are restricted to only solar energy potential with minimal or no wind potential, especially if they are not coastal states. Thus, states need to capitalize on their endowments for which regional policymakers should ensure an investment-friendly opportunity within their respective states.

Financial mechanisms such as Green Bonds, Green Insurance, as well as micro-credit schemes at the community level through pilot projects, are also new alternatives entering the market. The more we focus on transitioning to clean energy, the higher the level of investment is needed. To this end, it has been studied that financing of high-risk/new technologies, especially in emerging economies largely depends on public sector agents, which later provide direction for private players (Semieniuk & Mazzucato, 2018). On the other hand, Azghaliyeva, Kapoor, & Liu, (2020) find that in emerging economies such as the ASEAN members, private finance

for renewable energy and energy efficiency is critical in the long run. Thus, at different stages, it is observed that both the public and private players play an important role in RE promotion.

India has been witnessing record investments in the renewable energy sector in recent years (Figure 8.6). As discussed earlier in the chapter, India took a leap in its RE ambitions only in 2015 when the government first announced the national 175 GW RE target to be achieved by 2022. Thus, the latest data available in terms of RE investments was from the period 2017 as presented in Figure 8.6.

Figure 8.6: Year-wise investments in the Renewable Energy sector in India (in US Billion Dollars)

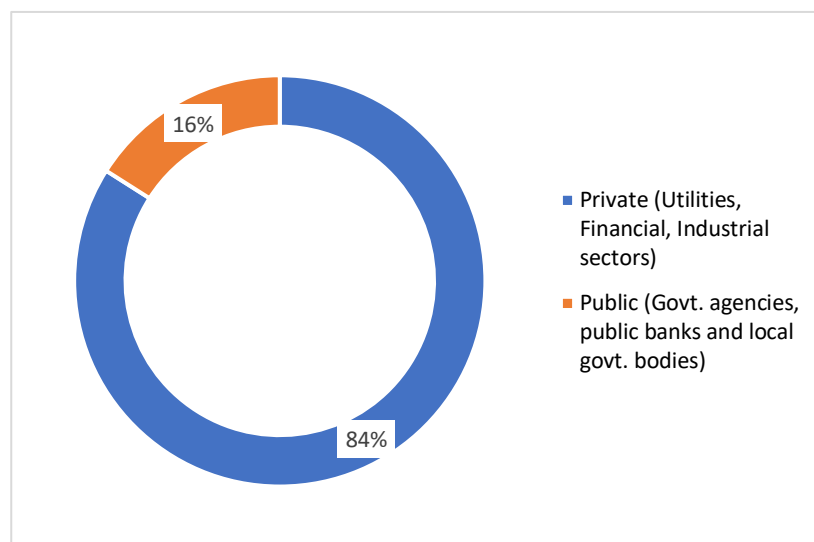


Source: (WEF, 2022; OGD, 2023)

It can be observed from Figure 8.5 that India received a record \$14.4 billion investment last year after a low of \$6.6 billion dollars investment during the COVID year 2020. One of the factors contributing towards this investment drive is the National government's 'Production Linked Incentive (PLI) Scheme: National Programme on high Efficiency Solar PV Modules' in which GW scale manufacturing of PV modules is encouraged with a subsidy outlay of Rs. 24,000 crores (USD 2.8 billion). For wind energy, recently the Ministry of Power in collaboration with the Bureau of Energy Efficiency (BEE) announced the minimum share of consumption as energy or feedstock for designated consumers with respect to electricity distribution licensees which ranges from 29.9% in 2024-25 to 43.3% in 2029-30 (GOI, 2023). With these subsidization and RE consumption regulations put forth by the government, both solar and wind are expected to constitute a higher share of the energy mix.

Apart from government subsidization and incentives, another key and rising financial instrument in this regard is Green Bonds. Green Bonds can be differentiated from a regular bonds as ‘a commitment to exclusively use the funds raised to finance or re-finance ‘green’ projects, assets or business activities (OECD, 2015). In India, the green bonds formally received recognition with the formation of the Indian Green Bonds Council as a joint project between the Federation of Indian Chambers of Commerce Industry (FICCI) and the Climate Bonds Initiative in 2017 with the aim of building India’s green debt markets (Climate Bonds Initiative, 2018). In January 2023, the national government issued the first tranche of sovereign green bonds worth \$980 million and another tranche of green bonds worth \$968 million in February 2023. With private players also entering the green bonds market, today it is worth \$21 billion (Huassain & Dill, 2023). Given below is the green-bonds issuance share between private and public players in India (Figure 8.7).

Figure 8.7: Green bonds issuance by type (As percentage of total)



Source: (Huassain & Dill, 2023)

More than 4/5th share of the total green bond issuance is by the private players. The largest green bond issuer in India is the Greenko group, which is funding hydro, solar and wind power projects in different states. Despite taking significant steps in green financing, India still has a long way to go. According to Jain, Gangopadhyay, & Mukhopadhyay, (2022), there is still high dependence on regular loans and govt. subsidies with relatively minimal exposure to alternate financing options. The liquidity in capital bond markets is very low combined with a lack of wider adoption to international certification and guidelines.

Putting into perspective, the significance of green-financing at the sub-national level, the market being at a very early stage in its development, the state-wise statistics in terms of financing of RE projects are not yet compiled for different states. Furthermore, green financing includes financing all RE projects, including small hydro, and biomass along with solar and wind energy projects. To narrow down further to the statistics focusing only on solar and wind energy is also a challenge. Thus, this parameter was not taken into consideration for the sub-national level index construction. Nevertheless, its pivotal role in influencing the indicators considered in this study is highlighted.

8.4 Concluding remarks

The theme of the study undertaken in this chapter is not directly related to the attributional and consequential LCA exercise conducted at the national level presented in chapters 4, 5 and 6. Nevertheless, the key outcomes from the preceding chapters are also applicable at the sub-national level, since different states are contributing towards the same goal of 280 GW solar and 140 GW wind capacity installation. As evaluated in this chapter, the scope for incremental solar and wind capacity installation is not equally distributed across states and the burden is largely on a select few states on the western belt of the country, namely Rajasthan, Haryana, Gujarat, Maharashtra, Karnataka, Tamil Nadu, Telangana and Andhra Pradesh.

While for the states on the eastern belt of the country, alternative solutions for energy transition need to be sought. Coal plays an integral role in the economic and energy portfolio of these states and is the key supplier of coal to the rest of the states. Since labour cannot be directly transferred from the coal sector to solar PV modules and wind turbine manufacturing as different skillsets are required, capacity-building initiatives need to be promoted by the government such that alternative employment opportunities can be explored. As a net loss is expected in the economy through the substitution of coal by solar and wind in the current Indian economic structure, demonstrated using the Indian I-O framework in Chapter 6, several states need to take prior initiatives to tackle the economic ramifications of pursuing the energy transition trajectory.

Finally, the significance of green financing was again reiterated in the G20 summit held in New Delhi, India wherein, the G20 Sustainable Finance Working Group (SFWG) which aims to mobilise private and public sustainable finance towards greener economies narrowed down its priorities to six key areas: 1) Mechanism for mobilization of timely and adequate resources for climate finance, 2) Policy measures and Financial Instruments for Catalysing the Rapid

Development and Deployment of Green and Low- Carbon Technologies; (3) Scaling-up the adoption of social impact investment instruments; (4) Improving Nature-related Data and Reporting; (5) G20 Technical Assistance Action Plan; (6) Overcoming data-related barriers to climate investments (GOI, 2023). Towards this end, the role of green financing will also vary in terms of its type and magnitude in different states based on the evaluation conducted in this chapter. For instance, the high scoring western and southern states have currently a more conducive environment for RE financing whereas the low-scoring eastern and central states need to focus more on ‘Just transition’ which will be a longer process. These factors need to be taken into consideration such that the policies lean more towards a ‘Pareto-efficient’ solution in light of the clean energy transition.

CHAPTER 9 CONCLUSION AND POLICY RECOMMENDATION

Over the past few decades, climate-change related disasters have raised awareness regarding the necessity to restrict the pace of global warming, leading to economic losses in affected communities and countries at large. The adoption or transition towards RES by substituting conventional fossil-fuel sources is considered to be an important alternative owing to its significant potential for GHG emission reduction. However, from a policy perspective neither developed nor developing/emerging economies can pursue the long-run benefits of environmental sustainability at the cost of economic growth and energy security in the short-to-medium run. While the environmental benefits of RES have been widely acknowledged by the scientific community, the economic ramifications of the clean energy transition, especially in developing and emerging economies like India has been given minimal importance, as has been reiterated in Chapter 2.

India which is experiencing rapid population growth along with several socio-economic issues at hand, has also been steadfast in its efforts over the past decade towards clean energy transition and has further solidified its commitment in this regard through various international forums. However, the impact of the recent COVID-induced strict lockdowns in the year 2020 and partial lockdowns in the year 2021 have heightened not only the socio-economic depravity faced by the majority of the Indian populace, but also unmasked the loopholes in the existing energy security situation with a significant slowdown in RE capacity addition and several Distribution Companies defaulting on their payments to generators (Mahaurja, 2021). With this intersection between ensuring socio-economic well-being and environmental sustainability, it is pivotal to find policy prescriptions which balance the pursuit of economic as well as environmental targets simultaneously in the medium-to-long run.

Given this backdrop, the study has been conducted at a critical juncture, wherein India's commitment towards clean energy transition with special emphasis on solar and wind energy has been holistically evaluated at the intersection of Economy-Energy-Environment dimensions. Furthermore, these initiatives and developments related to India's decarbonization trajectory have been announced only during the past 5-6 years. Thus, India is at a very initial stage in its pursuit of environmental goals which makes the relevance and the practical applicability of this study even more significant from an academic as well as policy standpoint. In 2016, India submitted its instrument of ratification to the United Nations Paris Climate Agreement (UN, 2016) in which it committed to:

- i) Reduce Emissions Intensity to GDP by 45% by 2030, from the 2005 level.
- ii) Achieve 50% cumulative electric power installed capacity from non-fossil fuel-based energy resources by 2030.
- iii) To create an additional carbon sink of 2.5 to 3 billion tonnes of CO₂ equivalent through additional forest and tree cover by 2030.

Consequently, in 2021, India's Prime Minister Narendra Modi again reiterated the country's commitment towards the adoption of greener initiatives during the Conference of Parties (COP) 26 event in Glasgow, UK, wherein it was announced:

- i) Non-fossil fuel energy capacity of 500 GW by 2030.
- ii) 50% energy requirements to be met by Renewable Energy by 2030.
- iii) To reduce projected carbon emissions by one billion tonnes between 2021-30.
- iv) Reduce carbon intensity of its economy by more than 45%.
- v) To achieve a Net Zero emissions target by 2070.

The non-fossil fuel or RE sources such as solar, wind, biomass and small hydro have been globally acknowledged to be relatively cleaner energy sources to fossil fuels such as coal and natural gas and share the burden amongst them in pursuing clean energy adoption. Amongst these sources, solar and wind energy have received higher emphasis in India amongst all RE sources with the allocated targets of 280 GW and 140 GW, respectively to be achieved by 2030. One of the novelties of the study lies in the adoption of the Life Cycle Analysis which provides a more holistic outlook towards Net zero targets. Today, policymakers and other global leaders are reiterating the promotion of RE sources, primarily solar and wind energy with the justification that they are less GHG emission-intensive compared to fossil fuel sources. The emphasis here is only on the 'operational phase' of solar and wind energy, where the emissions through electricity generation are significantly lower than coal-fired Thermal Power Plants (TPPs). Coal-fired TPPs can remain operational through regular repairs and maintenance for more than a century. In India, the Paras Thermal Power station in Akola District in Maharashtra state is considered to be one of the oldest functioning thermal power plants in the world which has been operational since 1961, with periodic upgradations and repairs & maintenance (TNN, 2011). However, that is not the case with the greener alternatives such as solar and wind. The solar PV modules and wind turbines are expected to be functional for only 25-30 and 20 years, respectively after which they need to be decommissioned in the End-of-life phase. The environmental and health damages arising from untreated RE waste have the potential to reverse the positive impact of green technologies. The motivation for this comprehensive study

arises from the minimal attention provided in literature towards the indirect and unintended consequences of rapid clean energy transition in India from a life cycle perspective. In this regard, the GHG reduction from the commissioning of solar and wind energy can be observed immediately in the present and will continue to be accounted for in the future as well with higher capacity addition. Nevertheless, the adoption of the LCA method in this study points out that this cannot be the sole criterion for substituting coal-TPPs with solar and wind as the untreated waste in the EoL phase has the potential to reverse the positive gains arising from its operational phase. To this end, this study also contributes directly to Sustainable Development Goal 7 (SDG 7) – Providing Affordable, Reliable and Clean energy for all and SDG 13 – Taking action against climate change.

The results from the Attributional LCA studies for solar and wind energy presented in chapters 5 and 6, respectively indicate that significant waste amounting to 19,832 tonnes from 280 GW solar PV modules and 65 million tonnes from 140 GW wind turbines is expected to be generated in the EoL phase. This scenario of waste accumulation also provides an economic opportunity through the circular economy framework of re-utilizing the decommissioned waste materials using the 3R strategy of Recycle, Reuse, and Reduce. Currently in India, the importance of recycling has been gaining attention in other areas of the economy such as plastics and electronic products. In the case of RE waste, it has received minimal or no attention. One of the factors could be that the current share of solar and wind installed capacity is very low while the cumulative waste generation is expected to be incurred only in the future. Thus, policymakers focus more on the immediate gains that can be reaped without analyzing the long-term impacts. Even short-term policies such as capacity installation targets within a period of five years are also acceptable if they are complemented with strategies that focus on their long-term consequences. For this purpose, academic studies with policy perspectives are essential for aiding this process and this study is contributing towards that end.

The outcome of this study in terms of monetizing the externality in the form of environmental and human health costs shows that India needs to start preparing the groundwork for dealing with waste accumulation through the setting up of solar PV and wind turbine recycling technologies. For this purpose, a synergy between all the stakeholders involved is pivotal in the proper execution of the 3R strategy. From a macro-perspective, a top-down approach in the form of government support for recycling is encouraged. Currently, the central government is promoting the manufacturing of solar PV modules and wind turbines in the country through the Production-Linked Incentive (PLI) scheme (MNRE, 2023). A similar strategy to encourage waste abatement in the EoL phase of solar PV and wind turbines is essential. This has been

discussed further in detail in the next chapter. It is expected that the inclusion of the A-LCA study on solar and wind energy in literature will generate more awareness regarding the direct positive impact as well as drawbacks from a life cycle perspective which will give a broader overview of India's net-zero aspirations.

From a macro-perspective, the promotion of solar and wind energy in India is in combination with other electricity sources in its energy portfolio to meet the power demand across different economic categories in the country (Industrial, Residential, Agriculture etc.). Currently, coal power has more than 2/3rd share in India's electricity portfolio (CEA, 2022), ensuring not only energy security within the country but it also has been historically contributing significantly to the economy in terms of GDP, Output and Employment. In the recently held COP26 event in Glasgow, UK, India was being pressured especially by the developed nations to commit towards phasing out coal power in the near to long-term future from its energy portfolio (Sharma, 2021). Despite the objections by several advanced nations, the Indian Prime Minister remained steadfast in the commitment to utilizing coal to ensure the economic and social well-being of the country; but negotiated a 'phase-down' of coal power instead of a 'phase-out' that most of the countries have committed to. This implies that India is willing to steadily reduce the share of coal power in its electricity portfolio in the near to long-term future but is unwilling to completely shut down its coal-fired TPPs which will be counter-intuitive to India's economic growth ambitions. This was also one of the reasons India aims to achieve the Net zero target by 2070, instead of 2050 which most countries are aspiring to achieve. The strategy adopted by the Indian government was further ratified from this study, wherein using the IO-LCA framework, it was observed that an increase in solar and wind energy generation in India's electricity mix with a simultaneous decrease in coal power in varying degrees in different scenarios leads to a minimal, yet net loss to the economy across different macroeconomic parameters, namely Total output, GDP and Employment. In order to strengthen the credibility of these results, this study estimated the impact across different scenarios and across five different baseline projections. The results across both the scenarios over the five baseline projections tend to converge to the same outcome, that is a net loss to the economy.

Along with coal power constituting the highest share in India's electricity mix portfolio, India is also the second largest coal producer in the world, with a global share of 8.6% in 2022 (Statista, 2023b). With 64% of coal being consumed by the Thermal Power Plants (GOI, 2022), any displacement in coal power can have a high indirect impact across the supply chain of coal production, which is captured using the I-O framework. On the other hand, solar and wind energy are at a very nascent stage in their development, hence the linkages of these new

industries with the rest of the economy are not as strong as coal power which has historically remained the sole energy provider as well as a source of employment for millions across the country for decades. The results from this study have revealed that coal is expected to play a pivotal role in India's energy security as well as economic growth in the present and the near future.

The importance of coal power generation in developing economies has also been emphasized many times. China, which is the largest coal producer witnessed higher coal power generation in the first three months of year 2023 which was higher than the coal power generated in the entirety of the year 2021 (Hawkins, 2023). This is despite the Chinese Communist Party's pledge of achieving carbon neutrality by 2060. More than 50% of energy consumption is from coal power and with the issue of power outages, it becomes a highly sophisticated task to displace coal power as the base-load electricity supplier (Springer, Kudrimoti, & Shi, 2022). Similarly, in Vietnam concerns related to regular power outages and incomplete regulatory frameworks for clean power options are the major obstacles for phasing out of coal power in their electricity mix (Do & Burke, 2023). In the case of India, the economic impact of the energy security concerns arising from the curbing of coal power generation in a macroeconomic framework has been presented here, which is one of the key novelties of this study.

Nevertheless, this does not discredit the positive impact of solar and wind energy's positive environmental impact through GHG and non-GHG emissions savings by steady increase in its share in India's electricity mix portfolio. Using the SEEA framework, the results also reveal the negligible impact on the economy arising from the combined impact of external cost savings from reduced coal power generation and the incremental impact of solar and wind waste generation in the EoL phase. Provided that the defensive expenditure in terms of the recycling technology for managing the waste accumulation received appropriate government support, not only can the minimal negative impact be eliminated, but the economic benefits from the circular economy framework as discussed earlier in the A-LCA studies, can be realized.

In pursuit of the clean energy transition goals, it was also observed that at the regional level, different states are expected to contribute differently. This depends on an array of economic, energy and environmental indicators that have been studied. There are certain indicators which are their natural endowments that are irreplaceable. In this case, the states which have higher solar irradiation levels and wind velocities can optimize through maximizing their solar and wind potential through incremental capacity installation. On the other hand, there are other

states which are largely coal-bearing states which do not have high levels of solar and wind potential. For these states alternative policy solutions are essential. Either way, for both categories of states, by combining the energy and economic indicators it was observed that the states on the western and southern belt of the country, namely Rajasthan, Gujarat, Maharashtra and Karnataka, which are also the relatively more economically developed states demonstrate higher rankings in terms of solar and wind capacity installations. These states should be at the forefront and undertake the major share in pursuing the national 450 GW 2030 RE target. On the other hand, the relatively less developed coal-bearing states on the eastern belt of the country perform lower than the All-India average score. A more socio-economically sensitive policy prescription is essential since a significant share of the population in these states directly or indirectly relies on coal mining for their livelihood. Moreover, this study also reveals that equitable capacity installation share allocation amongst states is essential such that not only is the 2030 target achieved in a timely manner, but the states also reap the benefits of India's clean energy transition pursuit.

Given that India is at a unique critical juncture in terms of its economic growth trajectory as well as the ambitious environmental targets that have been recently announced, policymakers need to be equipped with a holistic macroeconomic perspective of the complementarity between the economic and environmental goals for constructing balanced long-term strategies. Given the major findings from this study with regards to the pivotal role of coal power and the inevitable waste impact of solar and wind capacity addition, a few policies have been recommended that are attuned with India's existing economic status and future ambitions.

1) Extended Producer Responsibility (EPR)

The potential economic and environmental benefits from the circular economy framework cannot be yielded without the proactive involvement of the producers, through the EPR strategy. If the commercial gains from the resale of recovered materials do not outweigh the recycling, landfilling and external costs of solar PV modules and wind turbines, it is an unfavourable scenario for the producers to undertake recycling on a voluntary basis as it will generate economic stress. To this end, government support in the form of incentives and subsidies is essential to encourage the producers to undertake solar PV and wind turbine recycling such that not only the break-even point can be achieved, but also economic gains can be realized through the resale of recovered materials. This study proposes the inclusion of the cost of recycling which is estimated to be \$0.026/kWh for solar PV modules and \$0.0046/kWh for wind turbines (discussed in Chapters 4 and 5, respectively) to be included in the power

generation tariff from solar and wind energy, respectively. This would imply that the solar and wind power tariff determination will include not only the levelized cost of generation, transmission and distribution but also the recycling as well. Through this tariff break-up, the government can accumulate revenue that can be transferred to supporting producers through the EPR strategy when the solar PV modules and wind turbines will be decommissioned in the EoL phase.

Recently, the Ministry of New and Renewable Energy, Government of India, released the ‘Solar Waste Treatment under E-Waste (Management) Rules, 2022’ which has laid down the rules for every solar PV module and PV cells producer in the country to (PIB, 2023):

- i) Registration on the government portal.
- ii) Storage of solar PV modules or cells as per the guidelines laid down by the Central Pollution Control Board (CPCB), Government of India.
- iii) The inventory of solar PV modules or cells is to be recorded distinctly on the portal and
- iv) Comply with the standard operating procedure and guidelines laid down by the CPCB.

The maintenance of records of Solar PV modules being currently installed and operational is a significant development since it will also help in estimating the waste generation in real-time. On the other hand, these rules do not emphasize on the financial aspects of waste abatement and to this end, our study can contribute and complement the support for the producers to undertake not only the storage of waste but also adopt the 3R strategy with financial support from the government. Through the registration of inventories as mentioned in the rules, the government can also identify the disbursement of financial support for the respective producers through the EPR strategy. A similar concept also needs to be proposed by the government for wind turbines which is currently lacking, primarily due to the lack of large-scale turbine recycling technologies currently available in the market. Nevertheless, the storage of turbine wastes is important, since the development and R&D on the technological front will enable easier access to turbine recycling.

Currently, the European Union is the only region with a fully operational ‘Waste Electrical and Electronic Directive (WEEE)’ for the Solar PV sector which has legalized and categorized the responsibilities of all the involved stakeholders, including i) Collection & Recycling, ii) Compliance requirements by Producer, iii) Waste management Programs for Capacity Building and iv) Compliance Inspector for monitoring companies (EU, 2012). The adaptability of such

streamlined procedures is also an incentive for all the stakeholders to execute their roles in the supply-chain. The central and state governments, solar PV module and wind turbine producers and the power purchasers, namely power distribution companies as well as the power consumers should actively participate in the 3R strategy such that the economic gains through the circular economy framework can be realized.

Finally, the majority of the waste materials which are generated such as Aluminum, Glass, Iron&Steel and Electronics from Solar PV modules and Wind Turbines are common amongst waste generation from other sectors such as automobiles, computer and peripheral equipment, hardware products etc. Thus, a more centralized approach can be adopted wherein the waste generation from the decommissioned solar PV modules and wind turbines can be included in the waste collection and treatment plants which engage in waste accumulation from other sources. In this way, the market for scrap metal and recycling products is expected to broaden. Thus, the financial burden of solar and wind can be reduced through economies of scale.

2) Land Use and Water use Management for Solar PV modules and Wind turbine installations

The constitution of Land as a requirement for faster solar PV and wind turbine installations has been given less attention primarily because studies have focused on identifying and ensuring robust global supply chains for the RE technologies which directly contributes towards capacity expansion. In order to achieve the 280 GW solar and 140 GW wind capacity targets, our study shows that approximately 0.2% of India's total landmass is required. While at the outset the land requirement seems negligible, the cost of land and its socio-economic impact is significant. Factors such as site selection, efficient land utilization, regulatory compliance and strategic planning play a pivotal role in the producer's land cost optimization for RE projects (Koundal, 2023). Apart from the economic aspects, the environmental impact from Land Use Change (LUC) emissions estimated to be 12g/kWh (van de Ven, et al., 2021) with the resulting cumulative emissions have also been documented in this study.

In the case of Canada, concerns were raised in the Alberta province regarding the increasing share of farmland being allocated for constructing 'solar farms' which may hamper the scale of food production (Chung, 2023). Similarly, in the European Union, countries such as Germany, Italy and France which are deemed to achieve 50% of EU's RES installations by 2040 are estimated to require 23,000 to 25,000 sq. kms of land, which is equivalent to the land area of Belgium (Bampinioti, et al., 2023). The EU expects to adopt spatial optimization and satellite monitoring techniques to identify land requirements with the least displacement of

farmlands. Given that even developed countries will be facing competition for land for RES installment, in the case of India which has a much higher population density than the Western countries and a higher requirement of area under food production to sustain the country's needs, solar PV transition becomes a more sophisticated task.

One solution to this issue is the utilization of wasteland or barren areas. Studies have shown significant Solar PV potential by measuring the solar PV irradiation levels over wasteland or barren areas (which constitute 316 million hectares or 15% of the national land area) in different states of the country (Mahtta, Joshi, & Jindal, 2014; Van der Ven, 2021). Studies have already shown that the districts in the states of Gujarat and Rajasthan, which constitute high solar irradiation levels also composed of significant wasteland and barren areas (Mahtta, Joshi, & Jindal, 2014). For this purpose close coordination between the Centre, states and other stakeholders is important. Redesignating grazing land as a 'wasteland' in India has impacted the herder's community within India because of reduced pastures for their livestock (Deshpande, 2023). While there are studies which show that the socio-economic and ecological impact of using wastelands in India is lesser compared to land parcels for solar PV parks in urban-semi urban areas with an opportunity cost (Thomas, Thomas, Sahoo, Gobinath, & Awad, 2022), a more sensitized approach is essential for a Pareto-efficient outcome.

Similarly, the water requirement which is attributed to the washing of solar PV modules to maintain the module efficiency in the operational phase is also to be monitored for ensuring optimal water management. Given that India is already a water-scarce nation and with rapid urbanization and a growing population, irregular water management solutions are expected to lead to sub-optimal outcomes in terms of maintaining solar module efficiency levels. Since water requirement is to be met by diverting or allocating a portion of the water use that is attributed to other sectors in the economy such as for agricultural or industrial purposes, proper planning at the local level is to be encouraged.

3) Focus on Balanced Electricity mix portfolio.

Scientific studies across the globe have unequivocally proven that solar and wind energy, relative to coal power have significant GHG and local pollution savings per unit of electricity generated. In this regard, the RE alternatives should always be the first choice in comparison to fossil-fuel sources in terms of taking action against climate change. The results from this study reveal that the aggressive pursuit of substituting coal-power with an optimal mix of solar and wind energy can lead to GHG emission savings of 1.6 – 5.8 BT CO₂eq. in different scenarios which exceeds the government's target of 1 billion tonnes emission savings by 2030

(PIB, 2021). Furthermore, this study has shown that complementary to environmental benefits from reduced emissions, there is no significant economic impact of incremental solar and wind capacity addition in the case of India. There is a negative, yet minimal impact with a simultaneous proportional decrease in coal power generation. The results from this study reiterate India's stand at the COP26 and COP27 events where the Prime Minister opposed the complete coal phase-out and substituted it with the term 'phase-down'. A gradual reduction in the share of coal power generation with an increase in solar, and wind energy as proposed in this study's scenarios should remain the main focus. Along with solar and wind, other RE sources, namely biomass and small hydropower should also be given importance. Though this has not been the main focus of this study, the RE portfolio as a whole should be enhanced in order to substitute coal power which remains the pillar of India's energy security.

However, solar and wind are variable in nature, that is their performance is dependent on the weather conditions, such as solar irradiation levels and wind velocity at a particular point in time and thus, their integration with the electricity grid remains vulnerable (Mathiesen, et al., 2015). Thus, sudden variation in the Variable RE (VRE) can pose a serious threat to the grid stability, reliability and security. Due to these issues, the incremental capacity addition has not translated into a higher share of RE in India's electricity mix portfolio. Even today, coal power constitutes 74% of the total electricity generated in the country (CEA, 2023). In order to meet the power demand in the country, India aims to increase the coal production in the country from the recorded 893 Million Metric Tonnes (MMT) in 2022-23 to 1 billion tonnes in the current financial year 2023-24 and aims to increase it to 1.1 – 1.3 billion tonnes by 2030. Furthermore, according to the National Electricity Policy 2022, India also aims to increase India's coal-based capacity by 25.6 GW by 2026-27 to meet the power demand in the country in the short-to-medium run (Powell, Sati, & Tomar, 2023). In the long run, the government aims to install 80 GW of coal capacity by 2035 to meet the energy demand in the country (ETEnergyworld, 2023). While this incremental capacity addition is smaller compared to the 300 GW of additional solar and wind capacity addition required to meet their respective 280 GW and 140 GW targets, respectively, this runs counter-intuitive to the government's ambition of 'phasing down' coal power. However, the main factor contributing towards the push for coal power is the issues related to the grid stability, reliability and flexibility from VRE as discussed earlier. To this end, the implementation of smart energy systems which induces intra-hour, daily, seasonal and biannual storage options for VRE can act as a pivotal tool in grid balancing along with coal power (Mathiesen, et al., 2015). Only recently in September 2023, the Government of India announced the Viability Gap Funding of 40% of the capital cost as budgetary support

for the development of 4,000 mWh of battery Energy Storage Systems (BESS) projects by 2030-31, designed primarily to harness the potential VRE (PIB, 2023). For this purpose, a hierarchical framework to fasten the transition towards sustainable electricity systems is essential, in terms of prioritizing energy options available for electricity generation and consumption, depending upon technical, socio-economic, environmental and technological factors (Mukhopadhyay, Sengupta, & Prabhu, 2023). Given that of all the RE sources, India is giving primary emphasis on solar and wind energy, the BESS projects directed towards solar and wind energy storage infrastructure can play a pivotal role in ensuring a balanced electricity portfolio such that it can compete with coal power in terms of achieving higher share in the energy mix in the long-term future. Furthermore, this study has already provided a basis for solar and wind energy and other electricity sources power consumption by different industries and by households in the I-O framework. The estimated power demand across agriculture, light and heavy manufacturing industries, and commercial and residential sectors can be used to estimate the requirement of BESS such that the incremental demand can be shifted from coal power to VRE sources as well.

4) Promoting Indigenous Manufacturing

A few years ago, India used to import 80% of its solar PV modules and cell requirements from China and its neighboring countries (Roy, 2022). Then in 2020, the government of India announced the Production Linked Incentive (PLI) scheme for producing High Efficiency Solar PV modules in India with a total outlay of Rs. 24,000 crores (INVEST India, 2022; GOI, 2023). Today, India has a solar PV module manufacturing capacity of 28 GW and cell capacity of 6 GW and under the PLI scheme, it is expected to reach 100 GW capacity by 2026 (Gupta, 2023). Furthermore, there is high potential for module exports from India to Western countries, especially to the USA with the export of solar cells and modules reaching \$628.4 million during April – July 2023, up 1,062% from \$54 million during the same period last year (Ramesh, 2023). With the higher rate of indigenous manufacturing, it is India can explore other export markets as well. Apart from the PLI scheme, the trade friction between the US and China led to India grabbing the opportunity to capture the US market for solar exports. Given this significant rise in exports along with the high domestic demand to meet the 2030 target, the macroeconomic impact of higher indigenous manufacturing is expected to have a positive impact across the supply chain of solar PV industry.

5) Sub-national level categorization

In pursuit of India's 2030 solar PV and wind capacity targets, different states are expected to contribute differently. While the more economically developed northern and western states, namely Rajasthan, Gujarat, and Maharashtra. Karnataka and Tamil Nadu constitute a higher capacity to contribute towards the national targets, while the less-developed coal-bearing eastern and central states, namely West Bengal, Jharkhand, Chhattisgarh, Madhya Pradesh and Odisha face a different challenge for clean energy transition. Given that millions of livelihoods are served in these areas through coal mining it is essential to be sensitive to the socio-economic impact of coal phasing out in these regions. To this end, capacity building programs initiated by the central and state governments play a crucial role in providing alternative employment options for those currently working in the coal sector. In addition, it should be acknowledged that the skill sets required for coal mining do not necessarily align with those needed for jobs in solar PV and wind turbine manufacturing, making direct transfers difficult. Recently, the India-US Clean Energy partnership was announced by Niti Aayog wherein the sharing of best practices and exploring regional collaboration and strategies between coal-rich US and Indian states was proposed to ensure a 'Just transition' (Niti Aayog, 2021). Such initiatives are pivotal for ensuring equitable distribution of the national RE targets such that each state as per its existing economic and energy endowments will contribute towards the national goals.

Given the major findings and the practical and relevant policies that have been proposed here, certain limitations have also been noted and considered for conducting this study. Firstly, in the existing Indian Supply Use Table (SUT) since electricity is considered a homogenous industry without distinction between solar and wind and other electricity sources, there is no accounting of imports of solar PV modules and cells or wind turbine components exclusively by the Indian consumers which can be ground-mounted PV as well as rooftop PV. However, the latest SUT was only for 2018-19 where the installed solar PV and wind capacity was very small. Given that India is expected to become the second largest indigenous solar PV module manufacturer in the world after China by 2025 (ETEnergyworld, 2023), the 2030 scenarios that have been constructed for this study represent the macroeconomic impact across the supply chain that solar PV and wind turbine industries are expected to have been established indigenously in the long run. Secondly, this study has not taken into consideration the technical nuances of power generation, transmission and distribution synergy that affect the grid reliability, stability and flexibility arising from seasonality, changing load factors and the variable nature of renewable energy. For this purpose, power optimization models need to be adopted which focus on non-linear dynamic forecasting of changing demand-supply equilibrium over a period of time. Nevertheless, the Energy-Economy-Environment framework constructed in this study serves

as a conducive template wherein such optimization exercise can be complemented with economic modelling in the future, such that the dynamic macroeconomic impact can be evaluated.

This study has been conducted with a futuristic outlook for which steady actions need to be undertaken in the present for yielding the benefits of clean energy transition in the long run. Policymaking in its spirit should be practiced more from the point of view of initiating preventive measures for avoiding unintended consequences of economic aspirations in the first place, rather than curative measures where the negative impacts are to be minimized for the present and future generations. This study has attempted to contribute in this regard which not only takes into consideration the viability of the economic system to sustain the changing landscape of the Energy dimension in India but also the sustainability of the ecosystem on which we inherently depend upon for our present needs as well as for a sustainable future. This study can also act as a template for other developing/emerging economies which are undergoing a similar phase when it comes to decarbonization strategies. It is hoped that this study also encourages more economic studies which consider the environmental dimension more frequently in academic as well as policymaking contexts.

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APPENDIX

Table A1: Typical definitions of Circular Economy

Sr. no.	Definition	Reference
1.	“CE is a closed loop material flow in the whole economy system [...] in association with the so called 3R principles [...] Taking into account economic aspects, CE [...] minimizes matter without restricting economic growth.	(Lieder & Rashid, 2016)
2.	CE is a mode of economic development [...], requires compliance with ecological laws [...] It is essentially, an ecological economy that follows the principles of “reducing resource use, reusing and recycling”.	(Nailing & Zhijun, 2007)
3.	The core of CE are the ‘3R’ principles – reduction, reuse and recycling of materials and energy [...] The approach is expected to achieve an efficient economy while discharging fewer pollutants. The strategy requires complete reform of the whole system of human activity.	(Yuan, Bi, & Moriguichi, 2008)
4.	[CE] is about decoupling growth from resource consumption [...] It’s about designing products [that] are easier to reuse or recycling [...]	(Dupont-Inglis, 2015)

Source: (Kirchherr, Reike, & Hekkert, 2017)

Table A2: Technologies in the FTT:Power model

Nuclear	Solid Biomass	Wind onshore
Oil	Solid Biomass + CCS	Wind offshore
Coal PC	Biomass IGCC	Solar Photovoltaic
Coal IGCC	Biomass IGCC + CCS	Concentrated Solar Power
Coal PC + CCS	Biogas	Geothermal
Coal IGCC + CCS	Biogas + CCS	Wave
Gas CCGT	Tidal	Fuel Cells
Gas CCGT + CCS	Large Hydro	CHP

Table A3: Aggregated Sector list for the Indian Input-Output Table

Sr no.	Sector List	
1	Agriculture	1)Paddy, 2) Wheat, 3) Coarse Cereals, 4) Gram, 5) Arhar, 6) Other pulses, 7) Groundnut, 8) Rapeseed and mustard, 9) Other oil seeds, 10) Kapas, 11) Jute, hemp and mesta, 12) Sugarcane, 13) Coconut, 14) Tobacco, 15) Tea, 16) Coffee, 17) Rubber, 18) Fruits, 19) Vegetables, 20) Other food crops

2	Animal husbandry	21) Milk, 22) Wool, 23) Egg and poultry, 24) Other livestock products
3	Forestry and logging	25) Industry wood, 26) Firewood, 27) Other forestry products
4	Fishing	28) Inland fish 29) Marine fish
5	Coal and Lignite	30) Coal and Lignite
6	Natural Gas	31) Natural Gas
7	Crude petroleum	32) Crude petroleum
8	Iron ore	34) Iron ore
9	Manganese ore	35) Manganese ore
10	Bauxite	36) Bauxite
11	Copper ore	37) Copper ore
12	Other Metallic minerals	38) Other Metallic minerals
13	Limestone	39) Limestone
14	Mica	40) Mica
15	Other non-metallic minerals	41) Other non-metallic minerals
16	Food and food products	42) processed poultry meat & poultry meat products, 43) Processed other meat & meat products 44) Processed fish & fish products, 44) Processed fruits & processed vegetables, 45) Dairy products, 46) Edibles oils and fats, 47) Grain mill products, starch and starch products, 48) Sugar, 49) Bread & Bakery products, 50) Miscellaneous food products
17	Beverages and tobacco products	51) Alcoholic beverages, 52) Non-alcoholic beverages, 53) Tea processed, 54) Coffee processed, 55) Tobacco products
18	Textiles and textile products	56) Cotton yarn and cotton textiles, 57) Synthetic yarn and synthetic textiles, 58) Wool yarn and woolen textiles 59) Silk yarn and silk textiles 60) Carpet weaving, 61) Ready-made garments, 62) Misc. textile products
19	Leather and leather products	63) Leather footwear, 64) Leather and leather products except footwear
20	Wood and wood products except furniture	65) Wood and wood products except furniture
21	Paper, Paper products and newsprint, publishing, printing and allied activities	66) Paper, paper products and newsprint 67) Publishing, printing, and allied activities
22	Furniture & Fixtures	68) Furniture & Fixtures
23	Rubber products	69) Rubber products
24	Plastic products	70) Plastic products
25	Petroleum products	71) Petroleum products
26	Coal tar products	72) Coal tar products
27	Inorganic chemicals	73) Inorganic chemicals
28	Organic chemicals	74) Organic chemicals
29	Fertilizers and pesticides	75) Fertilizers, 76) Pesticides
30	Paints, varnishes and lacquers	77) Paints, varnishes and lacquers
31	Drugs and medicine	78) Drugs and medicine

32	Soaps, cosmetics and glycerin	79) Soaps, cosmetics and glycerin
33	Synthetic fibres, resin	80) Synthetic fibres, resin
34	Other chemicals and chemical products	81) Other chemicals and chemical products
35	Cement	82) Cement
36	Non-metallic mineral products	83) Non-metallic mineral products
37	Iron and steel Ferro alloys	84) Iron and steel Ferro alloys
38	Iron and steel casting and forging	85) Iron and steel casting and forging
39	Iron and steel foundries	86) Iron and steel foundries
40	Nonferrous basic metals (including alloys)	87) Non-ferrous basic metals (including alloys)
41	Hand tools, hardware	88) Hand tools, hardware
42	Miscellaneous metal products	89) Miscellaneous metal products
43	Tractors and other agricultural implements	90) Tractors and other agricultural implements
44	Industrial machinery for food and textile industry	91) Industrial machinery for food and textile industry
45	Industrial machinery (except food and textile)	92) Industrial machinery (except food and textile)
46	Machine tools	93) Machine tools
47	Other non-electrical machinery	94) Other non-electrical machinery
48	Electrical industrial machinery	95) Electrical industrial machinery
49	Electrical cables, wires	96) Electrical cables, wires
50	Batteries	97) Batteries
51	Electrical appliances	98) Electrical appliances
52	Communication equipment	99) Communication equipment
53	Other electrical machinery	100) Other electrical machinery
54	Electronic equipment including T.V	101) Electronic equipment including T.V
55	Medical precision, optical instrument, watches and clocks	102) Medical precision, optical instrument, 103) Watches and clocks
56	Ships and boats and rail equipment	104) Ships and boats 105) Rail equipment
57	Motor vehicles, motor cycles and scooters, bicycles, cycle-rickshaws	106) Motor vehicles 107) Motor cycles and scooters 108) Bicycles, cycle-rickshaw
58	Aircrafts and spacecrafts, other transport equipment	109) Aircrafts & Spacecrafts 110) Other transport equipment
59	Gems and jewellery and miscellaneous manufacturing	111) Gems & jewellery 112) Miscellaneous manufacturing
60	Construction and construction services	113) Construction and construction services
61	Electricity	114) Electricity
62	Gas	115) Gas
63	Water Supply	116) Water Supply
64	Trade	117) Trade
65	Repair & Maintenance of Motor Vehicle	118) Repair & Maintenance of Motor Vehicle
66	Hotels & Restaurant	119) Hotels & Restaurant

67	Transport services and auxiliary activities	120) Railway Transport 121) Land transport 122) Air transport 123) Water Transport 124) Supportive and Auxiliary transport activities
68	Storage and warehousing	125) Storage and warehousing
69	Communication services	126) Communication services
70	Financial and insurance services	127) Financial services 128) Insurance services
71	Ownership of dwellings, Renting of machinery & equipment, Real estate services, research & development services, legal services, other business services, computer related services, public administration and defence, education services, human health and social care services, community, social and personal services, recreation, entertainment and radio & TV broadcasting and other services	129) Ownership of dwellings, 130) Real estate services 131) Renting of machinery & equipment, 132) Research & Development services, 133) Legal services, 134) Other business services, 135) Computer-related services, 136) Public administration and defence 137) Education services 138) Human health and social care services 139) Community, social and personal services, 140) Recreation, entertainment and radio & TV broadcasting and other services

For the estimation of the environmental and human health cost of Solar PV waste, the external costs provided by Markert, Celik, & Apul, (2020) have been referred. The per unit costs have been converted from USD to INR based on the Purchasing Power Parity for 2019, provided by OECD (USD 1 = INR 21.073). The per unit costs were also provided in per m² unit which have been converted to per KW terms based on the assumption that 1 KW is equal to approximately 10m² (Nawaz & Tiwari, 2006; Home Scape, 2019). These have been shown in Tables B1 to B3.

Table A4: Solar PV waste external process input costs

Sr. no.	Impact Category	Cost (USD) / 1 m ²	Cost (USD)/KW	Cost (Rs/KW)
1	Cumulative energy demand (MJ)	0.40	4.0	84.3
2	Freshwater ecotoxicity (CTUe)	0.83	8.3	174.9
3	Marine eutrophication (kg N eq)	0.21	2.1	44.3
4	Freshwater eutrophication (kg P eq)	1.5*10 ⁻³	0.0	0.3
5	Acidification (molc H ⁺ eq)	2.4	24.0	505.8
6	Photochemical ozone formation (kg NMVOC eq)	9.6*10 ⁻²	1.0	20.2
7	Ionizing radiation human health (kg U235 eq)	2.2*10 ⁻²	0.2	4.6
8	Particulate matter (kg PM2.5 eq)	0.46	4.6	96.9
9	Human toxicity non-cancer effects(CTUh)	6.2*10 ⁻⁹	0.00000006	0.00000131

10	Human toxicity cancer effects (CTUh)	9.4*10 ⁻⁹	0.00000009	0.00000198
11	Ozone depletion (kg CFC 11 eq)	1.9*10 ⁻⁵	0.0	0.0
12	Global warming potential (kg CO2 eq)	0.24	2.4	50.6
13	Total Cost (USD) / 1 m2	4.62	46.6	981.9

Source: Markert, Celik, & Apul, (2020) and Authors' calculations

Table A5: Solar PV waste external transportation costs

Sr. no.	Impact Category	Cost (USD) /1m ²	Cost (USD)/KW	Cost (INR/KW)
1	Acidification (kg SO2 eq)	0.44	4.4	92.7
2	Ecotoxicity (CTUe)	0.12	1.2	25.3
3	Process Inputs	5.4*10 ⁻³	0.1	1.1
4	Global warming potential (kg CO2 eq)	4*10 ⁻²	0.4	8.4
5	Particulate matter (kg PM2.5 eq)	0.11	1.1	23.2
6	Human toxicity cancer effects (CTUh)	6.0*10 ⁻¹²	0.00000001	0.00000019
7	Human toxicity non-cancer effects (CTUh)	3.4*10 ⁻⁹	0.00000005	0.00000095
8	Ozone depletion (kg CFC 11 eq)	1.8*10 ⁻⁹	0.0	0.0
9	Cumulative energy demand (MJ)	1.8*10 ⁻²	0.2	3.8
10	Total Cost (USD) / 1 m2	0.73	7.3	154.5

Source: Markert, Celik, & Apul, (2020) and Authors' calculations

Table A6: Solar PV waste external landfilling costs

Sr. no.	Impact Category	Cost (USD) / 1 m2	Cost (USD)/KW	Cost (INR/KW)
1	Cumulative energy demand (MJ)	-4*10 ⁻²	-0.4	-8.4292
2	Freshwater ecotoxicity (CTUe)	0.65	6.5	136.9745
3	Marine eutrophication (kg N eq)	-3.9*10 ⁻³	-0.039	-0.82185
4	Freshwater eutrophication (kg P eq)	-1.4*10 ⁻⁴	-0.0014	-0.0295
5	Acidification (molc H+eq)	-0.21	-2.1	-44.2533
6	Photochemical ozone formation (kg NMVOC eq)	-3.4*10 ⁻³	-0.034	-0.71648
7	Ionizing radiation human health (kg U235 eq)	-4.6*10 ⁻³	-0.046	-0.96936
8	Particulate matter (kg PM2.5 eq)	-6.0*10 ⁻²	-0.6	-12.6438

9	Human toxicity non-cancer effects (CTUh)	9.0×10^{-10}	9E-09	1.9E-07
10	Human toxicity cancer effects (CTUh)	4.5×10^{-9}	4.5E-08	9.48E-07
11	Ozone depletion (kg CFC 11 eq)	-5.2×10^{-6}	-0.000052	-0.0011
12	Global warming potential (kg CO ₂ eq)	3.0×10^{-2}	0.3	6.3219
13	Total Cost (USD) / 1 m ²	0.36	3.5795	75.4318

Source: Markert, Celik, & Apul, (2020) and Authors' calculations

In Tables B1 to B3, the colour distinction highlights the environmental and human health costs incurred from solar PV waste in the end-of-lifetime phase.

Similar to the solar PV waste, the external costs for wind turbine waste were not available, which is attributed to the turbine recycling being at a nascent stage in its development. Nevertheless, the authors intend to provide preliminary estimates attributed to turbine waste, using the information provided for solar PV waste recycling.

According to the USEPA, the priority contaminants present in Solar PV that are harmful for the groundwater and soil based on metal leaching studies are Silver (Ag), Arsenic (As), Copper (Cu), Cadmium (Cd), Chromium (Cr), Lead (Pb), Nickel (Ni), Selenium (Se) and Zinc (Zn) (Nain & Kumar, 2020). The environmental and human health impacts presented in tables C1 to C3 above are attributed to the metal leaching effects of the aforementioned elements. In this regard, based on the Life Cycle Assessment of report on wind energy authored by Mali & Garrett, (2022), the same type of harmful contents are observed in wind turbines post-decommissioning in end-of-lifetime. To this end, the study assumes the same per unit cost values that are attributed to solar PV in Tables B1 to B3, since the metal contents, irrespective of the source from which the leaching potential exists will have the similar impacts on soil and groundwater.

Table A7: Per unit Cost Benefit Analysis of 1 kWh/m² c-Si PV module

Sr. no.	Particulars	Value (in USD)
1.	Private Costs (transportation, landfilling/disposal, electricity consumed materials etc.) ^a	6.72
2.	External Costs ^b	5.71
3.	Commercial/Economic value of recovered materials (Aluminium, glass, silver, silicon, copper)	13.62
4.	Net Benefit (Sr. no. 3 – 1 - 2)	1.19

Source: (Markert, Celik, & Apul, 2020)

^aPrivate costs include the cost of investment, processing, transportation and disposal;

^bExternal costs are from Cumulative Energy Demand, Global Warming potential, acidification, freshwater toxicity, particulate matter etc.

^cAluminium, glass, silver, silicon, copper

Table A8: Material-wise Solar PV module waste generation (in tonnes) SCENARIO 1

Sr. no.	Materials	BAU	CEA Base (2020)	CEA NEP (2022)	TERI (2018)	TERI (2020)	E3 2030
1	Glass	1379.0	1211.4	629.9	1162.9	775.3	1405.2
2	Aluminium frame	354.6	311.5	162.0	299.0	199.4	361.3
3	Copper connector	19.7	17.3	9.0	16.6	11.1	20.1
4	Polymer-based adhesive (EVA) encapsulation layer (from cables)	100.5	88.3	45.9	84.7	56.5	102.4
5	Back-sheet layer (based on polyvinyl fluoride)	29.6	26.0	13.5	24.9	16.6	30.1
6	Silicon metal solar cell	71.9	63.2	32.8	60.6	40.4	73.3
7	Silver	1.0	0.9	0.5	0.9	0.6	1.1
8	Aluminium, internal conductor	10.4	9.2	4.8	8.8	5.9	10.6
9	Copper, internal conductor	2.2	2.0	1.0	1.9	1.3	2.3
10	Various metal (tin, lead)	1.0	0.9	0.5	0.9	0.6	1.1
11.	TOTAL	1970.0	1730.6	899.9	1661.3	1107.6	2007.5

Source: Authors' calculations

Table A9: Material-wise Solar PV module waste generation (in tonnes) SCENARIO 2

Sr. no.	Materials	BAU	CEA Base (2020)	TERI (2018)	TERI (2020)	E3 2030
1	Glass	5121.0	2847.5	9188.9	16644.8	8313.9
2	Aluminium frame	1316.8	732.2	2362.8	4280.1	2137.9
3	Copper connector	73.2	40.7	131.3	237.8	118.8
4	Polymer-based adhesive (EVA) encapsulation layer (from cables)	373.1	207.5	669.5	1212.7	605.7
5	Back-sheet layer (based on polyvinyl fluoride)	109.7	61.0	196.9	356.7	178.2
6	Silicon metal solar cell	267.0	148.5	479.1	867.9	433.5
7	Silver	3.9	2.2	7.0	12.6	6.3
8	Aluminium, internal conductor	38.8	21.6	69.6	126.0	62.9
9	Copper, internal conductor	8.3	4.6	15.0	27.1	13.5
10	Various metal (tin, lead)	3.9	2.2	7.0	12.6	6.3
11.	TOTAL	7315.7	4067.9	13126.9	23778.2	11877.1

Source: Authors' calculations

Table A10: Material-wise wind turbine waste generation (in tonnes) SCENARIO 1

Sr. no.	Materials	BAU	CEA Base (2020)	CEA NEP (2022)	TERI (2018)	TERI (2020)	E3 2030
1	Unalloyed, low alloyed	1338351.5	1115920.0	1255410.0	1534390.0	2092350.0	1673880.0
2	Highly alloyed	130870.4	109120.0	122760.0	150040.0	204600.0	163680.0
3	Cast iron	167521.8	139680.0	157140.0	192060.0	261900.0	209520.0
4	Aluminium and aluminium alloys	31758.1	26480.0	29790.0	36410.0	49650.0	39720.0
5	Copper	13432.4	11200.0	12600.0	15400.0	21000.0	16800.0
6	Polymer materials (total)	76277.1	63600.0	71550.0	87450.0	119250.0	95400.0
7	Modified organic natural materials	4029.7	3360.0	3780.0	4620.0	6300.0	5040.0
8	Ceramic / glass	89901.5	74960.0	84330.0	103070.0	140550.0	112440.0
9	Concrete	4639855.3	3868720.0	4352310.0	5319490.0	7253850.0	5803080.0
10	SF ₆ gas	22.5	18.8	21.2	25.9	35.3	28.2
11.	Magnets	8731.1	7280.0	8190.0	10010.0	13650.0	10920.0
12.	Electronics	2014.9	1680.0	1890.0	2310.0	3150.0	2520.0
13.	Electrics	6716.2	5600.0	6300.0	7700.0	10500.0	8400.0
14.	Lubricants	4029.7	3360.0	3780.0	4620.0	6300.0	5040.0
15.	Coolant / other glycols	671.6	560.0	630.0	770.0	1050.0	840.0
16.	TOTAL	6514184.1	5431538.8	6110481.15	7468365.85	10184135.3	8147308.2

Source: Authors' calculations

Table A11: Wind turbine waste generation in End-of-life Phase: SCENARIO 1 (in tonnes)

Sr. no.	Materials	BAU	CEA Base (2020)	TERI (2018)	TERI (2020)	E3 2030
1	Unalloyed, low alloyed	5131797.6	418470.0	439273.9	16712430.7	7414377.9
2	Highly alloyed	501811.7	40920.0	42954.3	1634221.5	725013.4
3	Cast iron	642348.5	52380.0	54984.0	2091899.3	928059.6
4	Aluminium and aluminium alloys	121774.0	9930.0	10423.7	396574.3	175938.0
5	Copper	51505.6	4200.0	4408.8	167735.3	74414.9
6	Polymer materials (total)	292478.2	23850.0	25035.7	952497.1	422570.1
7	Modified organic natural materials	15451.7	1260.0	1322.6	50320.6	22324.5
8	Ceramic / glass	344719.6	28110.0	29507.5	1122628.7	498048.0

9	Concrete	17791139.1	1450770.0	1522894.0	57939381.6	25704487.7
10	SF ₆ gas	86.5	7.1	7.4	281.6	124.9
11.	Magnets	33478.6	2730.0	2865.7	109028.0	48369.7
12.	Electronics	7725.8	630.0	661.3	25160.3	11162.2
13.	Electrics	25752.8	2100.0	2204.4	83867.7	37207.4
14.	Lubricants	15451.7	1260.0	1322.6	50320.6	22324.5
15.	Coolant / other glycols	2575.3	210.0	220.4	8386.8	3720.7
16.	TOTAL	24978096.7	2036827.05	2138086.45	81344734	36088143.4

Source: Authors' calculations

Table A12: Environmentally adjusted GDP in SEEA framework Scenario 1 – BAU

Sr. no.		Domestic production	Final cons. (households, govt.)	Capital formation	Rest of the world
1.	Supply of products	i) 363,123,643			45,172,559
	408,296,203	ii) 623,859			
2.	Use of products	175,402,830	139,546,218	55,684,220	37,662,939
	408,296,203	5,154,834	109,035		
3.	Use of fixed capital	19,842,840		19,842,840	
4.	Value added (VA/NDP)	213,050,532			
5.	Defensive expenditure	352325	-63469	388186	
	Agriculture impact due to reduced insolation	-2398			
	Environmental cost of mining	-11590			
	Solar PV waste environmental impact	18693			
	Wind PV waste environmental impact	24042			
	Environmental value addition	212662346			
	Environmentally adjusted domestic product	212725815			
	<i>% loss in terms of GDP</i>	-0.15%			

Source: Authors' calculations

Table A13: Environmentally adjusted GDP in SEEA framework Scenario 1 – CEA BASE CASE

Sr. no.		Domestic production	Final cons. (households, govt.)	Capital formation	Rest of the world
1.	Supply of products	i) 363,123,643			45,172,559
	408,296,203	ii) 623,859			
2.	Use of products	175,402,830	139,546,218	55,684,220	37,662,939
	408,296,203	5,154,834	109,035		

3.	Use of fixed capital	19,842,840		19,842,840	
4.	Value added (VA/NDP)	213,050,532			
5.	Defensive expenditure	310259	-65815	339006	
	Agriculture impact due to reduced insolation	-2398			
	Environmental cost of mining	-11590			
	Solar PV waste environmental impact	18693			
	Wind PV waste environmental impact	24042			
	Environmental value addition	212711526			
	Environmentally adjusted domestic product	212777340			
	<i>% loss in terms of GDP</i>	-0.13%			

Source: Authors' calculations

Table A14: Environmentally adjusted GDP in SEEA framework Scenario 1 – CEA NEP

Sr. no.		Domestic production	Final cons. (households, govt.)	Capital formation	Rest of the world
1.	Supply of products	i) 363,123,643			45,172,559
	408,296,203	ii) 623,859			
2.	Use of products	175,402,830	139,546,218	55,684,220	37,662,939
	408,296,203	5,154,834	109,035		
3.	Use of fixed capital	19,842,840		19,842,840	
4.	Value added (VA/NDP)	213,050,532			
5.	Defensive expenditure	305212	-70920	333960	
	Agriculture impact due to reduced insolation	-2398			
	Environmental cost of mining	-11590			
	Solar PV waste environmental impact	18693			
	Wind PV waste environmental impact	24042			

	Environmental value addition	212716572			
	Environmentally adjusted domestic product	212787493			
	<i>% loss in terms of GDP</i>	-0.12%			

Source: Authors' calculations

Table A15: Environmentally adjusted GDP in SEEA framework Scenario 1 – TERI (1)

Sr. no.		Domestic production	Final cons. (households, govt.)	Capital formation	Rest of the world
1.	Supply of products	i) 363,123,643			45,172,559
	408,296,203	ii) 623,859			
2.	Use of products	175,402,830	139,546,218	55,684,220	37,662,939
	408,296,203	5,154,834	109,035		
3.	Use of fixed capital	19,842,840		19,842,840	
4.	Value added (VA/NDP)	213,050,532			
5.	Defensive expenditure	236737	-64886	265484	
	Agriculture impact due to reduced insolation	-2398			
	Environmental cost of mining	-11590			
	Solar PV waste environmental impact	18693			
	Wind PV waste environmental impact	24042			
	Environmental value addition	212785048			
	Environmentally adjusted domestic product	212849934			
	<i>% loss in terms of GDP</i>	-0.09%			

Source: Authors' calculations

Table A16: Environmentally adjusted GDP in SEEA framework Scenario 1 – TERI (2)

Sr. no.		Domestic production	Final cons. (households, govt.)	Capital formation	Rest of the world
1.	Supply of products	i) 363,123,643			45,172,559
	408,296,203	ii) 623,859			
2.	Use of products	175,402,830	139,546,218	55,684,220	37,662,939
	408,296,203	5,154,834	109,035		
3.	Use of fixed capital	19,842,840		19,842,840	
4.	Value added (VA/NDP)	213,050,532			
5.	Defensive expenditure	347038	-66743	375785	
	Agriculture impact due to reduced insolation	-2398			
	Environmental cost of mining	-11590			
	Solar PV waste environmental impact	18693			
	Wind PV waste environmental impact	24042			
	Environmental value addition	212674747			
	Environmentally adjusted domestic product	212741490			
	<i>% loss in terms of GDP</i>	-0.15%			

Source: Authors' calculations

Table A17: Environmentally adjusted GDP in SEEA framework Scenario 1 – E3-India

Sr. no.		Domestic production	Final cons. (households, govt.)	Capital formation	Rest of the world
1.	Supply of products	i) 363,123,643			45,172,559
	408,296,203	ii) 623,859			
2.	Use of products	175,402,830	139,546,218	55,684,220	37,662,939
	408,296,203	5,154,834	109,035		
3.	Use of fixed capital	19,842,840		19,842,840	
4.	Value added (VA/NDP)	213,050,532			

5.	Defensive expenditure	325149	-62102	353897	
	Agriculture impact due to reduced insolation	-2398			
	Environmental cost of mining	-11590			
	Solar PV waste environmental impact	18693			
	Wind PV waste environmental impact	24042			
	Environmental value addition	212696635			
	Environmentally adjusted domestic product	212758737			
	<i>% loss in terms of GDP</i>	-0.14%			

Source: Authors' calculations

Table A18: Environmentally adjusted GDP in SEEA framework Scenario 2 – BAU

Sr. no.		Domestic production	Final cons. (households, govt.)	Capital formation	Rest of the world
1.	Supply of products	i) 363,123,643			45,172,559
	408,296,203	ii) 623,859			
2.	Use of products	175,402,830	139,546,218	55,684,220	37,662,939
	408,296,203	5,154,834	109,035		
3.	Use of fixed capital	19,842,840		19,842,840	
4.	Value added (VA/NDP)	213,050,532			
5.	Defensive expenditure	837295	-238115	891372	
	Agriculture impact due to reduced insolation	-8992			
	Environmental cost of mining	-43463			
	Solar PV waste environmental impact	79024			
	Wind PV waste environmental impact	27509			
	Environmental value addition	212159160			
	Environmentally adjusted domestic product	211505903			

	<i>% loss in terms of GDP</i>	-0.73%			
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Source: Authors' calculations

Table A19: Environmentally adjusted GDP in SEEA framework Scenario 2 – CEA BASE CASE

Sr. no.		Domestic production	Final cons. (households, govt.)	Capital formation	Rest of the world
1.	Supply of products	i) 363,123,643			45,172,559
	408,296,203	ii) 623,859			
2.	Use of products	175,402,830	139,546,218	55,684,220	37,662,939
	408,296,203	5,154,834	109,035		
3.	Use of fixed capital	19,842,840		19,842,840	
4.	Value added (VA/NDP)	213,050,532			
5.	Defensive expenditure	447822	-97094	468206	
	Agriculture impact due to reduced insolation	-3633			
	Environmental cost of mining	-17557			
	Solar PV waste environmental impact	43941			
	Wind PV waste environmental impact	-2367			
	Environmental value addition	212582326			
	Environmentally adjusted domestic product	212679419			
	<i>% loss in terms of GDP</i>	-0.17%			

Source: Authors' calculations

Table A20: Environmentally adjusted GDP in SEEA framework Scenario 2 – TERI (1)

Sr. no.		Domestic production	Final cons. (households, govt.)	Capital formation	Rest of the world
1.	Supply of products	i) 363,123,643			45,172,559
	408,296,203	ii) 623,859			
2.	Use of products	175,402,830	139,546,218	55,684,220	37,662,939
	408,296,203	5,154,834	109,035		
3.	Use of fixed capital	19,842,840		19,842,840	
4.	Value added (VA/NDP)	213,050,532			
5.	Defensive expenditure	1616297	-303799	1692640	
	Agriculture impact due to reduced insolation	-11624			
	Environmental cost of mining	-56183			
	Solar PV waste environmental impact	141795			
	Wind PV waste environmental impact	2355			
	Environmental value addition	211357892			
	Environmentally adjusted domestic product	211661691			
	<i>% loss in terms of GDP</i>	-0.66%			

Source: Authors' calculations

Table A21: Environmentally adjusted GDP in SEEA framework Scenario 2 – TERI (2)

Sr. no.		Domestic production	Final cons. (households, govt.)	Capital formation	Rest of the world
1.	Supply of products	i) 363,123,643			45,172,559
	408,296,203	ii) 623,859			
2.	Use of products	175,402,830	139,546,218	55,684,220	37,662,939
	408,296,203	5,154,834	109,035		
3.	Use of fixed capital	19,842,840		19,842,840	
4.	Value added (VA/NDP)	213,050,532			

5.	Defensive expenditure	4389717	-82901	4684782	
	Agriculture impact due to reduced insolation	-8806			
	Environmental cost of mining	-42564			
	Solar PV waste environmental impact	256849			
	Wind PV waste environmental impact	89586			
	Environmental value addition	208365750			
	Environmentally adjusted domestic product	208448652			
	<i>% loss in terms of GDP</i>	-2.21%			

Source: Authors' calculations

Table A22: Environmentally adjusted GDP in SEEA framework Scenario 2 – E3-INDIA

Sr. no.		Domestic production	Final cons. (households, govt.)	Capital formation	Rest of the world
1.	Supply of products	i) 363,123,643			45,172,559
	408,296,203	ii) 623,859			
2.	Use of products	175,402,830	139,546,218	55,684,220	37,662,939
	408,296,203	5,154,834	109,035		
3.	Use of fixed capital	19,842,840		19,842,840	
4.	Value added (VA/NDP)	213,050,532			
5.	Defensive expenditure	2106904	-335937	2199038	
	Agriculture impact due to reduced insolation	-13012			
	Environmental cost of mining	-62892			
	Solar PV waste environmental impact	128294			
	Wind PV waste environmental impact	39744			
	Environmental value addition	210851494			
	Environmentally adjusted domestic product	211187431			

	<i>% loss in terms of GDP</i>	-0.88%			
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Source: Authors' calculations

The parameter-wise discussion is discussed here:

I. Progressive Indicators

1. Current solar/wind share in the total energy mix

The combined share of solar and wind energy generation in the respective state's electricity portfolio is calculated. Higher the share, better the score for the respective state.

Table A23: Combined share of Solar+Wind energy in total electricity generation (2021-22)

Sr. no.	State Name	Solar	Wind	Biopower	Small Hydro	Thermal Power Generation	Total power generation	Solar+Wind share in total (in %)
1	Andhra Pradesh	7832.51	7134.58	311.43	384.08	57690.12	73352.72	20.4%
2	Bihar	163.09	0.00	67.99	8.77	43623.44	43863.29	0.4%
3	Chhattisgarh	436.55	185.66	1315.98	0.00	140928.2	142866.39	0.4%
4	Gujarat	6774.51	17854.77	0.00	0.00	63453.77	88083.05	28.0%
5	Haryana	572.85	0.00	292.44	270.13	22914.46	24049.88	2.4%
6	Karnataka	13169.45	9491.62	3512.35	2460.91	51980.29	80614.62	28.1%
7	Madhya Pradesh	4006.71	4346.67	141.79	221.44	133920.67	142637.28	5.9%
8	Maharashtra	3787.18	7085.98	4785.31	787.16	134063.64	150509.27	7.2%
9	Orissa	603.72	0.00	100.08	377.29	64892.71	65973.80	0.9%
10	Punjab	1473.42	543.37	785.39	0.00	27862.46	30664.64	6.6%
11	Rajasthan	17219.88	6493.20	378.41	0.00	59757.55	83849.04	28.3%
12	Tamil Nadu	7832.51	7134.58	311.43	384.08	90184.13	105846.73	14.1%
13	Telangana	6536.94	275.68	442.30	90.99	57904.37	65250.28	10.4%
14	Uttar Pradesh	2900.42	0.00	3266.00	162.54	136777.25	143106.21	2.0%
15	West Bengal	86.96	145.10	1593.95	0.00	86392.37	88218.38	0.3%
16.	Kerala	496.93	136.41	48.93	932.37	8148.41	9763.05	6.5%
17.	Jharkhand	19.68	0.00	0.00	10.49	28941.46	28971.63	0.1%

Source: (CEA, 2022b)

2. 2022 Solar/Wind targets: This parameter is taken into consideration for evaluating the targets provided by Niti Aayog to be achieved by 2022.

Table A24: Target and actual installed capacity as of December 2022 (in GW)

Sr. no.	State Name	Solar	Wind
1	Andhra Pradesh	9.8	8.1
2	Bihar	2.5	0.0
3	Chhattisgarh	1.8	0.0
4	Gujarat	8.0	8.8
5	Haryana	4.1	0.0
6	Karnataka	5.7	6.2

7	Madhya Pradesh	5.7	6.2
8	Maharashtra	11.9	7.6
9	Orissa	2.4	0.0
10	Punjab	4.8	0.0
11	Rajasthan	5.8	8.6
12	Tamil Nadu	8.9	11.9
13	Telangana	0.0	2.0
14	Uttar Pradesh	10.7	0.0
15	West Bengal	5.3	0.0
16	Kerala	1.9	0.0
17	Jharkhand	2.0	0.0

Source: (CEA, 2022c)

3. 2022 Solar/Wind actual targets: Given the state-wise targets allocated by niti Aayog, the actual installed capacity achieved by December 2022 has been evaluated.

Table A25: Actual installed capacity as of December 2022 (in GW)

Sr. no.	State Name	Solar	Wind
1	Andhra Pradesh	4.5	4.1
2	Bihar	0.2	0.0
3	Chhattisgarh	0.9	0.0
4	Gujarat	8.7	9.9
5	Haryana	1.0	0.0
6	Karnataka	8.0	5.3
7	Madhya Pradesh	2.8	2.8
8	Maharashtra	3.7	5.0
9	Orissa	0.5	0.0
10	Punjab	1.2	0.0
11	Rajasthan	16.4	4.7
12	Tamil Nadu	6.5	10.0
13	Telangana	4.7	0.1
14	Uttar Pradesh	2.5	0.0
15	West Bengal	0.2	0.0
16	Kerala	0.7	0.0
17	Jharkhand	0.1	0.0

Source: (CEA, 2022c)

4. Solar/Wind Actual vs Potential:

Every state has a identified potential in terms of the maximum capacity (in GW) that can be installed for harnessing solar and/or wind energy within its state boundaries. Thus, higher the potential, higher the scope for installing additional solar/wind capacity.

Table A26: Actual vs Potential Solar and Wind capacity installed (in GW)

		SOLAR	WIND
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Sr. no.	Row Labels	Potential	Actual	Difference	Potential	Actual	Difference
1	Andhra Pradesh	38.4	4.5	-33.9	44.2	8.1	-36.1
2	Bihar	11.2	0.2	-11.0	0.0	0.0	0
3	Chhattisgarh	18.3	0.9	-17.3	0.1	0.0	-0.1
4	Gujarat	35.8	8.7	-27.0	84.4	8.8	-75.6
5	Haryana	4.6	1.0	-3.6	0.0	0.0	0
6	Karnataka	24.7	8.0	-16.7	55.9	6.2	-49.7
7	Madhya Pradesh	61.7	2.8	-58.9	10.5	6.2	-4.3
8	Maharashtra	64.3	3.7	-60.6	45.4	7.6	-37.8
9	Orissa	2.4	0.5	-1.9	3.1	0.0	-3.1
10	Punjab	2.8	1.2	-1.7	0.0	0.0	0
11	Rajasthan	142.3	16.4	-126.0	18.8	8.6	-10.2
12	Tamil Nadu	17.7	6.5	-11.2	33.8	11.9	-21.9
13	Telangana	20.4	4.7	-15.8	4.2	2	-2.2
14	Uttar Pradesh	22.8	2.5	-20.3	0.0	0.0	0
15	West Bengal	6.3	0.2	-6.1	0.0	0.0	0
16	Kerala	6.1	0.7	-5.4	0.0	0	0
17	Jharkhand	18.2	0.1	-18.1	0.0	0	0

Source: (MNRE, 2022; CEA, 2022c)

Note: A negative difference (Actual minus Potential) implies that there is higher scope for installed solar/wind capacity over and above the actual installed capacity whereas zero implies there is no further scope. Thus lower the difference higher the index score for the respective state.

5. Solar/Wind financing

As discussed in Table 7.2, using the per unit solar PV and wind energy industry costs, the financing required in respective states was calculated and has been presented in Table A5.

Table A27: Solar/Wind financing

Sr. no.	States	In Rs. Million	in USD million
1	Gujarat	21193.8	1005.7
2	Tamil Nadu	19854.8	942.2
3	Rajasthan	17668.9	838.5
4	Karnataka	13373.8	634.6
5	Maharashtra	10262.0	487.0
6	Andhra Pradesh	9325.6	442.5
7	Madhya Pradesh	6244.5	296.3
8	Telangana	3123.1	148.2

9	Uttar Pradesh	1563.5	74.2
10	Punjab	724.1	34.4
11	Haryana	629.3	29.9
12	Chhattisgarh	592.5	28.1
13	Kerala	431.6	20.5
14	Orissa	283.9	13.5
15	Bihar	121.0	5.7
16	West Bengal	112.9	5.4
17	Jharkhand	59.5	2.8

Source: Authors' calculations

6. 2030 Solar+Wind mix in RE portfolio:

Given that the 450 GW 2030 target constitutes not only solar and wind, but also other RE sources such as biomass and small hydro, the share of only solar and wind in the total RE portfolio is evaluated.

Table A28: Solar and Wind combined mix in RE portfolio 2030

Sr. no.	State Name	Solar	Wind	Biopower	Small Hydro	Solar+Wind
1	Andhra Pradesh	13172.3	11998.6	523.7	645.9	25170.9
2	Bihar	272.3	0.0	113.5	14.6	272.3
3	Chhattisgarh	177.2	75.4	534.1	0.0	252.5
4	Gujarat	17392.6	45839.6	0.0	0.0	63232.3
5	Haryana	2457.6	0.0	1254.6	1158.9	2457.6
6	Karnataka	16296.8	11745.6	4346.4	3045.3	28042.3
7	Madhya Pradesh	4375.6	4746.9	154.8	241.8	9122.5
8	Maharashtra	6330.3	11844.3	7998.7	1315.7	18174.6
9	Orissa	515.3	0.0	85.4	322.1	515.3
10	Punjab	4672.2	1723.0	2490.5	0.0	6395.2
11	Rajasthan	32619.8	12300.1	716.8	0.0	44919.9
12	Tamil Nadu	12580.2	11459.2	500.2	616.9	24039.4
13	Telangana	11117.4	468.8	752.2	154.7	11586.2
14	Uttar Pradesh	4655.7	0.0	5242.5	260.9	4655.7
15	West Bengal	90.5	150.9	1658.1	0.0	241.4
16	Kerala	2008.7	551.4	197.8	3768.8	2560.1
17	Jharkhand	21.1	0.0	0.0	11.3	21.1

Source: CEA, (2022b) and Authors' calculations

II. Regressive Indicators

1. Electricity intensity:

Table A29: State-wise Electricity intensity

Sr. no.	State/Union Territory	Total electricity consumption (in gWh) (2021-22)	GSDP (in Rs. Lakhs) (2021-22)	Electricity intensity to GDP
1	Andhra Pradesh	144417	67032150	0.02154
2	Bihar	106030	38572820.42	0.02749
3	Chhattisgarh	100511	24545166	0.04095
4	Gujarat	71097	124818912	0.00570
5	Haryana	65659	53622560	0.01224
6	Karnataka	62680	114387339	0.00548
7	Madhya Pradesh	62575	56451437	0.01108
8	Maharashtra	60495	188930666	0.00320
9	Odisha	52080	38147033	0.01365
10	Punjab	45210	39978038	0.01131
11	Rajasthan	43061	66011779	0.00652
12	Tamil Nadu	31619	124559515	0.00254
13	Telangana	28472	60992733	0.00467
14	Uttar Pradesh	27026	107739186	0.00251
15	West Bengal	26281	79272009	0.00332
16	Kerala	23061	55092006	0.00419
17	Jharkhand	14361	23681637	0.00606

Source: (CEA, 2022b; RBI, 2022)

2. GHG Emission intensity

The GHG emission factors for power generation from coal, solar, wind energy, biomass and small hydro is estimated to be 957gCO₂/kWh, 38gCO₂/kWh and 9gCO₂/kWh, 241gCO₂/kWh, 10gCO₂/kWh, respectively (GOI, 2021), Given the source-wise power generation in 2021-22, presented in Table A1.

Table A30: State-wise GHG emission intensity

Sr. no.	State/Union Territory	Total GHG emissions (in tonnes)	GSDP (in Rs. Lakhs) (2021-22)	GHG emission intensity to GDP
1	Andhra Pradesh	55650187	67032150	8.3
2	Bihar	41770303	38572820	10.8
3	Chhattisgarh	135203698	24545166	55.1
4	Gujarat	61143382	124818912	4.9
5	Haryana	22024086	53622560	4.1
6	Karnataka	51202087	114387339	4.5
7	Madhya Pradesh	128389842	56451437	22.7
8	Maharashtra	129667721	188930666	6.9
9	Odisha	62153157	38147033	16.3
10	Punjab	26914534	39978038	6.7
11	Rajasthan	57991966	66011779	8.8
12	Tamil Nadu	86746954	124559515	7.0
13	Telangana	55772871	60992733	9.1

14	Uttar Pradesh	131794776	107739186	12.2
15	West Bengal	83066250	79272009	10.5
16	Kerala	7839255	55092006	1.4
17	Jharkhand	27697830	23681637	11.7

Source: (GOI, 2021)

3. RE waste generation

As discussed in the attributional LCA studies on solar and wind energy in chapters 4 and 5, respectively, a significant amount of waste is expected to be generated post-decommissioning of solar PV modules and wind turbines. Given the installed capacity as of December 2022, the waste generation at the rate of 69.2 tonnes/GW of solar PV modules (Latunussa et al., 2016) and 680,304 tonnes/GW wind turbines (Mali & Garrett) is estimated in the respective states (Table A9). Higher the waste generation, lower their index score.

Table A31: State-wise and waste generation from solar and wind energy

Sr. no.	States	Installed capacity		Waste Generation	
		Solar	Wind	Solar	Wind
1	Andhra Pradesh	4.5	8.1	313	55,10,462
2	Bihar	0.2	0.0	13	-
3	Chhattisgarh	0.9	0.0	65	-
4	Gujarat	8.7	8.8	605	59,86,675
5	Haryana	1.0	0.0	69	-
6	Karnataka	8.0	6.2	555	42,17,885
7	Madhya Pradesh	2.8	6.2	192	42,17,885
8	Maharashtra	3.7	7.6	256	51,70,310
9	Orissa	0.5	0.0	31	-
10	Punjab	1.2	0.0	80	-
11	Rajasthan	16.4	8.6	1,132	58,50,614
12	Tamil Nadu	6.5	11.9	450	80,95,618
13	Telangana	4.7	2.0	322	13,60,608
14	Uttar Pradesh	2.5	0.0	173	-
15	West Bengal	0.2	0.0	12	-
16	Kerala	0.7	0.0	48	-
17	Jharkhand	0.1	0.0	7	-
	Total	61.7	59.4	4,270	4,04,10,058

Source: Latunussa et al., (2016); Mali & Garrett (2022) and Authors' calculations

Table A32: Parameter-wise scorecard across states

Sr. no.	State Name	Solar/Wind Power Mix 2022	2022 Solar wind targets	2022 Solar wind actuals	Green Financing	Solar actual vis-a-vis potential	2030 Solar+Wind mix	Waste generation	Electricity intensity	GHG emission intensity	Total
1	Andhra Pradesh	3	3	2	2	2	2	1	1	2	18
2	Bihar	1	1	1	1	1	1	3	1	2	12
3	Chhattisgarh	1	1	1	1	1	1	3	1	1	11
4	Gujarat	3	3	3	3	3	3	1	3	3	25
5	Haryana	1	1	1	1	1	1	3	2	3	14
6	Karnataka	3	2	2	2	2	2	2	3	3	21
7	Madhya Pradesh	1	2	1	1	2	1	2	2	3	15
8	Maharashtra	1	3	2	2	3	1	2	3	2	19
9	Orissa	1	1	1	1	1	1	3	2	1	12
10	Punjab	1	1	1	1	1	1	3	2	2	13
11	Rajasthan	3	2	3	3	3	3	1	3	2	23
12	Tamil Nadu	2	3	3	3	1	2	1	3	2	20
13	Telangana	2	1	1	1	1	1	3	3	2	15
14	Uttar Pradesh	1	2	1	1	1	1	3	3	1	14
15	West Bengal	1	1	1	1	1	1	3	3	2	14
16	Kerala	1	1	1	1	1	1	3	3	3	15
17	Jharkhand	1	1	1	1	1	1	3	3	1	13
18	INDIA	1	2	1	1	1	1	3	3	2	15

Source: Authors' calculations

