Circular economy initiatives in Indian manufacturing: *an ecosystem view*

by

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STATEMENT OF ORIGINAL AUTHORSHIP

This thesis is submitted in fulfilment of the requirements for the degree of Doctor of Philosophy in the Macquarie Business School, Macquarie University. Except as acknowledged in the references, the material included in the thesis represents the original work and contributions of the author.

I hereby certify that the research described in this dissertation has not been submitted for a higher degree to any other university or institution. The research presented in this thesis is approved by the Macquarie University Human Research Ethics Committee via Reference number 5201700967 (Appendix 16).

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Signed:

Date: 25th July 2021

This thesis is dedicated to my paternal grandfather, Brigadier Prabhjot Singh Talwar, who tugged me along, always encouraging and beaming with pride. Sadly, he isn't with us today. I know he is shining his light and love while he smiles over me.

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LIST OF ABBREVIATIONS

AFRs	Alternative Fuels and Raw Materials
AGEE	Working Group on Renewable Energy Statistics, The Federal Ministry for Economic Affairs and Energy, Germany
ALEAP	Association of Lady Entrepreneurs of Andhra Pradesh
API	Active Pharmaceutical Ingredients
APIIC	Andhra Pradesh Industrial Infrastructure Corporation
APPCB	Andhra Pradesh Pollution Control Board
BEE	Bureau of Energy Efficiency
BOOT	Build–own–operate–transfer
BW	Business Wire
CAGR	Compounded Annual Growth Rate
CE	Circular Economy
CEA	Central Electricity Authority
CETP	Common Effluent Treatment Plant
CMA	Cement Manufacturers Association
CNG	Compressed Natural Gas
CO_2	Carbon Dioxide
COD	Chemical Oxygen Demand
CPCB	Central Pollution Control Board
CRAMS	Contract Research and Manufacturing Services
CRM	Cold Rolling Mill
CSO	Central Statistics Office
CWMP	Coastal Waste Management Plant
DMC	Domestic Material Consumption
DMI	Direct Material Inputs
DMIC	Delhi Mumbai Industrial Corridor
DPIIT	Department for Promotion of Industry and Internal Trade
EC	European Commission
EIP	Eco-industrial Park
EKC	Environmental Kuznets Curve
ELV	End-of-life vehicle
EMF	Ellen MacArthur Foundation
ENEA	National Agency for New Technologies, Energy and Sustainable Economic Development
ENVIS	Environmental Information System
EU	European Union
FDI	Foreign Direct Investment
GCPC	Gujarat Cleaner Production Centre

GDP	Gross Domestic Product
GEI	Global Efficiency Intelligence
GESCSL	Green Environment Services Co-operative Society Limited
GHG	Greenhouse gases
GIDB	Gujarat Infrastructure Development Board
GIDC	Gujarat Industrial Development Corporation
GIS	Geographic Information System
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
GJ/t	Gigajoules per tonne
GMF	Global Material Flows
GoG	Government of Gujarat
GOI	Government of India
GPCB	Gujarat Pollution Control Board
GPMDG	Green Power Market Development Group
GSFC	Gujarat State Fertilisers and Chemicals
GW	Giga Watt
HDI	Human Development Index
HTDS	High Total Dissolved Solids
HUG	Help Us Green
IBEF	India Brand Equity Foundation
ICR	Indian Cement Review
IDMA	Indian Drug Manufacturers' Association
IEA	International Energy Agency
IFC	International Finance Corporation
IGEP	Indo German Environment Partnership
IHA	International Hydropower Association
IIR	India Infrastructure Report
INDC	Intended Nationally Determined Contribution
INR	Indian rupee
IP	Industrial Park
IPAT	Impact, population, affluence, technology
IRP	International Resource Panel
IS	Industrial Symbiosis
ISI	Industrial Symbiosis Indicator
ISIE	International Society for Industrial Ecology
ISN	Industrial Symbiosis Network
ITI	Industrial Training Institute
JLR	Jaguar Land Rover
JNPC	Jawaharlal Nehru Pharma City

$kgCO_2$	Kilogram Carbon Dioxide
kWh/t	Kilowatt hours per tonne
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCOE	Levelized Cost of Electricity
LED	Light-emitting diode
LISP	Landskrona Industrial Symbiosis Programme
LMDI	Logarithmic mean Divisia index
LSHS	Low Sulphur Heavy Stock
LTDS	Low Total Dissolved Solids
MFA	Material Flow Accounting and Analysis
MI	Material intensity
MLD	Millions of Litres per Day
MMSME	Ministry of Micro, Small & Medium Enterprises
MMTPA	Million Metric Tonne Per Annum
MNRE	Ministry of New and Renewable Energy
MoEFCC	Ministry of Environment, Forest and Climate Change
MoP	Ministry of Power
MoRTH	Ministry of Road Transport and Highways
MoS	Ministry of Steel
MOSPI	Ministry of Statistics and Programme Implementation
MRAI	Material Recycling Association of India
MSME	Micro, Small and Medium Enterprises
MSTI	Maruti Suzuki Toyotsu India
MT	Million Tonnes
Mtoe	Million tonne of oil equivalent
MTPA	Million tonnes per annum
MW	Mega Watt
MWh	Megawatt hour
NAPCC	National Action Plan for Climate Change
NDC	Nationally Determined Commitments
NDRC	National Development and Reform Commission
NECL	Nandesari Environment Control Limited
NIA	Naroda Industries Association
NISP	National Industrial Symbiosis Programme
NITI	National Institution for Transforming India
NREP	National Resource Efficiency Policy
NUS	Naroda Utility Services
NUTEK	Swedish Business Development Agency

OECD	Organisation for Economic Co-operation and Development
PAT	Perform, Achieve and Trade
PCSD	President's Council of Sustainable Development
PICF	Participant Information and Consent Forms
POP	Plaster of Paris
PPP	Public-private Partnership
PTI	Press Trust of India
3R	Reduce, Reuse, Recycle
R&D	Research and Development
RDF	Refuse-derived fuel
REALCAR	REcycled ALuminium CAR
RECP	Resource Efficient and Cleaner Production
RECPnet	Resource Efficient And Cleaner Production Network
RES	Renewable energy sources
RMB	Renminbi
RO	Reverse Osmosis
SAIL	Steel Authority of India Limited
SCD	Symbiosis Center Denmark
SDP	State Domestic Product
SERI	Sustainable Europe Research Institute
SETDZ	Shenyang Economic and Technological Development Zone
SEZs	Special Economic Zones
SIDC	State Industrial Development Corporation
SMEs	Small and Medium Enterprises
SMP	Steel Melt Plant
TDI	Toluene Diisocyanate
TDS	Total Dissolved Solid
TEDA	Tianjin Economic-Technological Development Area
TERI	The Energy and Resources Institute
TRIPS	Trade-Related Aspects of Intellectual Property Rights
TWh	Terawatt-hour
UK	United Kingdom
UN	United Nations
UNCRD	United Nations Centre for Regional Development
UNCTAD	United Nations Conference on Trade and Development
UNEP	United Nations Environment Program
UNFCCC	United Nations Framework Convention on Climate Change
UNIDO	United Nations Industrial Development Organisation
UN SDGs	United Nations Sustainable Development Goals

USA	United States of America
USD	United States Dollar
USEIA	United States Energy Information Administration
USEPA	United States Environmental Protection Agency
USFDA	United States Food and Drug Administration
VIA	Vatva Industries Association
WB	World Bank
WCED	World Commission on Environment and Development
WEF	World Economic Forum
WHO	World Health Organisation
WRI	World Resources Institute
WSA	World Steel Association
WTO	World Trade Organisation
WU	Vienna University of Economics and Business Administration
WWS	Wind, Water, Solar
YoY	Year on year

ABSTRACT

Escalating consumption patterns in India on account of the expansion in manufacturing and economic growth, are resulting in a complicated web of interdependencies between economic growth and the nation's resources dependence. Re-circulation of resources, to create closed-loop systems for technical and biological nutrients, as a means of extending the useful life of materials and reducing losses through atmospheric emissions and wastage indicates a shift to a *circular economy*. This is a marked transformation from the predominantly linear economy, which relies on materials extraction, production, use and disposal. Delinking resource consumption (quantity and intensity) from economic growth and ecological impact, also referred to as decoupling, promises sustainable development. The dichotomy of India's expected pace of industrialisation in the face of multifarious resource exigencies is the research motivation for this study.

Manufacturing is intrinsically linked to India's economic growth, and the sector is expected to attain a 25% share of GDP by 2025. Concomitantly, the nation's escalating material, energy and water consumption, coupled with challenges in the recovery and management of waste have put *resources efficiency* at the forefront of current policy. The circular economy in Indian industry is grimly under-explored. This thesis presents a multi-stakeholder *ecosystem view* by investigating India's realisation of the circular economy through the evaluation of macro (nationwide) material and energy use patterns, and six case studies in manufacturing industrial parks (N*aroda, Nandesari, Jawaharlal Nehru Pharma City*), and industrial sectors (*steel*, *cement*, *bio-products)*. The researcher used secondary data, field studies, and interviews to investigate macro (national) level, meso (industrial region/park) level and micro (firm) level drivers for resource efficiency and productivity in India's manufacturing sector.

Time-series analyses for *macro* nation-level material and energy performance revealed interesting patterns. India's domestic material consumption (DMC) in 2017 rose sharply by 92% over the year 2000. This surge was led by non-metallic minerals as well as fossil fuel materials and can be directly linked to the expansion of industrial, infrastructure and housing sectors. By contrast, India's IPAT identity recorded increasing affluence as one of the main drivers for material demand, although lowered material intensity due to rising GDP suggests relative decoupling for India's material performance. Material consumption (per capita) of 5.26 tonnes is far lower than in the USA (21.03 tonnes) and China (17.73 tonnes), signalling opportunities to leapfrog traditional material intensive growth patterns.

India’s electricity demand is expected to triple by 2040 to 15,280 TWh; a green energy shift is underway through the scaling up of wind, water, solar infrastructure, generation and storage. Renewable energy sources (RES), which contributed a negligible (<1%) share of India’s energy mix in 2000, had achieved a 1000-fold increase in capacity by 2017. In March 2019, India’s total energy capacity stood at 356 Giga Watt (GW), of which coal and thermal sources had a large but declining share at 64%, followed by the rapidly expanding RES at 22% and large hydro at 13%.

The research uncovered nineteen industrial symbiosis networks through circular loops for heat-steam exchange; centralised treatment and recovery for hazardous wastes; chemical gypsum as an alternative material in cement; spent acid; treated effluent and wastewater recovery and reuse; product upcycle for bio products; and iron fines and dust by-products transformed into valuable materials. The results suggest early signs of eco-industrial transformation and resource efficiency advances reported through intra- and inter-firm resource exchanges, product and process innovations. The case studies demonstrated not just successful examples of industrial symbioses through resource exchange and shared services but also distinctive institutional structures and support networks to facilitate a circular economy amongst industrial actors.

The research contributes to the evolving literature on the circular economy, by examining ecosystem perspectives for the initiation, implementation and accomplishment of green industrialisation models. The study is the first holistic assessment of circular economy initiatives in Indian manufacturing, adding a novel dimension of eco-industrialisation pathways in a fast-developing economy. Small and medium enterprises (SMEs) constitute the vast majority of enterprises in India, but they face technological and financial limitations in the adoption of resource efficiency. This research found successful examples of circular economy practices in Indian SMEs, in addition to identifying relevant mechanisms for fostering stronger knowledge and resource exchange networks. The industrial symbiosis patterns in India are proximate to the ‘spontaneous and voluntary’ emergence of symbiosis networks in Europe; contrasting with ‘planned’ symbioses in China, Korea and the USA.

Keywords

Circular economy; India; manufacturing; resource efficiency; domestic material consumption (DMC); renewable energy sources (RES); industrial symbiosis networks; small and medium enterprises (SMEs); ecosystem perspectives.

CHAPTER 1. INTRODUCTION AND RESEARCH BACKGROUND

1.0 Introduction

India's manufacturing sector is intrinsically linked to the country's economic growth, targeting 25% share of GDP by 2025 (IBEF, 2019b). Concomitantly, the nation's escalating material, energy and water consumption, coupled with challenges in the recovery and management of waste have put *resources efficiency* at the forefront of current policy. Circularity of resources in order to create closed-loop systems for technical and biological nutrients, as a means of extending the useful life of materials and reducing losses through atmospheric emissions and wastage, signifies a shift to a *circular economy*. This is a marked transformation from the predominantly linear economy which relies on material extraction, production, limited use and disposal. Delinking resource consumption (quantity and intensity) from economic growth and ecological impact, also referred to as decoupling, promises more sustainable development.

Circular economy in Indian industry is severely under-explored. Paucity of field data and the lack of common indicators for measurement, coupled with variations in data collection and reporting methodologies have limited scholarly examination of the circular economy in India, to date. This thesis presents a multi-stakeholder *ecosystem view* by investigating India's realisation of the circular economy through six case studies in manufacturing industrial parks (*Naroda, Nandesari, Jawaharlal Nehru Pharma City*), and industrial sectors (*steel*, *cement*, *bio-products)*. This research is the first holistic assessment of circular economy initiatives in India, and adds a novel dimension of eco-industrialisation pathways in a fast developing economy. The research contributes to the expanding literature on the circular economy, by examining ecosystem perspectives for the initiation, implementation and accomplishment of green industrialisation models.

The dichotomy of India's expected pace of industrialisation in the face of multifarious resource exigencies is the research motivation for the study. Established quantitative methodologies for nationwide resources performance, along with case study approaches, enabled empirical assessment of India's circular economy landscape. The research aimed to assess India's decoupling strategies as a means of greening the industrial sector. The following research questions guided the inquiry ***What prospects does the circular economy hold in India's developmental plans? How does the Indian industrial sector compare in circular economy***

adoption vis-à-vis global counterparts? Is current policy an enabler or disabler for long-term circular economy attainment?. This thesis expands on India's transition to the circular economy by: investigating progress at various levels of the economy, patterns of circular economy advancement and stakeholder perspectives for network emergence.

A few common meanings and definitions are adopted throughout the study to facilitate consistent analysis. The definitions for *developing nation/economy* and *developed nation/economy* are as outlined in the country classification by the United Nations World Economic Situation & Prospects Report (UN, 2016c, pp. 159-160). Therefore, the terms *developing* and *emerging* in the context of nation/economy are used interchangeably. The terms *manufacturing* and *industrial* are used synonymously to signify any industrial activity involving the use of materials, energy and water, in the production of intermediate and final goods. *Industry, sector* and *business* imply a dedicated section or specialisation, for example, automotive industry/sector/business. *Materials, energy* and *water* are collectively labelled *resources* to denote inputs into economic/industrial/production activities. *Sustainable development or sustainability*, as described by The Brundtland Report (WCED, 1987), refers to the pursuit of an equilibrium between economic, environmental and social goals, in other words as "development which meets the needs of the present without compromising the ability of future generations to meet their own needs" (as cited in Murray, Skene, & Haynes, 2015, p. 5).

1.0.1 Thesis outline

This chapter introduces the *research context and motivation* for the study. Circular economy meanings and definitions are explored with applications for specific industries and stages within an economy, followed by a review of the circular economy imperatives for India. Policy frameworks relevant to the circular economy in India are discussed. From a conceptual standpoint *industrial symbiosis,* as the pathway for circular economy in manufacturing, is evaluated. India's surging place in world manufacturing highlights the enormous contribution of developing economies to international trade and development. These positive trends when juxtaposed with the impacts of population, affluence, materials, water and energy growth, indicate the complexities facing a fast-industrialising nation like India. Table 1 presents the research flow for this thesis.

Table 1: Research flow in the thesis

Chapter	Content
Chapter 1: Introduction and research background	• Research context and motivation • CE meanings and imperatives for India
Chapter 2: Literature review	• Conceptualisation of CE and industrial symbiosis networks • Learnings from global and Indian experience
Chapter 3: Research methodology	• Research design and methodological approaches • Ethical considerations
Chapter 4: Assessment of India's resources performance	• Quantitative data analysis for India's material and energy use
Chapter 5: Case studies of CE in Indian manufacturing	• Empirical data analysis for CE initiatives in Indian industry
Chapter 6: Data synthesis and findings	• Collective insights from quantitative and qualitative data analyses
Chapter 7: Discussion and conclusions	• Conclusions, contributions and future research

Source: Author

Chapter 2 presents the *literature review* drawing from conceptualisations of the circular economy, associated policy and business models, in the fields of industrial ecology as well as environmental economics, and management theory. In-depth examination of industrial symbiosis, as one of the core foundations of circular economy thinking, is presented by critiquing global developments in eco-industrial parks, industrial symbioses networks, measurement and indicators. Industrial symbiosis progress in India is reviewed and comparisons drawn with notable international industrial symbiosis programs and implementation experiences. Lastly, ecosystem perspectives of industrial symbiosis networks (ISNs) and the circular economy are evaluated.

These concepts and perspectives logically precede Chapter 3, which sketches the *research design and methodological approaches* for data collection, evaluation and analysis. Scholarly contributions that influenced the writer's inquiry and research strategy are examined. Owing to the cross-disciplinary nature of the study, rationalisation for chosen methods is presented; primary and secondary data collection for macro (national), meso (industrial region/park) and micro (firm) levels are elaborated. Elements of the field study design are summarised, including: interview protocols, participant profiles and ethical considerations. Case study methodology was adopted and primary data were supplemented by secondary sources including government and industry reports, statistical databases and quantitative metrics for macro trends in India's material and energy performance.

Chapter 4 presents the *quantitative data analysis* for India's resources performance, adopting *material use, energy capacity and electricity generation metrics*. Critical comparisons are drawn with leading industrial hubs, in order to compute macro nationwide trends, and identify the direction of *decoupling* in India. Time-series data were mined from international datasets of the International Resource Panel (IRP), Organisation for Economic Co-operation and Development (OECD), various United Nations (UN) agencies, and the International Energy Agency (IEA). Additionally, statistics released by India's National Institution for Transforming India (NITI) Aayog, and Central Electricity Authority (CEA) were used, to ascertain longitudinal trends in material and energy use.

Chapter 5 examines *empirical data for qualitative assessment* of circular economy applications in Indian industry. Six case studies uncovered the latest developments in eco-industrialisation, resource efficiency and circular economy implementation. Field study visits and interviews informed *three case studies of manufacturing industrial parks in India*, to ascertain ongoing industrial symbiosis exchanges, eco-industrial policy and initiatives. Additionally, *three industrial sector case studies* were examined for resource efficiency and circular economy implementation. Together, the six case studies were produced to ascertain cross-actor interactions, collaboration drivers and the emergence of circular economy networks for information and resource sharing. Nineteen industrial symbiosis networks (ISNs) were revealed through the research. All of the reported cases involved active participation of more than one actor, suggestive of ecosystem emergence for circular business models.

These case study assessments lead on to Chapters 6 and 7, which present the *main findings and conclusions*, respectively. Collective insights from both quantitative and qualitative analyses are considered in Chapter 6. These findings are evaluated in the context of theoretical and practical implications. The concluding Chapter 7 reflects on the main contributions of the study; methodological limitations and future research avenues are explored.

The next section examines the research background and pitches the research problem in the context of macro developments driving India's economic growth, and the dichotomous challenges facing the country's sustainable development.

1.1 Research background

Strategic imbalances between industrialisation and resources security is a dichotomy facing manufacturing nations like India, charted on an intensive growth trajectory. Complicated interdependencies exist between economic growth, rising affluence and adversarial impacts on population health, quality of life, and the nation's resource dependence (Figure 1). Augmented consumption, excessive demand for virgin materials and energy as well as waste to landfill mark conventional growth paradigms, which have proven to conflict with a nation's long term sustainability (WCED, 1987).

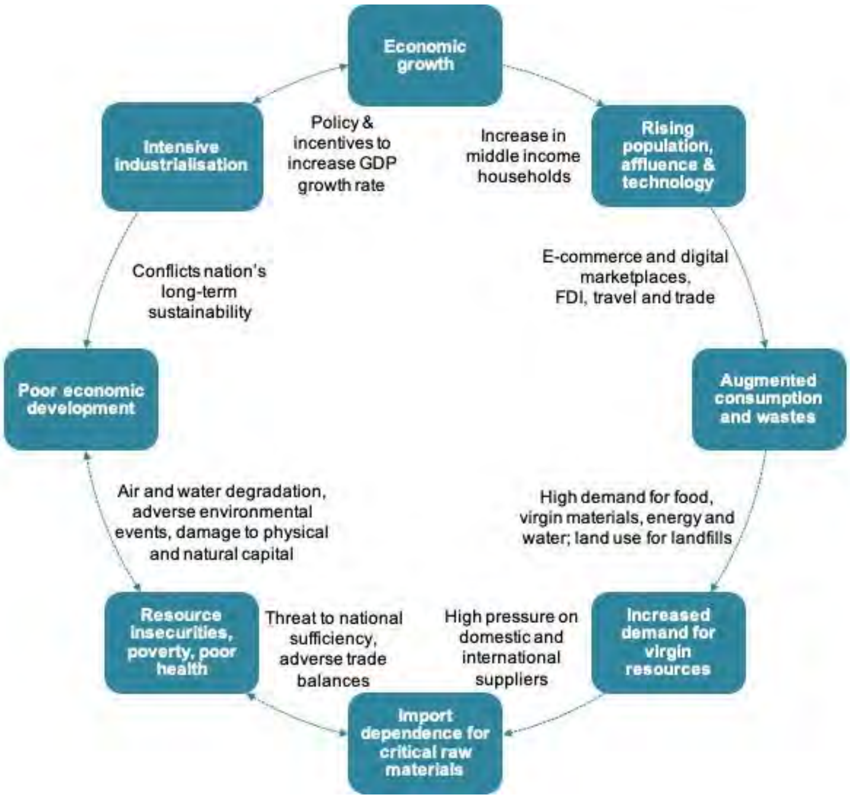

Figure 1: Research problem: resource interdependencies resulting from rapid industrialisation

Source: Author generated

Commoner (1972) and Ehrlich and Holdren (1972) introduced IPAT; where environmental impact (I) was calculated using three factors: population (P), affluence (A) and technology (T). Waggoner and Ausubel (2002) improvised the IPAT formula by including Consumers' intensity of use (C) per GDP to estimate ImPACT. Conventional policy interventions suggest limiting the growth of population (P), affluence (A) and technology (T) to reduce environmental impact (Im). This is hardly appealing for a fast-industrialising country where rising population, greater affluence and technology are essential to maintain development. Not surprisingly, Ausubel and Waggoner (2008) reported divergent results for India and China due to Environmental Kuznets Curve (EKC) effects.

The Environmental Kuznets Curve (EKC) with an 'inverted-U' shape, describes the association between industrial emissions and economic growth/GDP (Grossman & Krueger, 1991; Selden & Song, 1994). Typically, an increasing rate of emissions in the early stages of development is followed by stabilisation and consequent reduction in net emissions as the economy progresses. The EKC predicts that an industrialising country like India will worsen its footprint and emissions as it industrialises, before pollution levels steady and eventually decline, with increases in per capita income. Thus, complex resource dependencies emerge as a result of rapid industrialisation, and the case is no different for India.

Apergis and Ozturk (2015) conducted multivariate analysis for 14 Asian countries to assess test the EKC hypothesis over the period 1990–2011. In order to assess the income-emissions relationship of the EKC hypothesis, the CO_2 emissions, GDP per capita, population density, land area, industry share of GDP were included in the multivariate framework. These were compared against four indicators to measure the quality of institutions: political stability and absence of violence; government effectiveness; quality of regulations; corruption control. The authors reported an inverted U-shaped association between emissions and income per capita, confirming the presence of an EKC, for all 14 Asian countries, including India. Yet, given the pace of industrialisation and resulting CO_2 emissions, coupled with rising population and income, India will need to closely monitor the energy-growth-emissions nexus with the support of deliberate energy and environmental policy planning (Apergis & Ozturk, 2015).

Figure 2: Favourable factors driving the Indian economy
Source: Author generated

Rising middle income households are boosting economic growth, expanded by technological improvements, wireless internet connectivity and e-commerce. Other mega developmental projects include Delhi Mumbai Industrial Corridor, Skill India, Smart Cities Mission, Make in India, and Clean India (Figure 2). A more detailed commentary on the choice of Indian manufacturing as the subject of analysis for this thesis is provided in a later section. Favourable macro advances notwithstanding, augmented consumption patterns are posing serious threats to public health, trade balances and India's import dependence for critical raw materials, challenging the survival of conventional virgin resource dependent industries (Figure 1).

1.2 The transition from linear to circular economy

Resources dependence, primarily on virgin materials, fossil fuels and fresh water encapsulate industrialisation patterns, implying linear models of economic growth where, resources extracted from natural habitats are transformed through production processes, for intermediate and final consumption and eventual disposal. Losses in energy, material value and waste outflow at every stage mark antiquated linear economic models. Figure 3 illustrates technical and biological resource loss risks at different life cycle stages.

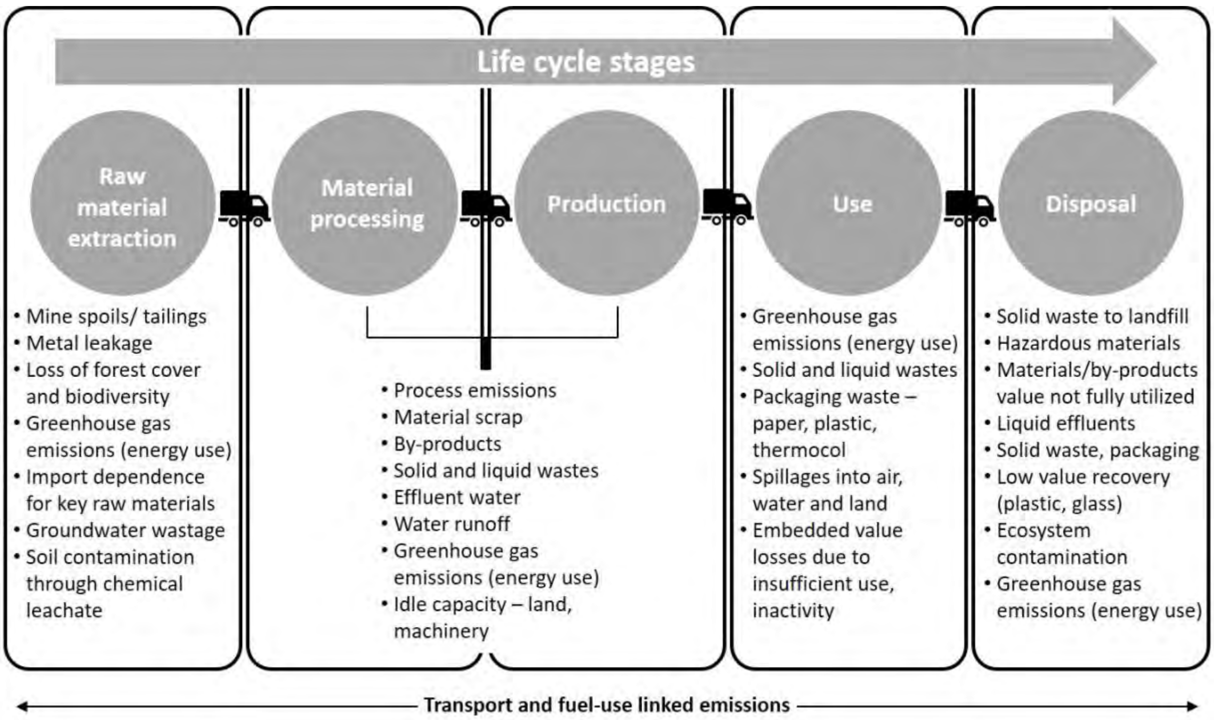

Figure 3: Technical and biological resource losses at different life cycle stages

Source: Author generated, based on multiple sources

A *circular economy* promotes judicious use of biological and technical components to mitigate the above value losses. This is possible through the creation of closed resource loops, that enable recovery, reuse, repurpose and overall reduction in virgin resource consumption. Some examples include value extraction from industrial wastes like waste engine oil, red muds, tires, bitumen, which are known to yield useful materials like carbon-based nanomaterials (Dunens, MacKenzie, & Harris, 2010; Mis-Fernández et al., 2012; Mittal et al., 2013; Suriani et al., 2015). Similarly, pyrolysis oil extracted from discarded printed circuit boards can be converted into resin to make carbon nanotubes (Quan, Li, & Gao, 2010). However, Deng et al. (2016) argue that despite better quality material recovery using high temperature syntheses, energy consumption and waste input material choices also must be considered, for maximum environmental gain.

The next section takes the example of the automotive car industry to differentiate between linear and circular approaches, as well as demonstrate emergent circular business models.

1.2.1 Automotive car industry: linear and circular value chains

Cars are known to be highly materials-intensive products, with long useful life capabilities and vast mass-consumer appeal. In India alone, between 2006-2016, average 150 million new vehicles were registered annually (MOSPI, 2018). Assuming a car's average life span as 15 years, India will have 75 million end-of-life vehicles (ELVs) by 2020, and 210 million ELVs by 2030; these are author estimates based on data released by government agencies (MoRTH, 2016; MOSPI, 2018). Production inputs include: mined metals (steel, aluminium, precious metals), man-made materials (plastic, glass, fibres), as well as land, energy, human manpower and machines used to manufacture automotive parts. An average car comprises 65 % steel, 10% plastics, 8% aluminium, 5% rubber, 1% copper, 1% glass.

An illustrative automotive value chain is described in Figure 4. Production inputs are used to manufacture and assemble automotive parts, the car itself may be assembled onsite or transported for later assembly closer to the end-use location (Figure 4). The decision to assemble on- or off-site has direct bearing on the costs of transportation and logistics, in turn, impacting the final price. The product is then transported to car dealerships/warehouses or end-consumers. The actual use-life varies greatly depending on national end-of-life vehicle guidelines, the financing model of the vehicle, as well as socio and psycho-graphic attributes of users. As stated earlier, an average car is designed for a useful life of 15 years, after which negative cost and environmental performance occurs. Despite its intended life, two main issues persist: idle capacity, i.e., periods when the car is not actually in use; and second, weak end-of-life vehicle (ELV) policies imply that cars remain on roads for shorter periods (in developed countries) or beyond their intended lifetime (in developing countries). In either case, resources aren't maximised; in the latter, issues with fuel consumption, air emissions, wear and tear of critical components exacerbate.

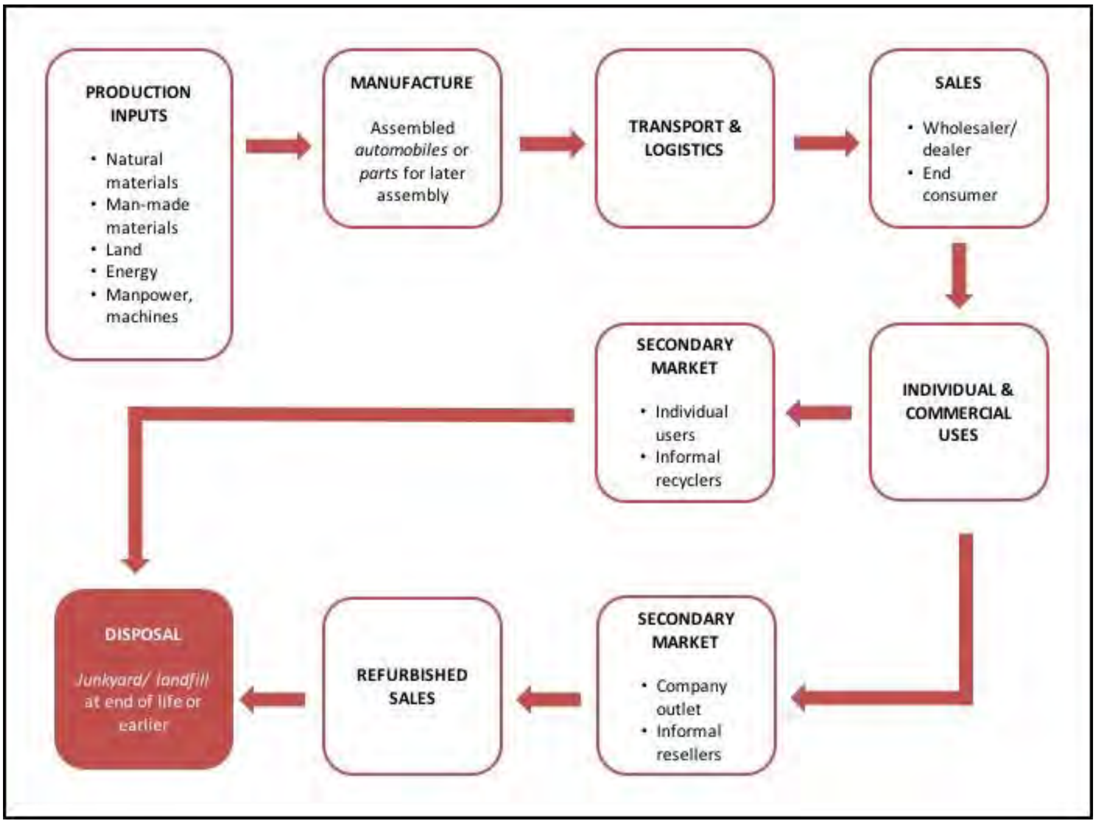

Figure 4: Typical automotive value chain

Source: Author

Note: The diagram is a representative illustration by the author. This example was taken to demonstrate ample opportunities for resource recovery and emergent business models for circular economy within the automotive industry.

After primary use, there are two main avenues for disposal/reuse presently (Figure 4). The first involves the sale of a used car to the secondary market, which may include formal collectors like automotive company second-hand outlets, or informal operators like private car dealers. The second avenue for disposal/reuse involves direct sale to another user (second-hand car buyer through direct contact or use of online marketplaces). In the case of sale to a formal operator, like company operated second-hand outlets of Toyota or Honda, the vehicle is refurbished and resold in the used-car market (Figure 4). This avenue is preferable from a resource-optimisation standpoint as the quality and functioning of the vehicle is closer to its original capabilities and its useful life is extended.

In either of the above scenarios, the end-of-life for a car is a junkyard or landfill (Figure 4). Most frequently, the actual useful life is shorter than its intended lifespan; although, this can differ depending on economic circumstances in a country. In developed countries, used cars end up in landfill sooner than developing countries, or they may be shipped off to developing countries for sale in secondary markets. The environmental and resources impact isn't significantly improved if the car is used beyond its intended life; in fact, it may result in negative externalities, diminishing operational quality and increased emissions. Significant issues exist in the linear automotive car industry model outlined above. The next figure (Figure 5) captures the main resource challenges at the production, use and disposal stages of a car's life. To mitigate these linear resource-intensive activities, circular economy can foster longer and enhanced value models. Some of the circular economy solutions currently underway in the automotive industry are outlined in Figure 6.

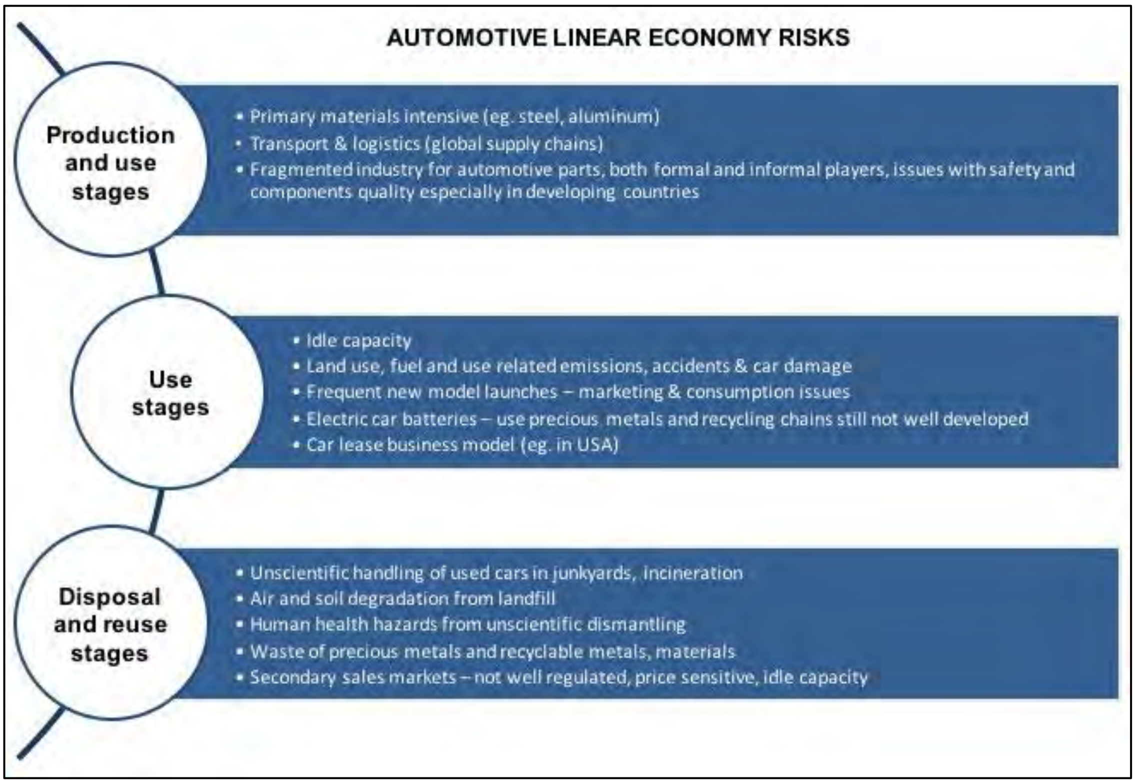

Figure 5: Resource challenges at the production, use and disposal stages of a car's life

Source: Author

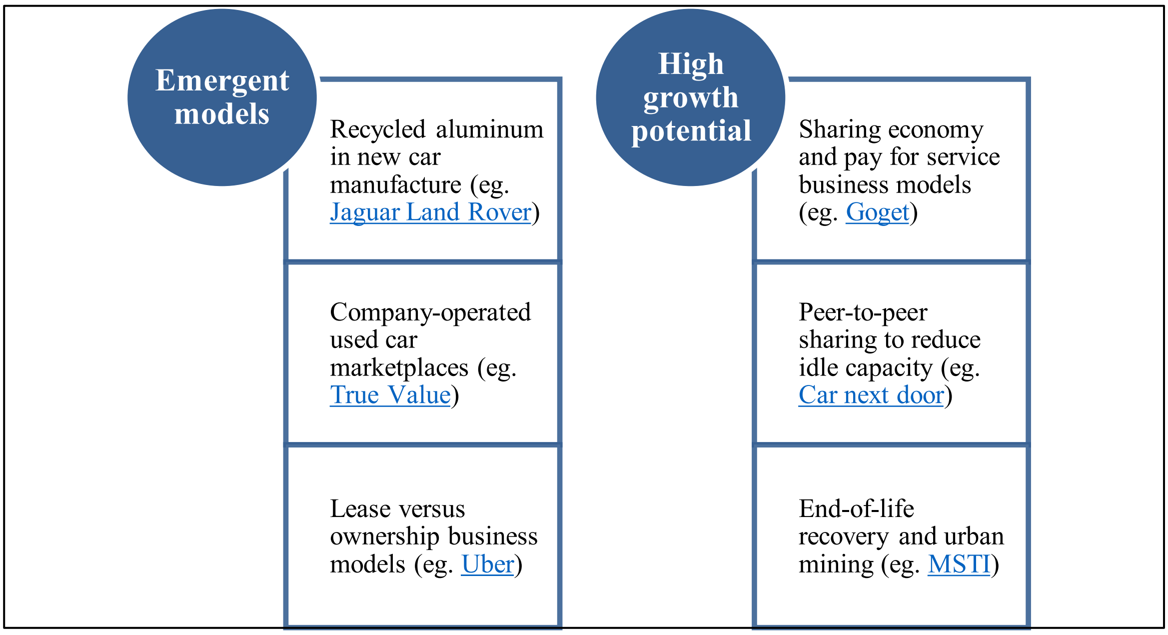

Figure 6: Automotive circular economy business models

Source: Author

Circular economy headways in automotive industry include: the use of recycled metals in new car manufacturing (eg. Jaguar Land Rover REALCAR aluminium recovery and reuse); scientific end-of-life recovery infrastructure and government policies (eg. Suzuki-Toyota MSTI joint venture); expansion of company-operated secondary car marketplaces like True Value in countries like India where the informal sector thrives; and peer-to-peer lease versus car ownership models like Uber, No birds. There are also examples with high and immediate circular economy potential like the sharing economy for cars with a pay-for-service model like Goget, peer-to-peer car sharing like Car next door and company operated end-of-life vehicle recovery and reuse models (Figure 6).

Jaguar Land Rover (JLR) implemented closed-loop metal recovery in the UK to reuse 50,000 tonnes of aluminium scrap in its vehicles in 2015-16. This aluminium recovery project complements the automotive giant's overarching shift to replace steel with aluminium, a strategic move to improve vehicle fuel efficiency and lower carbon emissions. The material swap has a significant impact on vehicular weight which directly influences fuel efficiency and overall performance. For example, the Jaguar XF model now has a 75% aluminium body, weighing 190kg less; and the Range Rover Sport SUV is now 420kg lighter owing to a higher proportion of aluminium. To mitigate some of the higher economic and environmental costs of sourcing aluminium (aluminium production is more expensive and energy-intensive than steel), JLR implemented REALCAR (REcycled ALuminium CAR) project, to establish value chains for recycled aluminium from its internal and suppliers' production sites. In its first phase, the project led to 500,000 tonnes of CO_2 equivalent emissions reduction for a phased £13m investment[1 2 3].

1.3 Circular approaches at different levels within the economy

Many regions have implemented policies for circular economy advancement in all facets of development, China and the European Union are prominent examples. A circular economy can be manifest through a variety of activities at different levels in an economy. The macro-level occurrence can be through policy, green finance, fiscal and monetary incentives, emissions monitoring, and the set-up of key physical infrastructure for efficient resource management. These can later translate to meso (regional, industrial cluster or industrial park) progress through inter-firm resource, by-product and knowledge exchange, shared infrastructure and pooling of resources to minimise idle capacity. Finally, at the micro-level, i.e., for a firm or individual, circular economy can result in effective waste management, reduced consumption of virgin materials, intermediate and final products, participation in peer-to-peer, sharing economy and collaborative business models.

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1 Ayres, M. (2014, November 13). The future for aluminium recycling, e-article. *Automotive World*. Retrieved from https://www.automotiveworld.com/articles/future-aluminium-recycling/

2 Ludwig, C. (2016, July 22). Jaguar Land Rover gets real about recycled aluminium loops, e-article. Retrieved from https://www.automotivelogistics.media/16068.article

3 Mace, M. (2017, September 7). Jaguar Land Rover expands its aluminium circular economy drive, e-article. *Edie Net*. Retrieved from https://www.edie.net/news/16/Jaguar-Land-Rover-expands-its-aluminium-circular-economy-drive/

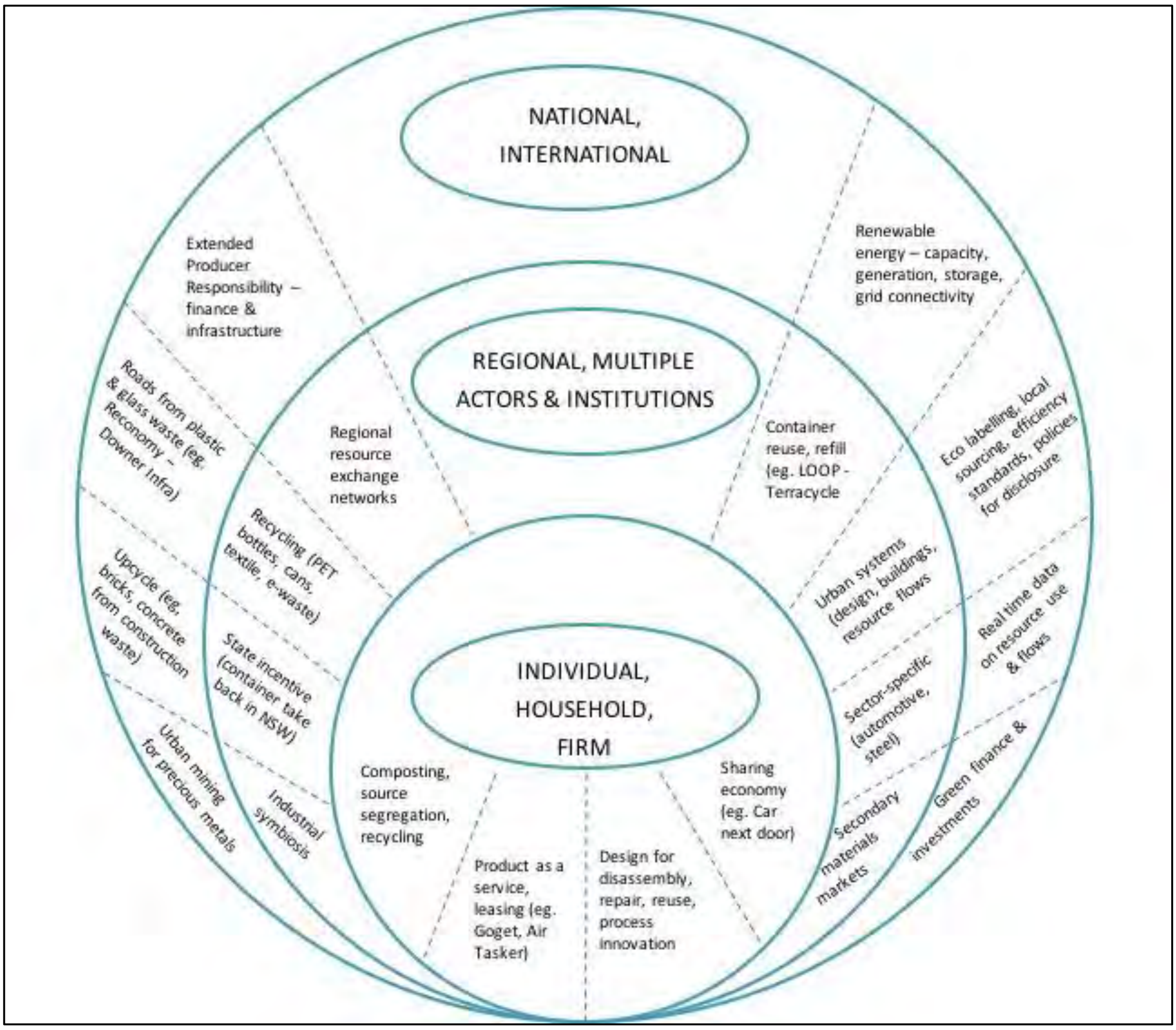

Figure 7: Circular economy implementation models at different levels

Source: Author

Note: The illustration is meant to exemplify the variety of initiatives that can be embodied within a circular economic system. The examples are limited to material, water and energy intensive sectors of the economy. A distinct set of circular economy applications can occur within services and knowledge-based industries, not listed here.

Different economic and social influences can enable the transition to circular economy at each level within a system. When viewed at the levels of a nation, region or individual, multi-faceted applications for the circular economy may be visible. Figure 7 exhibits different activities which can contribute to the creation of circular economies. Starting from the level of an *individual or firm*, where recycling, redesign, or servicisation (products as services) can be applied; onto *regional ecosystems* where inter-actor collaboration, policy tools, marketplaces and urban systems converge; and extending beyond geographic boundaries to foster *national and international loops* for material, energy and information exchange through technology transfer and knowledge sharing (Figure 7).

1.4 Industrial symbiosis networks: realisation of circular economy in manufacturing

High level economic analyses revealed India's potential to generate USD 624 billion with 44% reduction in greenhouse gas by 44% by 2050, if current growth was to incorporate circular practices (EMF, 2016). The policy brief for a specialised *resource efficiency programme* in India recommended fiscal instruments, eco certification, standardised indicators and consumer involvement to attain the realisation of the United Nations Sustainable Development Goals (UN SDGs) (GIZ, 2017)[4]. In addition to the economic potential of circular industrial approaches, India is viewing this as a means to accelerate the nation's green growth.

Industrial symbiosis points to business-to-business exchanges and networks; where, multiple interlinkages for materials, energy, water, waste and by-products, information and technology occur between diverse actors. A key facet of industrialisation and globalisation are the intricate supply chain networks that emerge as a result of complex interplay of resources and knowledge exchange to enable product and service delivery. An industrial symbiosis network (ISN) resembles this metaphor, except that the focal point is the use of waste as a resource, in order to capitalise on the dormant value of by-products and effluents. The core ideology, thus, moves away from viewing waste as a problem to be mitigated, towards creating a persistent loop of value optimisation from different parts of a resource. The reclamation of dormant value can occur through exchanges within a single firm, between multiple firms in close proximity or between previously unrelated firms scattered across geographies and industries.

ISNs have the potential to create a circular economy through efficiency improvements and increased competitiveness from re-circulation of existing resources within the economic system. Industrial symbiosis networks promote equitable and sustainable development, through reduction in virgin resource use, longer circulation of materials, water and energy in industrial activities as well as the advent of new industry sectors engaged in secondary material recovery, treatment, upcycle and use. The Organisation for Economic Co-operation and Development (OECD) and World Bank acknowledge *industrial symbiosis as a means of achieving green growth* (Lombardi & Laybourn, 2012; WB, 2017).

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4 Kapur, S., & Ghose, J. (2019, June 24). G20: Enable business models for a circular economy, policy brief. *The Energy and Resources Institute (TERI)*. Retrieved from https://www.teriin.org/policy-brief/g20-enable-business-models-circular-economy

ISNs are most frequently embedded within industrial park settings. Global experience of industrial symbiosis development varies greatly in terms of scale and complexity of networks formed; a thorough review is presented in the next chapter (literature review). Exemplars in Denmark, China and the USA have demonstrated industrial symbioses as a means of advancing the circular economy, although evidence from India is sparse. Divergent industrial symbioses patterns have emerged (Yap & Devlin, 2017), with authors reporting on the systems-level imperatives for industrial symbiosis in India (Erkman & Ramaswamy, 2000) and industrial estate planning in India (Singhal & Kapur, 2002).

1.5 India’s developmental pathways

1.5.1 Manufacturing in India: a key economic driver

The manufacturing sector, is considered to be one of the most materials- , energy- , and emissions-intensive sectors globally. Figure 8 compares manufacturing output over a decade from 2007-17. The share of developing countries in world manufacturing is consistently rising, the highest jump has been for China (99.98%) and India (98.18%), over the analysis period. Four of the top ten manufacturing nations in 2017 were developing countries (China, India, Korea, Indonesia). This trend has continued over the analysis period; although, country composition has changed and the highest positive change has been for India and South Korea. Among the top 10, China, India, Korea and Brazil have been steady developing economies with large manufacturing output (Appendix 1) (Figure 8).

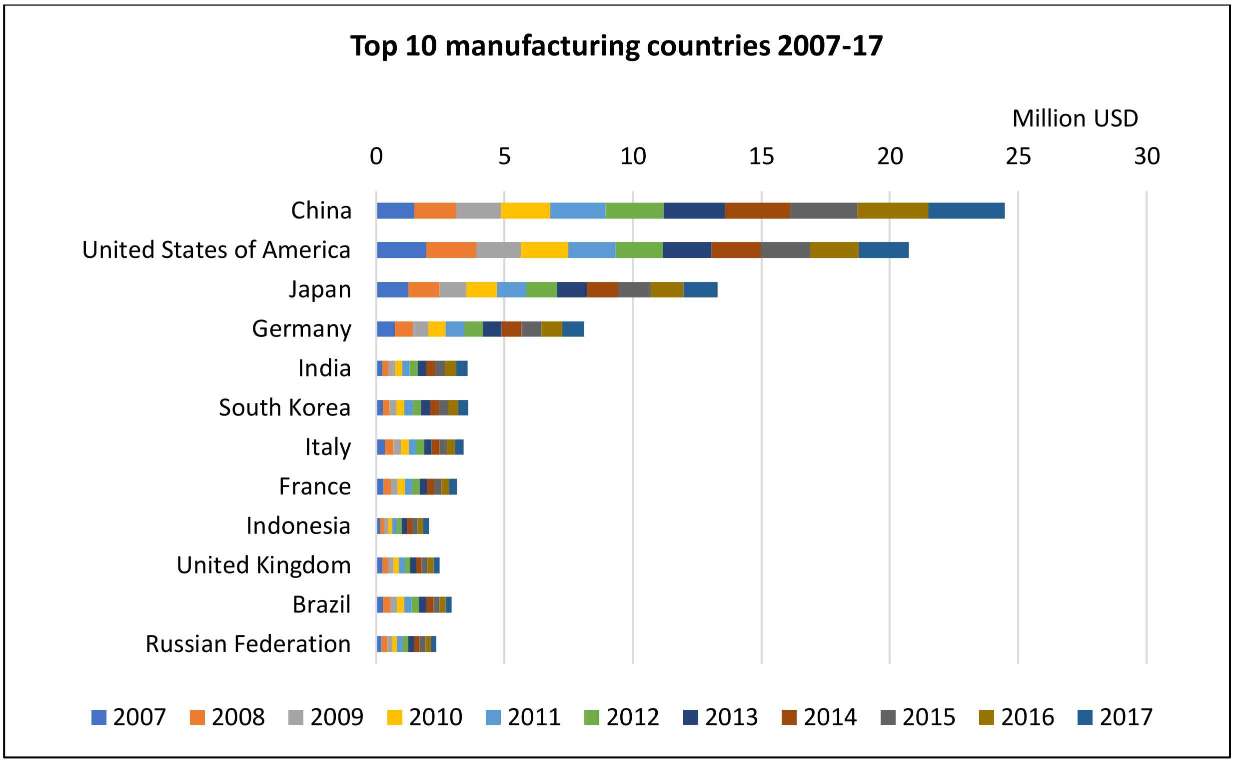

Figure 8: Top 10 manufacturing countries 2007-17

(ranked based on GDP from manufacturing; Million USD at constant 2010 prices)

Source: UNCTAD (2020), Gross Domestic Product by kind of economic activity

India's position jumped from tenth to fifth highest manufacturing output in 2015, overtaking South Korea which had the 5th highest output since 2010. In 2017, Indonesia was a new entrant among the top ten manufacturers, replacing Brazil which had consistently been among the top ten. Since 2010, China has superseded USA in manufacturing value added, contributing 30% to world manufacturing in 2017. Together, the top five nations (China, USA, Japan, Germany, India) had a 76% share of world manufacturing in 2017. India's share has been consistently rising from 3% in 2007 to 5% in 2017 (Figure 8) (UNCTAD, 2020). The surge in manufacturing activity is expected to continue into the next decade, with manufacturing to rise to 25% of GDP by 2025 (IBEF, 2019b).

1.5.2 Mega developmental projects in India

India is investing heavily to bolster its transport infrastructure, power and internet connectivity, semi-urban and rural economic development, as well as skills enhancement in its workforce. Mega developmental projects, like Make in India and Delhi Mumbai Industrial Corridor, are geared towards delivering 100 million new jobs in manufacturing by 2022, making it a USD 1 trillion sector (Auroville, 2014; GOIEconomicSurvey, 2016). Some of these major initiatives are briefly discussed below, with a view to understanding macro-economic trends, implementation plans and achievements.

1.5.2.1 Make in India

Make in India is an investment and capacity development initiative, launched in 2015, under the current government's first run. Domestic and international investment and entrepreneurship in seven key sectors (mobility, chemical, construction, electronics, food, power and mining, infrastructure) is targeted to boost high-value manufacturing and employment. Investment and financing of renewable energy projects is another focal area, given India's larger plans to reduced coal imports and limit domestic coal production (GOI, 2013)[5]. Major industry incentives include subsidised power at fixed long-term rates, preferential land allotment, state subsidies and tax breaks[6].

1.5.2.2 Delhi Mumbai Industrial Corridor

Five strategic industrial corridors spanning the length of the country and 1483 km across seven Indian states, are planned to augment rail, road and port connectivity. The corridor in its full form will encompass 24 industrial regions, eight smart cities, two airports, five power projects, two mass rapid transit systems and two logistical hubs, with the likelihood of employing 3 million people (GOIEconomicSurvey, 2016). Manufacturing activity will be the main economic driver in these regions, with smart integrated cities along the corridor to encourage employment.

1.5.2.3 Clean India (Swachh Bharat) Mission

Launched on October 2, 2014, this federal project distributed USD 2.7 billion in funding, in addition to a 0.5% Swachh Bharat Cess levied on all taxable services. In keeping with India's Sustainable Development Goals, the objective was to improve hygiene, sanitation and

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5 IBEF. (2016, September 1). India will have coal self-sufficiency in 3 years, e-article. *India Brand Equity Foundation (IBEF)*. Retrieved from http://www.ibef.org/news/india-will-have-coal-selfsufficiency-in-3-years-piyush-goyal?utm_source=phplist356&utm_medium=email&utm_content=HTML&utm_campaign=India+News+Alert%25253A+India+retains+top+spot+as+world%25253Fs+largest+remittance+recipient+in+2015%25252C+India+expected+to+achieve+coal+self-sufficiency+in+3+years

6 Jai, S., & Mukul, J. (2016, May 17). Cheap power for industry to push Make in India: Piyush Goyal, e-article. *Business Standard*. Retrieved from http://www.business-standard.com/article/economy-policy/cheap-power-for-industry-to-push-make-in-india-piyush-goyal-116051700040_1.html

cleanliness throughout the country by 2019. A continuing project, some 3.3 million individual toilets were constructed; and 129,000 community and public toilets were built. To foster stewardship, a competitive annual ranking system is in place for inter-state comparison. Source segregation for municipal solid wastes and stimulated citizens movements have been unprecedented achievements of this mission.

1.5.2.4 Smart Cities Mission

About 60% of India's population are expected to live in cities by 2050 (EMF, 2016), adding pressure to the already saturated urban infrastructure. To complement the aforementioned projects with a vision to developing self-sufficient satellite towns, the Smart cities mission expects to transform 100 existing mid-sized cities into smart integrated cities. An outlay of USD 15 billion is anticipated for city improvement (retrofitting), city renewal (redevelopment) and city extension (greenfield development).

1.6 Circular economy in India

1.6.1 Policy drivers for circular economy

Resource efficiency and the circular economy are at the epicentre of current policy planning and think tank discussions in India. State-level action plans are underway to integrate resource efficiency and circular economy within sectoral development strategies. Goa, India's popular international tourist destination, was the first state to initiate a circular economy strategy to advance its UN SDGs in the hospitality, construction, fishing and waste management sectors. Among the immediate recommendations were the roll out of environmental taxes and levies to polluters and users; the phasing out of single-use plastics; the institution of specific governmental bodies to implement and monitor resource efficiency and circular economy policies at the national, state, and local levels; green public procurement; quantification of material flows especially egregious wastes like single-use plastics, marine litter, construction and demolition wastes and packaging (TERI, 2020).

At the federal level, the Ministry of Environment, Forest and Climate Change (MoEFCC), with inputs from the National Institution for Transforming India (NITI) Aayog and The Energy and Resources Institute (TERI) are designing the National Resource Efficiency policy (NREP) which is presently under public consultation. The draft policy proposed the setting up of a National

Resource Efficiency Authority, a missing function within the current set up where regulatory and implementation roles range over various ministries and departments, making accountability and measurement challenging.

The main theme of the NREP is to set targets and enable adoption of resource efficiency and the circular economy in core sectors like heavy industry and metals, construction, transport, plastic and packaging, agriculture, renewable energy (wind, water, solar). A significant step will be the measurement of macro indicators (Resource Productivity, Domestic Material Consumption, Domestic Material Extraction, Direct Material Input), in addition to sector-specific indicators (environmental impact of primary and secondary raw materials used) for metals, non-metallic minerals, fossil fuels, biomass, water, land, and energy. Lastly, recovery rate and recycling indicators are proposed to be formalised (MoEFCC, 2019).

The 2007 National Action Plan on Climate Change, the updated 2016 Solid Waste Management Rules, policy dialogues on resource efficiency and sector-specific initiatives outline India's plans for ecological sustainability. The 2016 Solid Waste Management Rules specify targets for the segregation, recovery, treatment and scientific management of municipal solid waste, plastic, electronic waste, bio-medical waste and construction and demolition waste demonstrate India's resolve to tackling waste and offering incentive for waste recovery and reuse.

1.6.2 Dichotomous challenges between resources use and economic growth

With 29 years as the average age of India's employable population, and 10 million youth entering the workforce annually (GOIEconomicSurvey, 2014), favourable macroeconomic factors are yielding high consumption patterns for India. A deadly consequence of economic boom in electronic commerce, hospitality and automobile sectors is the alarming volume of waste being sent to landfill. The already burdened mega-cities of Mumbai, New Delhi, Bangalore and Chennai demonstrate the untenable over-stretching of present public transport systems, traffic congestion, air pollution, extreme weather events, and soaring land prices.

In order to actualise steady gains from expansion in manufacturing and economic growth, in the midst of growing geopolitical tensions and international trade uncertainties, India lies at the cusp of dichotomous challenges facing resources security and national dominance. The escalating consumption patterns are resulting in a complicated web of interdependencies between economic growth and the nation's resources dependence (Figure 1 – research problem). The dichotomy of India's expected pace of industrialisation in the face of multifarious resource exigencies is the research motivation for this study. This thesis is a timely exploration of circular economy approaches in Indian industry, suggestive of the green shift underway. Through critical evaluation of circular models at different levels of the Indian economy, and through a cross-sectoral assessment, the thesis aims to contribute to the evolving literature on circular economy as a model for sustainable development.

The average per capita consumption of plastic in India is 11 kg, which is staggering in comparison to 109 kg per capita in the USA. About 43% of manufactured plastics in India are used in packaging industries and most are for single use (TERI, 2018). Despite a 60% recycling rate for plastics, India still generates 5.6 million tonnes annually and accounts for 60% of plastic waste in oceans. The Indus and Ganges rivers were the second and sixth largest carriers of plastic debris to the world's oceans (WEF, 2018). In accordance with the Plastic Management Waste Rules 2016, consumer-centric implementation in many states restricted the use of single-use plastics and secondary packaging; Maharashtra, Tamil Nadu and Himachal Pradesh and Sikkim made notable progress. Concomitantly, India recorded the highest recycling rate at 90% for PET bottles globally, capitalising on the unorganised sector activities of kabadiwalas or garbage-collectors. PET bottles are shredded into plastic flakes and then used to manufacture polyester fibre, for application in textile and upholstery. In comparison, Japan recycles 72%, Europe 48% and USA 31% [7].

India's deep-rooted practices of frugality, repair and repurpose manifest in circular economy models in mainstream sectors like fashion, education and industry. Premier fashion events across the country have made headway in mainstreaming the use of recycled materials, discarded garments and accessories. Interesting projects like *I was a Sari* have spurred debate around the fashionable upcycle of used garments. At the same time, education and awareness of electronic waste has gathered momentum. Karo Sambhav, a project endorsed by Government of India (GOI) and the International Finance Corporation (IFC), is running school awareness programs across the country; in the first year they sent 3 billion tonnes of electronic waste for recycling (KaroSambhav, 2019).

7 Chatterjee, B. (2017, February 19). India recycles 90% of its PET waste, outperforms Japan, Europe and US: Study, e-article. *Hindustan Times*. Retrieved from https://www.hindustantimes.com/mumbai-news/india-recycles-90-of-its-pet-waste-outperforms-japan-europe-and-us-study/story-yqphS1w2GdlwMYPgPtyb2L.html

Scientific recovery of valuable materials and metals from electronic waste has drawn numerous technological interventions to minimise the leakage of toxic substances like lead, waste plastics, and non-metallic residues, on disposal. Printed circuit boards constitute an important e-waste stream; controlled experiments resulted in complete removal of lead and various metal components, with applications for leftover carbon in iron-making (Rajarao et al., 2014). Such a recovery process can yield zero waste solutions for efficient e-waste management.

1.6.3 Evidence of circular economy in India uncovered through the research

This thesis contributes to the intensifying discussion to balance eco-environmental goals of a fast-industrialising nation like India. Through critical evaluation of live case studies, the study presents an original contribution of nineteen industrial symbiosis networks in Indian manufacturing (Table 2). These networks explicate complex materials, energy and water exchanges, between multifarious actors and institutions involved in network activities. Detailed assessment of resource synergies, circular exchanges, and actor roles are summarised in Chapter 5. Comparisons drawn with international cases of industrial symbiosis networks are used to examine evolutionary characteristics and implementation experiences in India (Chapter 6).

Table 2: Evidence of circular economy in India

	Industrial symbiosis network (ISN)
1.	NOVEL – chemical gypsum as alternative material in cement
2.	NOVEL – acid reused in dye, chemical and textile manufacture
3.	Condensate and sludge recovery from liquid effluents
4.	Water, biomethane and biofertiliser from food industry wastes
5.	Inter-firm steam exchange via common boiler
6.	Alternative fuels in cement manufacture
7.	Water circularity to replace freshwater use
8.	Integrated services and shared infrastructure
9.	Zero waste operations
10.	Heat to steam exchange between co-located firms
11.	Intra-firm steam and solvent reuse
12.	Co-processing of alternative fuels from pharmaceutical wastes
13.	Circular economy in end-of-life vehicles through urban mining
14.	Electricity generation from surplus heat
15.	Intra-firm industrial by-product reuse
16.	Inter-firm industrial by-product reuse
17.	Closed loop water exchange between co-located power and steel plants
18.	Upcycle of biowaste
19.	Co-processing of chemical gypsum as alternative raw material in cement

Source: Author, based on case study data and analysis

1.7 Chapter conclusion

Current scientific inquiries into India's resource efficiency and circular economy are limited. While copious industry examples exist, few have been the subject of scholarly scrutiny. Cross-sectoral evidence will be useful to determine nationwide trends. India's manufacturing growth in the last decade, coupled with incentives to promote high-value manufacturing, merit critical examination of the sector's resources performance and implementation models. The thesis is structured to offer circular economy insights at multiple levels within a nation. The next chapter, Chapter 2, presents an up-to-date review on the topic of circular economy and industrial symbioses in the context of network emergence, ecosystem development, and India's experience so far. Chapter 3 outlines the methodologies adopted for data collection and analysis, the research design and key sources of primary and secondary information. Ethical considerations for the research and the overall rationale for the study are expounded.

The subsequent two chapters, Chapters 4 and 5, present the data analyses for the multi-tiered study. Chapter 4 examines macro (nation-level) indicators like domestic material consumption, material intensity, decoupling, IPAT identity, energy mix and renewable energy trends for India. Comparisons are made to assess India's performance against major industrial nations. Chapter 5 presents six case studies illustrating circular economy implementation in Indian industry. The first section outlines three case studies of manufacturing industrial parks – Naroda, Nandesari, Jawaharlal Nehru Pharma City. Field study primary data from these three major chemical and pharmaceutical manufacturing eco-industrial parks in India offers a meso view of eco-industrial park development and ISN emergence. Next, circular economy developments at the micro (firm, industry) levels are investigated through three case studies focused on the steel, bio-products and cement industries.

Together, these six case studies are investigated to identify nineteen industrial symbiosis networks currently being implemented in India, in order to assess resource synergies, network actors and present results from ongoing industrial symbiosis exchanges. The main findings of the field study are compiled and analysed in Chapter 6, along with the findings from the quantitative assessment of India's material and energy performance. Chapter 7 offers concluding thoughts, discussion and avenues for future research. The overarching research design is to offer a comprehensive view of the emergence characteristics for circular economy in India.

CHAPTER 2. LITERATURE REVIEW

2.0 Introduction

The seminal article by Frosch and Gallopoulos (1989) on ‘Strategies for Manufacturing’ stimulated scholarly interest in industrial ecology conceptualisation. However, the earliest connections between industrial and biological systems can be traced back to the mid-1970’s in the initial years of the United Nations Environment Program (UNEP) (Erkman, 2001). O'Rourke, Connelly, and Koshland (1996) offered an extensive appraisal of the state of the art for industrial ecology origins, cross-disciplinary meanings, tools and application. These authors contend that mere pollution prevention of efficiency improvements do not classify as industrial ecology achievement and that system-wide transformation by embedding industrial ecology in core business activities, is imperative. The extension of industrial ecology concepts to the circular economy are rooted in the works of Pearce and Turner (1990) (as cited in Ghisellini, Cialani, & Ulgiati, 2016). In January 2004, the first international meeting on the topic of industrial ecology was held at Yale University, New Haven, USA entitled ‘Industrial Symbiosis Research Symposium’ (Chertow, Ashton, & Kuppalli, 2004).

During the period from 2004-2010 similar inquiries from other regions were undertaken – most notably European nations, China (a fast emerging manufacturing hub) and some parts of South America. Policy dialogue and analysis gathered interest in relation to incentivisation of industrial symbioses and the setting up of eco-industrial parks. Throughout this phase, scant evidence was available from other developing economies, some of which (like India) were rapidly industrialising; yet, little was known about their adoption of industrial ecology. Some noteworthy studies by Bain, Shenoy, Ashton, and Chertow (2010); Erkman and Ramaswamy (2000); Saraswat (2008); Singhal and Kapur (2002) reported cases of cleaner production in metal foundries, textile and leather manufacturing. The investigations of industrial estate planning and management in India (Erkman and Ramaswamy, 2000; Singhal and Kapur, 2002), and the opportunities to transform conventional industrial estates into eco-industrial estates (Saraswat, 2008), informed the policy and administration at the time.

The first and most-inclusive study of industrial symbiosis material and energy exchanges in an Indian industrial estate was conducted by Bain et al. (2010), in Nanjangud, Karnataka. The authors quantified material flows for 7 resource categories and 11 self-organised symbiotic relationships within a 42 firm data-set. Besides a few comprehensive reports on industrial ecology in developing countries (except for China), tools and methodologies for eco-industrial development were established around developed country prerequisites until the United Nations Industrial Development Organisation (UNIDO) formalised Resource Efficient And Cleaner Production Network (RECPnet) in November 2010. RECPnet objectifies “effective and efficient development, application, adaptation, scaling up and mainstreaming of RECP concepts, methods, policies, practices and technologies in developing and transition economies” (RECPnet, 2020). India is a central participant in the Asia and Pacific chapter for RECPnet, giving participants access to web-based knowledge management systems, capacity building grants and implementation toolkits.

The current agenda for industrial ecology research is in devising and testing measurement indices; although, an analogous set of indicators is lacking. Another avenue for scholarly inquiry is conceptual, with methodological development of circular economy as a subset of industrial ecology. Circular economy is an inclusive concept and does not lie entirely in one conceptual domain; interdisciplinarity and varied applicability lie at the heart of circular economy research. Here too, a standardised set of indicators is necessitated, various efforts confirmed the complex nature of circular economic systems. The overarching schema in contemporary literature development is to boost cross-disciplinary research, to expand the realm of inquiry from engineering and environmental sciences into economic, business, management and accounting principles as well as design, urban planning and political sciences.

This thesis draws on circular economy concepts from the fields of industrial ecology, environmental economics and management theory, to identify patterns of circular economy advancement and stakeholder perspectives for network emergence. The scope of literature scanned included: industrial symbiosis as a basis for circular economy in manufacturing; indicators and measurement for circular economy, emergence characteristics of industrial symbiosis networks and institutional capacity building; comparative assessment of national policies for resource efficiency and circular economy; decoupling insights for eco-industrial progress (Figure 9). Various special issues on the circular economy (Bocken, Olivetti, Cullen, Potting, & Lifset, 2017; Nature, 2016), eco-industrial development (Geng, Fujita, Park, Chiu, & Huisingh, 2016), recent academic and government publications informed the research, in addition to seminal works from inter-disciplinary fields. The writer is also an active participant of the International Society for Industrial Ecology (ISIE), a 500+ worldwide community of academicians and students who advance scholarship on the intersectionality between industrial and ecological systems: industrial symbiosis, urban systems, circular economy, industrial metabolism, input-output analysis and life cycle assessment (ISIE, 2020).

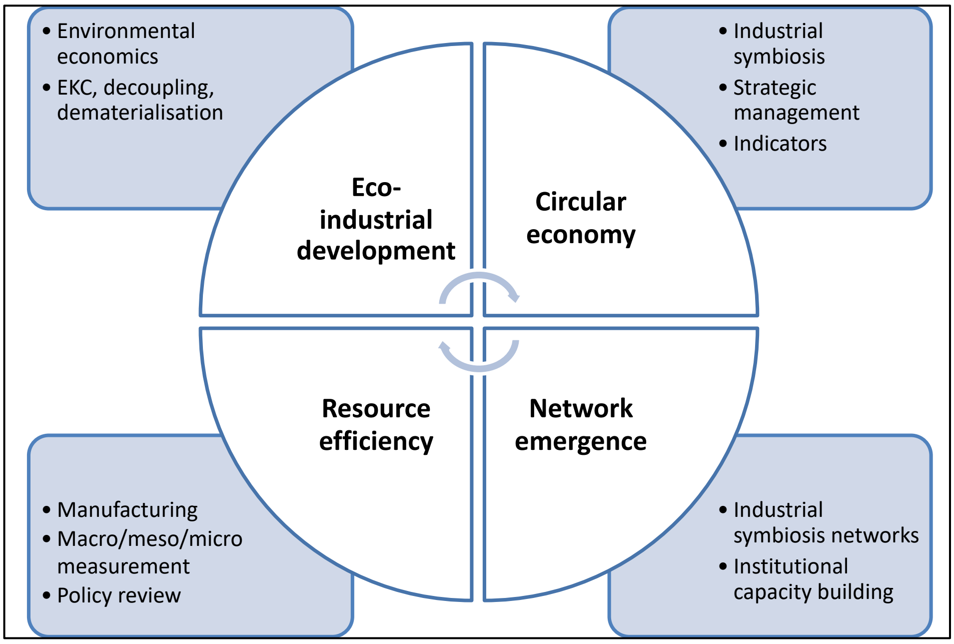

Figure 9: Theoretical foundations for the study

Source: Author

2.1 Literature review methodology

The keywords 'industrial ecology', 'industrial symbiosis', 'industrial symbiosis networks', 'circular economy', along with a combination of terms like 'manufacturing', 'indicators', 'case study', 'India' were searched in google scholar, web of science and Scopus databases. Furthermore, daily google scholar alerts via email were tracked to keep abreast of latest publications and special volumes. Due to the topical nature of the study, review of recent works was emphasised. Still, seminal studies in the areas of industrial ecology, industrial symbiosis and industrial symbiosis network development were instrumental in tracing historical roots of circular economy and eco-industrialisation. To maintain rigour while offering an in-depth and systematic literature review, the following steps characterised the literature search methodology:

- Generic search for keywords 'industrial symbiosis network' in google scholar.
- Relevant results appeared in the 1st 10 pages, after which frequency of articles on 'industrial optimisation', 'quantitative assessment', 'input-output models', Life Cycle Assessment' increased.

- The first level shortlist was made based on relevance of the paper title to industrial symbiosis network, sub-categorised into *concepts, theory, framework, case study, empirical evidence.* A filter for peer-reviewed articles and reputable journals was used.
- Book chapters and books were enlisted for later assessment, as many of those authors had also published similar works in the shortlisted journal articles.
- The next stage included reviewing the abstract text for content relevance – papers examining empirical cases, qualitative data and stakeholder roles, conceptual frameworks and developing economies were prioritised.
- Next, highly cited papers were shortlisted for review. Another shortlist was made for publications since 2016, here, data/results/methodology had higher significance over the number of citations.
- After consideration of shortlisted papers, additional papers from the reference list were included to deepen the inquiry qualitatively.

The above process was conducted iteratively since 2013 and for multiple keywords, hence a comprehensive list is not presented in this section. Duplicates were eliminated and the bulk of critiqued papers were published after 2004, when the topic first gained prominence. Priority was given to publications since 2010 to reflect the latest discourse. A similar set of search criteria were used for studies on India with significance to industrial ecology, industrial symbiosis and circular economy.

While the initial few years were instrumental to clarify concepts and theoretical frameworks, since early 2010 the focus has been on reporting case studies and indicators for measurement, delving into institutional mechanisms and policy performance. In the course of this examination, special attention was given to studies reporting developing country experience in eco-industrial park development.

This rigorous literature review process enabled tracing of the historical roots of industrial symbiosis network (ISN) development and to focus on major contributions and conceptual evolution. The works of Boons and Baas (1997); Boons and Spekkink (2012); Chertow (2000); Chertow and Ehrenfeld (2012); Ehrenfeld (2004); Ehrenfeld and Gertler (1997); Ghisellini et al. (2016); Lowe (2001); Lowe and Evans (1995); Mathews and Tan (2011, 2016) were instrumental in shaping the direction of the current research. While works in earlier years conceptualised industrial symbiosis foundations and network characteristics, Mathews and Tan (2011, 2016) exemplified circular economy progress through case studies of closed loop by-product exchanges in Chinese eco-industrial parks. Ghisellini et al. (2016) critically reviewed circular economy concepts, policy and inter-disciplinary links to present a meaningful up-to-date summary. These works will be drawn upon from time to time to critique conceptual foundations, methodological approaches, and to reflect on empirical findings from the Indian circular economy experience.

2.2 Circular economy: meanings and conceptual evolution

Circularity of resources in order to create closed-loop systems for technical and biological nutrients, as a means of extending the useful life of materials and reducing losses through atmospheric emissions and wastage signifies a shift to a circular economy (EMF, 2013; Mathews & Tan, 2011; Stahel, 2016) (Figure 10). This is a significant transformation from the predominantly linear economy, which relies on materials extraction, production, use and disposal. The rationale for a circular economy differs from mere environmental management and pollution prevention, as it is rooted in building economic growth through resource optimisation and ecological equilibrium. Delinking resource consumption (quantity and intensity) from economic growth and ecological impact is also referred to as *decoupling*, and promises sustainable development. In this sense, the pursuit of a circular economy is multidimensional and overlaps with engineering, technology and design, urban planning, political science, economics and business disciplines.

Image has been removed as it contains copyright material.

Figure 10: Circular economic system – conceptual illustration

Source: EMF (2020)

Multiple facets of a regenerative economic system coexist in a circular economy. *Reduction* in energy and materials use through efficient production and consumption; *reuse* of by-products, secondary materials, energy and water cascading; *recovery of* excess and post-consumption value through connected systems; *renewal* of resource use including the expansion of renewable energy capabilities; *repair and refurbish* economies to lengthen product life spans; *remanufacture* via easy disassembly to restore product value by rebuilding; *recycle* through the upcycle (same or higher value extraction) (EMF, 2020; Ghisellini et al., 2016; Ghisellini & Ulgiati, 2020). Stahel (2016) conceived systems thinking as the foundation of a circular economy; whereby, the closure of resource loops is monitored throughout extraction, manufacturing, distribution, use, and disposal stages. The author emphasised the centrality of user-consumers, stewardship, product- and process-innovation to realise a circular economic system.

Research publication about the circular economy has gathered momentum since 2004, dominated by China's adoption of a national circular economy strategy. The most comprehensive review of circular economy concepts and evolution was offered by Ghisellini et al. (2016) in a special issue on eco-industrial development. Using a cross-disciplinary lens, the authors traced methodological and analytical dimensions to scholarly inquiry on circular economy policy, implementation cases and measurement metrics. Ghisellini et al. (2016) exemplified the role of circular economy strategies to pursue decoupling, and that such strategies needed to be adapted to social, political and economic individualities of nations and regions.

The USA has initiated eco-industrial demonstration projects since 1994, supported by the US President's Council of Sustainable Development (PCSD); however, actual progress and scaled transition to the circular economy has been slow due to various administrative, fiscal and economic barriers. The Europe 2020 strategy advanced circular economy in material cycles through comprehensive materials and waste management systems and the strengthening of secondary (raw) material markets (EC, 2015). Among developing economies, China's Circular Economy Law (2009) was a first; where, phase-wise transformation of industrial parks into eco-industrial parks was promoted as a legal and regulatory mandate for rapid uptake of circular economy in industrial manufacturing (Mathews & Tan, 2011; Su, Heshmati, Geng, & Yu, 2013).

India's realisation of the circular economy is evident in resource-intensive sectors like steel, automobile, cement and chemicals. An all-encompassing circular economy framework for India is anticipated, with sector-specific targets and action-plans being implemented; individual states are leading the transition to green industrial practices and adopting clean energy at massive scales. The implications for a circular economy in India have not been fully explored in the academic literature. The majority of past inquiry delved into the inextricable role of informal waste collectors and rag pickers in the municipal waste ecosystem, with frameworks for inclusive organisation. Doron and Jeffrey (2018) offer distinctive insights on the indivisible social strands that bind India's informal waste sector together.

As mentioned previously, circular economy in Indian industry is grossly under-explored. Industrial waste exchange network studies are few, despite the aggressive manufacturing boom in the country. Bain et al. (2010) quantified material flows in the Nanjangud industrial area, to classify three main avenues for waste recovery: (i) reuse within the same facility, (ii) reuse within co-located firms and (iii) informal recycling. Shankar et al. (2017) presented advances in industrial sustainability of thermal power plants, sugar and cement industries in India. Ashton and Shenoy (2015) contrasted institutional structures in India and China, emphasising the potential for bottom-up (e.g., industry-led) green transformation in India. Extended producer responsibility, through formalised end-of-life vehicle recovery and remanufacturing, in the automotive industry showed likely prospects (Govindan, Shankar, & Kannan, 2016; Rathore, Kota, & Chakrabarti, 2011).

2.3 Industrial symbiosis networks as a means to achieving circular economy

Industrial symbiosis points to business-to-business exchanges and networks; whereby, multiple interlinkages for materials, energy, water, waste and by-products, information, technology occur between diverse actors. Some examples of recirculation of by-products or hitherto waste materials include the use of steel slag, waste glass, and automotive shredder residue plastics to produce ceramic surface layers (Handoko, Pahlevani, & Sahajwalla, 2019). These super-hard ceramic layers increase the corrosion resistance of high-carbon steel, which is widely used in mining and pharmaceutical industries. Although, alternative additives like alloying elements, protective coating and surface alloying exist (Handoko, Pahlevani, & Sahajwalla, 2018; Pei et al., 2017; Wu et al., 2017), the use of ceramic layers from waste alleviates changes to the steel's chemical properties, along with lowered maintenance costs and improved environmental outcomes from lowered demand for coating materials and the diversion of waste from landfill.

Technological interventions for resource recovery with reduced value losses are gaining attention. Plastic materials, which are widely used in intermediate and final products in an array of industries like packaging, automotive, pharmaceuticals, are largely subject to downstream recycling. Mechanical recycling of plastics is limited by the ability of thermoplastics to be repeatedly subjected to thermal or melt processing; multiple processing cycles can lower the recyclability of polymer chains, reducing value recovery and resulting in landfill. One value recovery mechanism is the use of green steel technology, which involves the capture of carbon at high temperatures from waste tyres and plastics, to reduce coking coal input in steel furnaces (UNSW, 2014). The business case, examined first in Australia, resulted in diversion of coal use, improved furnace efficiency and waste diversion (Sahajwalla et al., 2013).

Microfactories, which promote decentralised manufacturing, are being tested to extract higher value materials, mechanical and thermal properties, and energy from wastes like metals, timber, ceramics, glass and plastics (Sahajwalla & Gaikwad, 2018). Some promising solutions lie in the recovery of precious metals and rare earth elements from electronic waste like circuit boards, computer hard drives and mobile phones (Nogrady, 2016). Recovered resources like carbon, hydrogen, briquettes, printing filaments, and high strength composites find applications in metals manufacturing, construction and automotive industries (Heriyanto, Pahlevani, & Sahajwalla, 2018; Kumar, Gaikwad, & Sahajwalla, 2018; Sahajwalla & Gaikwad, 2018).

The transformation of linear value chains into closed-loop processes have varied patterns. As described in the introductory chapter (Figure 7 - circular economy implementation models at different levels), circular economy for manufacturing industries relies heavily on product and process redesign, firm-level innovation, and industrial symbioses involving multiple actors spread over industrial parks and regions. System-wide transformation distinguishes circular economy from more process-oriented cleaner production and efficiency strategies. The most common settings for industrial symbiosis are within an industrial park, between industrial parks, or through larger regional ecosystems where multiple tiers of actors are engaged in the resource exchange network.

2.3.1 Industrial parks and eco-industrial parks

Peddle (1993, p. 108) put forth a general definition of industrial parks to categorise “a large tract of land, subdivided and developed for the use of several firms simultaneously, distinguished by its shareable infrastructure and close proximity of firms”. Traditionally, industrial parks were meant to organise *manufacturing* activity while “accentuat[ing] the compatibility of the firms found therein” (Murphy & Baldwin, 1959, p. 79). Characteristics included: planned industrial district actions like zoning, design, minimum lot size, common utilities, adequate connectivity to major transport means; park management with decisive powers on tenant activity, new tenant approvals, any structural or operational changes; ample tenant restrictions in order to ensure park success (Murphy Jr & Baldwin, 1959). Today, this definition has been broadened to include an array of firm activity in business and technology parks, science and research parks, many services and peripheral activities.

The co-location of multiple firms within the bounds of an industrial park position them to be ideal sites for heightened sharing and communication. It is worth noting that *compatibility between firms* was one of the features presumed to be central to eco-industrial park development. The meanings, definitions and experiential development of eco-industrial parks is critiqued in the next section. Since the focus of the thesis is the manufacturing sector, all further mentions of industrial park will refer to 'manufacturing industrial parks' where, the core activity is the production and/or warehousing of particular goods or services for intermediate or final consumption; this may include multiple supply chain actors in the same or different industries. Furthermore, terms like park/estate/district/cluster will be used interchangeably to denote 'industrial parks' as defined by Peddle (1993, p. 108) and Murphy and Baldwin (1959, p. 79).

Different purposes of eco-industrial parks are considered in the literature. Côté and Hall (1995, p. 42) identified ecological objectives that would be most relevant to an [eco] industrial park as "conservation of natural and financial resources; reduced production, material, energy, insurance and treatment costs and liabilities; improved operating efficiency, quality, population health and public image; potential income through the sale of wasted materials". These objectives, while all-encompassing, clarify firm benefits which may accrue from ecological industrial activity. Lowe, Moran, and Holmes (1996, p. xii) refer to the "community" facets and "collective" benefits of an eco-industrial park (EIP) "[to seek] enhanced environmental and economic performance through collaboration in managing environmental and resources issues".

In building our understanding of eco-industrial parks, the *community*, *sharing* (of information, material and ecological resources) and *co-located* aspects will be central. Thus, *industrial parks in which co-located firms venture on intentional sharing of materials, energy, water, information with the objective of seeking economically and environmentally beneficial outcomes for reduced use of virgin materials, technology improvements for resource efficiency and cleaner production, and alternative applications for by-products and wastes*, may signify 'eco' aspects of an eco-industrial park. Detailed evaluation of the industrial and eco-industrial park landscape in India is presented in later chapters.

2.3.2 Global industrial symbioses networks

Complex industrial symbioses evolve over decades, and as such, there are few examples that are documented. The Kalundborg symbiosis in Denmark is globally the most advanced and enduring example of closed loop resource exchange, with: 5 power, steam and gas loops; 6 types of water loops; and 11 material loops that have yielded 65% improvement in resource use, and 635,000 tonnes CO2 emissions reduction annually (KalundborgSymbiosis, 2020; SCD, 2020). The Kalundborg symbiosis has evolved over time, today, multiple bilateral exchanges are active between nine public and private firms (Figure 11). Lowe and Evans (1995) presented an early observation of the *spontaneous* and *voluntary* symbioses in Kalundborg, with five main actors: Asnaes power station (steam transfer to Statoil, Novo Nordisk and the city of Kalundborg; fish farming; fly ash sent to cement industry; gypsum sent to Gyproc), Statoil refinery (excess gas sent to Gyproc; sulphur sent for sulphuric acid manufacture; user of by-product steam), Gyproc - plasterboard factory (user of by-product gypsum and gas), Novo Nordisk - biotechnology and pharmaceutical manufacturer (sludge sent for use as fertiliser in farming; surplus yeast sent to farmers for use as pig food; user of by-product steam), city of Kalundborg - supplier of water and district heating (user of by-product steam).

Monetary drivers, like *cost saving* from waste reduction and *supplementary revenue* from alternative uses for by-products, stimulated firms to share information and seek mutual gain. The resulting symbiotic exchanges at Kalundborg did not yield immediate benefits, but enabled further communication between firms and invited new firms to participate. Eventually, inter-firm collaboration led to heightened symbiotic exchange, with multiple firms entering and exiting as the network evolved. Historic origins of industrial symbiosis at Kalundborg reinforce economic benefit as the foremost driver for businesses and society to participate in any form of resources exchange (Desrochers, 2002). Unintended environmental and societal gains from multifaceted resource exchanges extended conceptual understanding of industrial symbiosis.

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Figure 11: Kalundborg symbiosis, Denmark, in its current form
Source: KalundborgSymbiosis (2020)

Across Europe, 46 cases of industrial symbiosis are known, dominated by 35 cases which align with networks in six EU countries – Italy, Sweden, UK, Germany, Denmark, Portugal (Domenech, Bleischwitz, Doranova, Panayotopoulos, & Roman, 2019; Holgado, Morgan, & Evans, 2016). Amongst these, UK and Italy had the highest number of symbiotic interactions and information reporting, owing to the institutional aegis from National Industrial Symbiosis Programme (NISP) in UK and National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) in Italy. Externally assisted symbioses were successful in the EU at varied scales: nationally in the UK through NISP; with similar patterns in Hungary, Finland, France, Denmark, accompanied by regional and local systems.

Ghisellini and Ulgiati (2020) offer an exhaustive review of circular economy typologies in Italy's industrial sector. Although downstream recycling dominated end-of-life resource recovery, circular models for repair, reuse, remanufacturing, regeneration are being propagated by localised non-profit organisations. Not surprisingly, environmental certification was common and technological innovation drove circular economy forays in large-scale manufacturing firms. Among significant barriers were market imperfections due to lower price competitiveness of secondary material inputs in contrast to virgin materials. A diversity of meanings, interactions and implementation models were reported, along with circular economy prospects and barriers. While a nationwide groundswell will accelerate the transition to circular economy in Italy, promising initiatives are evidenced at micro, meso and macro scales.

The core strategy for Europe 2020 circular economy advancement is the acceleration of industrial symbiosis networks (ISNs) as sources of innovation and collaboration. The European Union Circular Economy package, confirmed in July 2018, included financial and legal incentives to spur industry participation in industrial symbiosis. Within Nordic countries, different policies, institutional and economic structures contributed to industrial symbiosis development: in Denmark and Finland, policy and obligatory compliance drove top-down implementation; whereas, in Iceland, Norway and Sweden, more innovation and industry-driven bottom-up initiatives were recorded (Domenech et al., 2019; Johnsen et al., 2015).

Houston Ship Channel, Texas, was another example where chemical and petrochemical plants, oil and gas refineries, salt and sulfuric acid manufacturers created an ecosystem for by-product recovery, exchange and reuse (Holmes, as cited in Lowe & Evans, 1995). The surfacing of such examples extended the understanding of complex linkages and stakeholder roles in industrial ecology. Formal programs were launched to develop new eco-industrial parks or retrofit existing industrial parks with a system for resources exchange. The United States Environmental Protection Agency (USEPA) eco-industrial park initiative, and Dalhousie University's research project at Burnside industrial park in Nova Scotia were prominent examples at the turn of the century.

Economic drivers like current demand and market conditions characterise firm participation in spontaneously formed industrial symbiosis networks. Additionally, social, technical and political factors influence the degree of embeddedness for such networks (Baas, 2008; Chertow, 2007; Mirata & Emtairah, 2005; van Beers, Bossilkov, Corder, & Van Berkel, 2007). Designed symbiosis, in contrast to the spontaneous evolution in Kalundborg, was successful in South Korea. The country initiated a three-phase eco-industrial park plan in 2005 to evaluate and implement industrial symbioses in eight key industrial regions. Among the eight demonstration regions, Ulsan, the industrial capital, was one of the five selected since the first project phase (Park & Won, 2007). Through a systematic 'research and development into business' framework, the Ulsan Eco-Industrial Park Centre has initiated thirteen symbioses involving 41 firms; of this, there are 6 steam exchanges and 7 material/by-product exchanges (Behera, Kim, Lee, Suh, & Park, 2012; Geng et al., 2016).

China's national circular economy strategy centred around managing physical material flows, through strengthening industrial symbioses in extant regions and building greenfield eco-industrial parks. Extensive implementation and measurement has yielded strong exemplars like Tianjin Economic-Technological Development Area (TEDA) and Suzhou New District (Mathews & Tan, 2016; Shi, Chertow, & Song, 2010; Yu, de Jong, & Dijkema, 2014). The National Development and Reform Commission (NDRC) advanced industrial park transformation through the establishment of model demonstration sites. This model has witnessed success, mostly in the form of fiscal benefits and quantifiable targets linked to centralised measurement. The Chinese circular economy indicator system, a global first, measures progress at macro and meso levels through metrics like resource output, consumption, utilisation, waste, pollution and emissions (Geng, Fu, Sarkis, & Xue, 2012).

Patterns of industrial symbiosis development are evident in Japan (Kawasaki), China (TEDA, Suzhou), Korea (Ulsan), Australia (Kwinana, Gladstone), several sites across the USA and Europe (Eilering & Vermeulen, 2004; Mathews & Tan, 2011, 2016; Shi et al., 2010; Yu et al., 2014). In China, programs for circular economy centre on sustained production and consumption growth; whereas, in the USA, Europe, Japan, Korea, and Vietnam programs display closer ties to 3R (reduce, reuse, recycle), through sector-specific waste reduction and management (Sakai et al., 2011). The comparative performance of circular material and energy loops in China vis-à-vis Western and East Asian counterparts highlighted the nascence of implementation models. Additionally, top-down implementation in China through tight regulation, financial incentives and policy compliance contrasted with bottom-up and organic, industry-driven implementation elsewhere (Mathews & Tan, 2011).

2.3.3 Industrial symbiosis in India

A nationwide comprehensive assessment of industrial symbiosis has not been formalised yet; although, intensive discussions to encompass circular economy in the nation's resource efficiency strategy are in progress (MoEFCC, 2019; TERI, 2019). Previous studies, which assessed park/state level eco-industrial progress, demonstrated many by-product exchange possibilities, and network enhancing overtures. Singhal and Kapur (2002) proposed strategies to incorporate industrial ecology in industrial estate plans for India, by: classifying industry types, adopting regional environmental impact assessment for upcoming estates, integrated green industrial townships, and higher application of environmental management systems to manage park performance. Saraswat (2008) set out pathways for existing industrial parks to transition to eco-industrial parks; the suggestions spanned planning, setup, implementation and assessment phases, to accelerate industrial ecology awareness and toolkits among industry and government actors. Some states, such as Gujarat and Andhra Pradesh adopted a greening agenda early in their industrial development, by incorporating strategic design, co-located activity, shared infrastructure and common services in industrial estate planning.

In December 1998, a survey of 477 firms within Naroda industrial estate, Gujarat, revealed four by-product categories that could be exchanged within the park. The research, funded by the German Ministry for Education, identified spent acid—iron sulfate, chemical gypsum—cement, iron sludge—brick manufacturing, food waste—biogas, by-product reuses (Lowe, 2001; Von Hauff & Wilderer, 2000). An appraisal of industrial symbiosis progress at Naroda since, is offered through a detailed case study later in this thesis. In their examination of the environmental performance of 34 firms in Taloja industrial estate, Maharashtra, Unnikrishnan, Naik, and Deshmukh (2004) underscored government and institutional support, shared infrastructure development and financial incentives, to expand industrial symbiosis. Two ongoing by-product exchanges for scrubbed tailgas—maleic anhydride and brewery wastes—poultry feed, were reported (Unnikrishnan et al., 2004). Efforts by agencies like GIZ, GCPC, and IGEP had significant bearing on the increase in industrial symbiosis linkages in India (GIZ & IGEP, 2015; Nukala & Meyer, 2012).

Previous examination of IS benefits recognises the environmental and economic savings; yet the social and community benefits are sparsely understood. Further knowledge about "public co-benefits" can enhance the maximisation of existing infrastructure facilities, often constrained by space and capacity in dense urban settings. Chertow et al. (2019) modelled the industrial symbiosis potential for the formal industrial sector in Mysore district in southern India. Mysore is a typical tier-2 urban city in India, witnessing rapid urbanisation owing to its proximity to India's tech-capital Bengaluru, and a fast-expanding economy. Unsurprisingly, the city's waste management infrastructure is severely constrained, coupled with a rising demand for housing, water and energy.

Using life cycle inventory data, Chertow et al. (2019) conducted lifecycle assessment to identify resource efficiency improvement opportunities through industrial symbiosis in Mysore district. Interesting links between private production and public infrastructure were identified to quantify community benefits such as pollution abatement, less demand for landfill area, reduced use of water and energy resources. The modelling analysed 149 possible IS exchanges using 64 distinct industrial by-products, with reuse potential of 83,000 tonnes annually (Chertow et al., 2019). While actual data on by-product flows and operational ISNs in the region is not fully documented, the results expand on earlier empirical findings from Nanjangud industrial area in Mysore (Ashton & Bain, 2012; Bain et al., 2010).

More recently, the International Framework For Eco-Industrial Parks was formalised by the World Bank, UNIDO, and GIZ. One of the notable examples from India was the Association of Lady Entrepreneurs of Andhra Pradesh (ALEAP) Green Industrial Park. Spread across 33.5 hectares land area and housing 170 women entrepreneurs, the park embodies economic, social and resource efficiency advances in modern eco-industrial parks in India (WB, 2017). Implementation guidelines for eco-industrial parks, published by UNIDO (2017b), designated five Indian industrial parks for pilot testing of resource efficient and cleaner production strategies at the firm level and inter-firm synergies. Findings from 33 industrial parks in 12 countries where UNIDO's Resource Efficient and Cleaner Production (RECP) Programme for eco-industrial parks was piloted, recognised the need for training and replicable technical guidelines. Cohesive institutional strategies were noted to be crucial for global eco-industrial progress (UNIDO, 2019).

A survey of diverse industries in the ecologically fragile coastal zone of Puducherry in India identified several environmental, economic, technological, policy opportunities and threats for eco-industrial development in the region (Patnaik & Poyyamoli, 2015). Access to land, water, labour, power and government incentives have attracted numerous industries to the union territory, clustered around seven fully functional industrial estates. The region hosts many high polluting and hazardous waste creating industries such as electroplating, pharmaceuticals, chemicals, steel, textiles, electronics and distilleries.

Localised treatment and disposal of waste is a challenge due to limited resources, a single hazardous waste recycling unit unable to meet current demand, and the absence of a scientifically managed landfill. Owing to the inadequate waste management infrastructure, firms are burdened to trade waste with neighbouring regions or dispose of without proper treatment. Despite the current capacity constraints, Patnaik and Poyyamoli (2015) found optimistic prospects for eco-industrial development in Puducherry region due to the prevalence of large manufacturers in galvanising, paper, and gypsum industries, who could serve as anchor tenants for ISN. Some of the well-suited industries identified for IS were: sugar, paper, galvanising, and granite. Additionally, a proactive local government, specialised regional development agencies and close proximity of industries strengthened IS prospects (Patnaik & Poyyamoli, 2015).

The opportunities to pursue balanced economic and environmental industrialisation in India are ripe as elucidated from preceding examples. Latest policy announcements like the Steel Scrap Recycling Policy and National Resource Efficiency Programme set the backdrop for a circular economy in India, led by industrial action. Van Berkel (2006) called for strong business-driven arguments to demonstrate the benefits of eco-industrial development. Bain et al. (2010) indicated that multiple cases of localised industrial symbiosis may occur in India, owing to the nation's innovative capabilities as well as dynamic small and medium enterprise networks. Yet, gaps exist in a full understanding of the functioning of eco-industrial parks in India, administrative and institutional mechanisms, economic models as well as stakeholder roles for participating in symbiosis. Structured evaluation of industrial symbiosis networks (ISNs) is deficient, especially in relation to the recent surge in manufacturing activity. This thesis attempts to address some of the aforementioned gaps by presenting an up-to-date in-depth assessment of India's industrial symbiosis and circular economy accomplishments. India's pathways towards realising circular economy can be informed through critical examination of nineteen ISNs, operational in diverse industry sectors like chemicals, pharmaceuticals, steel, cement and bio-products.

2.4 Industrial symbiosis networks: an ecosystem view

In their conceptualisation of ISN emergence and evolution, Boons et al. (2017) defined a typology of seven industrial symbiosis dynamics: self-organisation; organisational boundary change; facilitation through brokerage; facilitation through collective learning; pilot facilitation and dissemination; government planning; eco-cluster development. Against each typology, scholarly findings on the *initial actors, motivation, overall storyline, and typical outcomes* were synthesised. The novelty of these seven evolutionary pathways for IS validates the dynamic nature of IS and provides a framework for comparison across different emergence contexts.

Certain direct commonalities can be drawn between agglomeration economies and ISN; these relate to: utility sharing; joint service provision; by-product exchanges (Chertow, Ashton, & Espinosa, 2008). *Utility sharing* has demonstrated multiple benefits for firms and the larger community. These include reduction in costs of production; access to basic utilities such as energy, water, heat; contraction of resource use and overall emissions. In terms of *joint services*, benefits such as economies of scale, improved efficiency and quality accrue, alongside reduction in material and energy intensity. Lastly, *by-product exchanges* can alleviate transportation and transaction losses when undertaken between co-located firms capitalising on geographic proximity, but also exchanges not constrained by spatial distances (high-value, low-volume by-products) and those enabling secondary material production to substitute virgin materials (Chertow et al., 2008).

It must be noted that geographic proximity is not a precondition for effective IS and that diversity among partner firms (firm size or industry type) has yielded many successful by-product exchanges. Furthermore, co-location does not necessarily result in agglomeration economies since not all benefits are obvious or require collaboration among co-located firms. For example, shared services such as roadways, power and water may be considered as basic services accorded to resident firms, not engaging actors in active pursuit of knowledge development or shared learning. Whereas, more incremental efforts towards encouraging common effluent treatment or conducting educational workshops for shared problem-solving might require inter-firm co-ordination; thereby, resulting in personnel engagement and information exchange (Chertow et al., 2008; Duranton & Puga, 2004).

Eco-industrial parks, by themselves, cannot be designated as an ecosystem; the design, location, infrastructure and shared services are one set of contributors for industrial symbiosis. The other, most significant set, are the firms, themselves. As mostly private businesses operate within industrial parks, physical factors external to the firm can contribute to some extent by fostering collaboration, however, the attainment of cyclical exchange will only develop by engaging diverse actors in active dialogue and collective problem solving. Although the agglomeration of industrial activities in industrial parks is to be expected, circular economy principles applied within these settings can nurture lengthier and higher value resource loops, promoting the use of secondary materials and easing the burden on finite virgin resources. A multi-stakeholder *ecosystem view* for circular economy is needed to ascertain roles and motivations.

Walls and Paquin (2015) conducted one of the most comprehensive reviews of organisational perspectives in industrial symbiosis literature. The systematic literature review posited a two-dimensional framework comparing the *antecedents* (preconditions), *consequences* (outcomes), *lubricants* (enablers) and *limiters* (barriers) with *institutional*, *network*, *organisational* and *individual* aspects. A similar approach for the first dimension (antecedents, consequences, lubricants, limiters) was adopted by Wassmer, Paquin, and Sharma (2014) who examined inter-firm engagement in environmental collaborations (similar to those in an ISN). The authors confirmed that IS conceptualisations are not yet closely integrated with the corporate environmental strategy literature. The second dimension of the framework by Walls and Paquin (2015) considered four levels for IS (institutional, network/systems, organisational, individual), following previous work by Andrews (2000) and Boons, Spekkink, and Mouzakitis (2011).

Proposing a 3-2 heuristic, Chertow (2007) proposed an initial ecosystem view, where at least 3 actors are involved in by-product exchange of a minimum 2 resources, but the core operations of none of these actors are related to recycling. Although a valuable conceptualisation, actual implementation at TEDA practically parallels this view. The industrial symbiosis network at TEDA is mature and a large number of actors participate in symbiosis. However, recyclers were specially invited to set up within TEDA in order to transform otherwise waste by-products (e.g. foam board). In this case, the recycling industry formed part of the network and was not external to the industrial symbiosis system.

Industrial ecosystems are suggested to connect at least one major resource or by-product exporting (donor) firm, with one or more receptor firms; for example, the material/energy/water recovered at the donor firm is sent for reuse within the receptor firm, as a means of replacing virgin resource use. Large donor firms around which the exchange ecosystem revolves are termed as “anchor” firms, tasked with building a network of “satellite” firms around resource exchange (Ayres, 1994). The role of the anchor firm in initiating symbiotic exchange is problematic. In most unorganised symbiotic networks, like the Kalundborg symbiosis, the anchor firm tended to be the one which had the largest diversity of exchange possibilities. Today, multiple anchor firms support vertical and horizontal symbioses in the Kalundborg municipality (Figure 11). In contrast, planned symbiosis in eco-industrial parks such as in the USA, where tenants were invited based on their applicability to participate in the network, met with limited success. In such cases, anchor tenants may be termed as firms which first initiated operations in the park, whose type and quantity of by-products were used as the basis of inviting other firms. So, anchor tenants, may also refer to demonstrator firms which display huge potential for symbiotic exchange.

Industrial symbiosis ecosystems have been viewed at a variety of scales. At one end of the spectrum bilateral firm exchanges exist and, at the other end, highly complex, multi-actor linkages expanding into wider regional ecosystems can develop (Baas, 1998). Scrutinising resilience and efficiency of industrial symbiosis networks has revealed the following. Network resilience was found to improve as different industries joined the network (Chopra & Khanna, 2014), but this decreased as interfirm dependency intensified (Zhu & Ruth, 2013). High interfirm dependency reduced eco-efficiency losses and was found to be directly proportional to the network's overall efficiency (Holgado et al., 2016). Clearly, a conscious *trade-off between resilience and efficiency* appears paramount to the network's success.

Fraccascia, Giannoccaro, and Albino (2017) expanded the conceptualisation of resilience in ISN by inspecting two known antecedents: *diversity* (at the levels of systems and firms) and *ubiquity of wastes*, through the resilience index which was tested on two active ISN in Jinan City, China, and Kalundborg, Denmark. The results highlighted the need for identifying networks that might be highly vulnerable to disruption, especially from firms dominated by diversity in waste exchanges, production and waste structures.

Côté and Hall (1995, p. 42) referred to the *design* element of industrial parks, one which encourages "mutualistic" and "commensalistic" interactions for the optimal use of raw materials, intermediate and finished products and wastes or by-products. The notion that industrial symbiosis can be *designed* has not been clearly established to date. Nonetheless, the existence of multiple-tiered (primary, secondary, tertiary) consumers and support actors places industrial parks in a favourable position for cyclical resource flows.

Physical proximity too can be an enabler for certain resource exchanges, depending on the specialisation of the industrial estate or cluster and its main industries. For example, metal and electronic by-products have high market value and a satisfactory value to volume ratio; these also require specialised separation and resource extraction, and are suitable for transport over longer distances. In contrast, plastics, paper, organic and inorganic wastes have a low value to volume ratios and may not be commercially sustainable for transport over long distances, unless there is external financial support and regional economies of scale are foreseeable. Ruiz, Arozamena, and Evans (2015) illustrated positive outcomes of *inter-firm collaboration* and *economies of scale* due to proximate industrial parks within a region.

A glaring deficiency in current research is the lack of actual realisation of industrial symbiosis. Abundant information on the *potential* for symbiotic exchange is available, firm surveys and material flow analyses in diverse industrial regions reveal possible exchanges and assumed benefits. For instance, the survey of 104 small and medium enterprises in Spain by Ruiz et al. (2015) identified marketable waste products and found opportunities for synergetic exchange. While scenario analyses and quantifiable outcomes are useful in preliminary assessment, subsequent implementation needs to be followed through. This is the stage where roles become ambiguous and, without external knowledge building, firms are challenged to seek solutions beyond day-to-day operations. In the case of Nanjangud in India, beyond the findings of Bain et al. (2010), no further progress on industrial symbiosis was reported.

2.5 Measurement and indicators

Life Cycle Assessment (LCA) is an established methodology for environmental impact assessment of products and services, to gain multicriteria and life cycle perspective. Initially, developed with a product-centric approach, LCA was used as a decision-making tool for eco-design and eco-labelling. In industrial symbiosis, LCA applications to quantify environmental benefits are varied. Using tiered hybrid LCA, Dong, Geng, Xi, and Fujita (2013) measured the total life cycle carbon footprint of Shenyang Economic and Technological Development Zone (SETDZ) in China. Direct (onsite), upstream and downstream carbon footprint analysis found the chemical industry and machinery manufacturers to have the highest life cycle carbon footprint.

Waste data for over 100 material categories, compiled by the Pennsylvania Department of Environmental Protection, along with life cycle inventory (LCI) data were used to ascertain savings and environmental benefits from the reuse of non-hazardous industrial wastes, which primarily constituted waste water and a few solid materials (Eckelman & Chertow, 2009). Similarly, territorial LCA in a region with 14 Municipalities located in the south of France, demonstrated that environmental impacts like climate change, particulate matter formation, human toxicity and land occupation extended beyond territory borders. Food imports and manufacturing had the highest impact, indicating adverse ecosystem quality owing to production activities in comparison to consumption (Loiseau, Roux, Junqua, Maurel, & Bellon-Maurel, 2014).

At the level of an industrial cluster, LCA to study industrial symbiosis progress is emerging. Daddi, Nucci, and Iraldo (2017) examined the benefits from infrastructure sharing in an Italian tannery cluster in Tuscany. Waste recovery plants and waste water treatment plants jointly managed by over 600 firms located in the cluster were the object of analysis. The results showed positive impact of industrial symbiosis activities on climate change and terrestrial eutrophication. Such findings have implications for policy direction, to guide future initiatives and ascertain comparative benefits of shared industrial symbiosis ventures. More importantly, collective action can improve individual firm efficiency while reducing the environmental footprint of the cluster; thereby, justifying the exchange of economic, technical and organisational knowledge to improve cluster competitiveness.

Mantese and Amaral (2018) compared eight sets of industrial symbiosis indicators (Table 3). Earlier works by these authors simulated symbiotic interactions within an eco-industrial park by introducing the *EIPSymb* model (Mantese & Amaral, 2017). The effectiveness of this model was tested to compare indicators proposed by Tiejun (2010) and Felicio, Amaral, Esposto, and Durany (2016). Although successful in calculating by-product generation and reuse, *EIPSymb* failed to reflect production and sale of final products to other firms in the park, the associated energy consumption and emissions and monetary value of symbiotic and non-symbiotic exchanges between park actors.

Comparative responses of the eight indicators under different scenarios in the EIPSymb#2 model found Industrial Symbiosis Indicator (ISI) and Eco-efficiency as the most complete. ISI was helpful in tracing industrial symbiosis evolution, while Eco-efficiency assessed efficiency variation for financial outcomes, input use and CO_2 emissions for the entire eco-industrial park (EIP). For holistic evaluation, a combination of the above indicators with Connectance and Eco-Connectance is advocated to study the level of relationship (Mantese & Amaral, 2018). The central concern in adopting these findings is the absence of factual data, as the simulations do not use data from an actual EIP.

Table 3: Summary of industrial symbiosis indicators

Name of indicator	Key metrics used	Purpose	Data sources
Connectance *Symbiotic Utilisation* (Hardy & Graedel, 2002)	Degree of association between EIP firms Magnitude and hazardousness of symbiotic relations	Study cooperation between firms Identify incentive for by-product exchange	Wastes/by-products flows of each firm within EIP Hazard level of each waste/by-product
Eco-Connectance *By-product and Waste Recycling Rate* (Tiejun, 2010)	Degree of association between EIP firms Degree of by-products and waste recycling in the EIP	Study cooperation between firms Identify waste reduction	Wastes/by-products flows of each firm within EIP
Industrial Symbiosis Index *Link Density* (Zhou, Hu, Li, Jin, & Zhang, 2012)	Intensity of resource utilisation Association density between EIP firms	Identify opportunities for waste and by-product exchange Study cooperation between firms	Wastes/by-products of each firm within EIP Existing links: origin and destination of products and by-products
Eco-efficiency (H. S. Park & Behera, 2014)	Net Economic Benefit Raw Material Consumption Energy Consumption CO_2 Emission	Evaluate the eco-efficiency of symbiotic transactions Encourage symbiotic relationships and improvement in eco-efficiency	Monetary savings from industrial symbiosis Firm level data for raw material and energy consumption Firm level CO_2 emissions
Resource Productivity Index (Wen & Meng, 2015)	Direct material input – virgin raw material Indirect material – reused raw material (wastes/by-products)	Evaluate contribution of industrial symbiosis to circular economy Productivity enhancement	Direct material input (amount) Industrial added value by firm
Environmental Impact (Trokanas, Cecelja, & Raafat, 2015)	Embodied Carbon Cost Virgin Materials *Financial* Saving Landfill Diversion *Financial* Saving Transportation *Financial* Impact Energy Consumption *Financial* Impact	Assess financial impact of environmental impact from symbiotic exchanges Assess financial savings from symbiotic exchanges and landfill diversion Assess financial impact of associated impact categories transportation and energy use	By-product exchange volume Energy use for by-product processing Geographic location of donor and receiver firms Price of replaced virgin materials vis-a-vis by-products
Industrial Symbiosis Indicator (Felicio et al., 2016)	Legislation Class of waste Use of waste Destination of waste Problems/risks	Performance of symbiotic relationships between firms within an EIP	Wastes and by-products flows Waste legislation Waste categorisation

Source: Author, adapted from Mantese and Amaral (2016)

Previous studies have been based on a range of assumptions. For example, firms are fully aware of the amount and type of by-products they generate and the ability of partner firms to utilise those by-products; linear associations between actors: firm-firm, firm-landfill, and so on. Empirical evidence, however, suggests that firms are not entirely aware of the value their by-products may generate. unless there is a concerted study to categorise and identify potential users. Also, in real scenarios, compound relations exist between firms participating in industrial symbiosis, with multiple inward and outward links to enable profitable by-product use.

Various proposed indicators have been ineffective in illustrating applicability or objective evaluation of their uses in industrial symbiosis. Conceptual validation of industrial symbiosis indicators has attained a certain degree of attention in scholarly debate; however, empirical validation still poses a significant gap. The inadequacy of the use of industrial symbiosis indicators is further exacerbated by partial or unavailable actual data. The underlying assumption of IS indicators is that where there is a functioning EIP, industrial symbiosis links are established. Actual cases of functioning EIPs are rare; here too, access to firm-level data is arbitrary at best.

As intellectual debate on the conceptualisation of industrial symbiosis indicators matures, a more robust system to uncover ongoing symbiosis needs to be established. Quantitative metrics alone are inadequate to gain a holistic view of symbiotic patterns and stakeholder motivations. A deeper, more qualitative introspection in conjunction with quantitative metrics is needed. A popular approach in recent years has been to design industrial symbiosis programs in order to mirror successful models. While such an approach is appropriate, albeit with limited success so far for new industrial parks, older and more mature industrial estates are regions that require different strategies to adopt circularity. The current study makes an attempt at addressing some of these gaps by presenting a multi-stakeholder *ecosystem* view of emerging symbiotic links in well-established industrial estates, which specifically lack a planned industrial symbiosis program but have shown interest in seeking profitable solutions to waste minimisation and profitable reuse.

Lastly, a comprehensive circularity measurement system is needed to identify social, economic, environmental and technological benefits and costs. Due to the absence of a holistic index, linear economic measures like Gross Domestic Product (GDP) dominate the study of resource flows through indicators like material intensity, energy and emissions intensity at the macro (nationwide) level. Some qualitative factors are included in Human Development Index (HDI) results; but, these do not entirely represent the impacts of realising circularity at the national level. Furthermore, ISNs are a means of achieving circularity at the meso levels; yet, measurement and reporting systems vary greatly.

Current measurement of circularity is ambiguous as it relies on traditional indices and their replication is limited due to variations in data collection, reporting and accuracy in different regions, especially developing economies. A valid criticism of circular economy thinking exists in the impracticality of end-to-end circularity within an economic system and the emergence of "rebound effects" due to differences in eco-efficiency and eco-sufficiency strategies (Figge, Young, & Barkemeyer, 2014). Increased resource consumption as the consequence of eco-efficiency strategies can outweigh benefits from improved efficiency in a circular economy; although, the actual effects are still to be demonstrated beyond doubt.

2.6 Industrial symbiosis programs and implementation experiences

The International Framework for Eco-Industrial Parks adopted by UNIDO, WB, and GIZ (2017) identified 51 performance indicators to assess global progress towards eco-industrial development. The UNIDO evaluated current and future performance of the industrial parks in eight countries: Colombia, Egypt, Indonesia, Nigeria, Peru, South Africa, Ukraine, and Viet Nam. Four main categories were assessed: park management, environment, social, and economic indicators. The authors found that the economic and park management indicators performed better than environmental and social performance indicators (van Beers et al., 2020).

The attainment of ISNs within industrial parks, industrial clusters and wider regions is subject to considerable debate. Mirata and Emtairah (2005, p. 994) defined an industrial symbiosis network as "a collection of long-term, symbiotic relationships between and among regional activities involving physical exchanges or materials and energy carriers as well as the exchange of knowledge, human or technical resources, concurrently providing environmental and competitive benefits". Regions, unlike states or nations, do not have geographic boundaries and yet, reflect a milieu of comparable political, cultural and economic influences. Various studies, referred to below, found that limiting industrial symbiosis networks within geographic regions did not always yield the most environmentally equitable or financially profitable solutions.

The view of regions as innovation (hubs) that interact at different levels with national and global systems (Cooke, Gomez Uranga, & Etxebarria, 1997, p. 480) fits within the context of the circular economy. These authors define regions as "… territories smaller than their state possessing significant supra [ ] local governance capacity and cohesiveness differentiating them from their state and other regions". Looking beyond sectors or clusters, strong regional governance and innovation support organisations promote systemic learning and interactive innovation for firms. Regional innovation systems hold three key institutional forms: "financial, learning and productive cultures"(p. 476); together these build systemic innovation capacity in regions.

Multiple ISN examples are known to have succeeded through *agility* and *self-organisation*. These attributes enable complex networks to adapt to changing market conditions and *self-evolve*, reducing dependence on a few actors. Industrial ecosystems as *complex adaptive systems* are known to exhibit ever-evolving, fast-paced, self-organising attributes, influenced largely by market demand and supply dynamics (Chertow, 2009; Kay, 2002; Spiegelman, 2003). Self-organising systems, are thus, posited to be drivers for industrial symbiosis, "*Self-organization is a process by which by which systems of diverse component entities form stable structures with many interactive links that pass energy, material, and information across their various nodal points. An observer might attribute some purpose to the arrangement, but self-organizing systems form without any overarching intention or teleology*" (Chertow & Ehrenfeld, 2012, p. 15).

Although many successful examples of ISNs emerged spontaneously, where actors self-organised within the network, a parallel argument can be made that industrial symbioses require *deliberate and intentional action*. The forthcoming discussion on the Landskrona industrial symbiosis programme (LISP) in Sweden and National Industrial Symbiosis Programme (NISP) in UK are cases of *facilitated symbiosis,* where a focal body intermediated activities of the industrial symbiosis network.

Sweden's Landskrona industrial symbiosis programme (LISP) began in 2002 with financial support from the Swedish Business Development Agency (NUTEK). Earlier a hub for small and medium sized businesses, the industrial profile of Landskrona altered to a few large employers with 20 private firms in chemicals, waste management, metals processing and recycling, printing and packaging, automotive components, agriculture, transport and logistics. In addition, 3 key public institutions responsible for district heating, environmental affairs and business development participated in the LISP. Based on their cross-disciplinary study on innovation and industrial symbioses, Mirata and Emtairah (2005) identified three factors that mediated the effect of industrial symbiosis networks on environmental innovation: "(a) the role of collective problem definition in the problematisation and search for solutions; (b) the benefit of search and discovery at the inter-sectoral interfaces; and (c) enhanced learning through inter-organisational collaboration" (Mirata & Emtairah, 2005, p. 996).

Actors links surfaced in the early stages of LISP through seminars that facilitated joint problem definition and shared goals for resolution. Subsequent interactions between actors expanded the realm of synergies, encouraging the search for knowledge and solutions beyond one's sectoral domain. While symbiotic links at Landskrona were active even before LISP, the programme *institutionalised* collective eco-environmental solutions. As a result of heightened communication between actors, shared utilities like storage spaces and transportation, a number of possibilities were identified. These included: synergies for waste water reuse from a car glass manufacturer into a printery, organic dust from agricultural seed production to produce briquettes at the district heating facility, construction and automotive industry exchange (Mirata & Emtairah, 2005).

The National Industrial Symbiosis Programme (NISP) started in 2005 as a national programme, and with government funding it was able to initiate regional industrial symbiosis projects across the UK. In designated locations, the programme launched seminars and workshops to facilitate avenues for information exchange between firms in diverse industry sectors and resource categories. The SYNERGie tool aided the mapping of resource flows and identification of potential matches. Between 2005 and 2013, 45 million tonnes of waste were diverted from landfill, CO_2 emission savings to the tune of 39 million tonnes accrued, saving 58 million tonnes of virgin raw materials and costs worth €1.21 billion across the UK (Domenech et al., 2019; Mirata, 2004; NISP, 2009, 2013). Specialised waste operators were key actors in NISP implementation and participant firms noted the activities of waste operators to be vital for achieving economies of scale (Paquin, Busch, & Tilleman, 2015; Zamorano, Grindlay, Molero, & Rodríguez, 2011).

Among the more successful facilitated EIP programs in Asia, was Korea's National Eco-Industrial Park Development Program, initiated in 2005 and formally supported by the government until 2016. Although, like China, the Korean government's involvement was paramount for national acceptance, the Korean EIP expansion was led by Regional EIP centres and supported by government financial and institutional mechanisms. While China's initial EIP development followed a decentralised and certification-based approach, Korea's Regional EIP centres enabled industry with process, design, consultation and capacity building (Park et al., 2019; Park et al., 2016).

2.7 Chapter conclusion

Since the early stages of industrial symbiosis research, 'ecological' and 'economical' goals have coalesced. Some of the early goals included: i) To conserve natural and financial resources; ii) To reduce production, material, energy, insurance and treatment costs and liabilities; iii) To improve operational efficiency, quality and population wellbeing; and iv) To identify a source of income through the sale of wastes (Côté & Hall, 1995). These goals have barely changed, and most evidence suggests that financial motivation is the driver for ecological transformation in business. While succinct in theory, the practical pursuit of ecological goals is convoluted. The opinions of Murphy and Baldwin (1959) which placed 'compatibility' between firms as central to the success of industrial parks, still hold true in the pursuit of industrial symbiosis networks. On one hand, firms' willingness to share information and by-products with external firms is paramount to the network's success; on the other, instances where eco-industrial parks invited firms based on their suitability to participate in by-product exchange, have been successful only in few instances, such as TEDA in China.

The review of varied industrial symbioses developments outlined spontaneous connections to create larger and deeper exchanges between firms, while also benefitting from central bodies like NISP in UK and eco-TEDA in China, which function as storehouses of collective learning and match-making between hitherto unrelated firms. Barring a few notable cases of operational symbiotic networks, evidence of implementation globally is weak. This gap is ascribed to unavailability of useable datasets or the paucity of industrial symbiosis nomenclature in business and political science disciplines. The urgency of expanding such approaches beyond environmental and engineering disciplines cannot be emphasised.

Most industrial symbiosis implementation detailed physical exchanges and material flows, less is known about co-ordination mechanisms and the creation of support structures to facilitate bottom-up action. Experience from diverse geographies and economic competencies reiterates spontaneous symbioses to yield high levels of sustainable development, and for such spontaneity, inter-firm collaboration is key. Channels of communication that nurture joint problem identification, definition, solution and implementation are vital to elicit bottom-up action. Support institutions in the form of local governments, advocacy groups, social and environmental organisations, research and think tanks are beneficial but effective only if the intra-firm and inter-firm networks can be established.

Moreover, firms operate within institutional structures beyond their immediate setting or influence. Larger industry standards and best practices are an example of external factors. There are knowledge gaps about the moderating and mediating effects of institutional structures within which firms operate. For example, good understanding of market dynamics for secondary materials, specialist labour and services; funding and insurance, fiscal and monetary incentives; legislative stimuli; socio-cultural factors could accelerate industrial symbioses pursuits. Yet, specific evidence to facilitate such pursuits is deficient. Advancing knowledge on new eco-industrial programmes in conjunction with older sites transiting to eco-industrial parks will be valuable to ascertain patterns of circular economy development amongst multi-actor symbiosis networks. These insights will also enable qualitative comparison of monetary flows, extending the scope of currently dominant ecological and environmental benefits.

Location and agglomeration systems are instrumental in transforming regional economies because of the co-ordination mechanisms that simultaneously help achieve *regional competitiveness* (Porter, 1998) and *environmental improvements* (Gibbs, 2000). 'Innovation' and 'collective learning' are found to enable these dual objectives. Formal and informal networks amongst actors foster innovation through intra-organisational and inter-organisational learning. Collaborative learning through the sharing of innovative solutions, technical and knowledge capabilities in individual actors, that spill over to the system and heighten regional innovative capacity and co-operative behaviours (Lundvall & Johnson, 1994; Mirata & Emtairah, 2005). Consequently, innovation capabilities of individual firms can translate into region-level progress; regional policies and sectoral roadmaps, while assisting localised solutions, can also contribute to national strategies for the circular economy.

CHAPTER 3. RESEARCH METHODOLOGY

3.0 Introduction

The literature review emphasised the growing body of knowledge on circular economy, underlining its cross-disciplinary links to industrial ecology, environmental economics and management. There are gaps in implementation evidence, especially from fast industrializing nations like India. Calls have been made for greater representation of developing economy idiosyncrasies to arrive at strategies for wider circular economy adoption. The agglomeration of industrial activities in industrial parks is not unfamiliar; however, circular economy principles applied within these settings can nurture lengthier and higher value resource loops, promoting the use of secondary materials and easing the burden on finite virgin resources.

Previously, park-wide material flow analyses produced quantifiable results on by-product flows, resource dependencies and potential exchanges. Bain, Shenoy, Ashton, and Chertow (2010) used mixed methods of Material Flow Accounting and Analysis (MFA) for 42 firms within one park, and structured interviews with managers, to report eleven self-organised exchanges for waste and by-products, most of which involved downstream recycling. While similar studies have revealed theoretical possibilities, few of the suggested exchanges have been implemented. To complement extant knowledge, this thesis adopted a qualitative approach to seek actual evidence of circular economic activity in Indian industry, and to translate empirical experiences to wider opportunities.

The paucity of practical examples from India is attributable largely to limited scholarly inquiry and the localised scale of industrial symbiosis trials. A myriad of factors influence the existence of industrial symbiosis relationships, including: the involvement of multiple actors, markets for secondary materials, fiscal and monetary incentives, ongoing monetary and physical resource flows. Furthermore, the circular economy extends beyond the confines of an industrial park, and can be manifested at different temporal and spatial scales. This thesis offers an exploratory investigation into the circular economy in India's manufacturing sector, through comparative assessment of nationwide trends and empirical evidence from industry participants.

A multi-stakeholder *ecosystem view* of the circular economy is presented through the theoretical lens of industrial ecology. This chapter outlines the methodological approaches and assumptions. The methodology followed noteworthy contributions by Ghisellini, Cialani, and Ulgiati (2016); Mathews and Tan (2011, 2016); Pinjing, Fan, Hua, and Liming (2013); Su, Heshmati, Geng, and

Yu (2013). These authors critically appraised key policies, national frameworks, and inter-disciplinary roots of circular economy concepts (Ghisellini et al., 2016; Pinjing et al., 2013; Su et al., 2013), and illustrated circular economy business models using specific case sites and measurement metrics (Mathews & Tan, 2011, 2016).

Owing to the cross-disciplinary nature of the study, a combination of established methods is used to seek holistic understanding of the circular economy landscape in India. Primary and secondary data on macro (nation) level, meso (industrial region/park) level and micro (firm) level were collected and analysed. Academic conference proceedings and participation in annual events like the Circular Economy Summit by Ellen MacArthur Foundation, United Nations Centre for Regional Development (UNCRD) Regional 3R Forums in Asia and the Pacific, as well as the Australasian Waste and Recycling Expo shaped the researcher's inquiry and research design.

3.1 Research motivation

Links between economic growth, environmental impact and the stage of development of a nation pervade empirical research and academic debate (Galeotti & Lanza, 1999; Grossman & Krueger, 1995; Holtz-Eakin & Selden, 1995). The literature defines decoupling as *the delinking of resource consumption (both quantity and intensity), economic advancement and environmental degradation*. India ranked as the seventh largest economy with 7% growth rate in 2018 (WB, 2018a, 2018b), and the country's future growth is considered to be intrinsically linked to its manufacturing sector, which is targeting a 25% share of GDP by 2025 (IBEF, 2019b). This study aims to investigate the direction of decoupling in India, and to compare progress with leading industrial hubs China, USA, Japan and Australia.

Conventional linear economy practices have resulted in alarming quantities of resource exploitation, waste accumulation, losses in embedded energy and material value. In contrast, circular economies further the purposeful design of regenerative business systems; whereby, closed-loop material, energy and water processes heighten reuse potential and minimise overall waste (EMF, 2013; Ghisellini et al., 2016; Mathews & Tan, 2011; Stahel, 2016; Webster, 2015; WEF, 2014). For India and similar fast-growth nations, the circular economy can offer resources security and long-term alternatives to virgin resource dependence.

Theoretical underpinnings of a circular economy, while nascent and evolving, are derived largely from the fields of industrial ecology and ecological economics. Popular scientific explorations are fixated on cases from North America, Europe, Japan and China Among developing regions, China was the first to adopt a nationwide circular economy plan through the setup of eco-industrial parks and multiple demonstration sites which commenced in early 2000 (Geng & Doberstein, 2008; Mathews & Tan, 2011; Yong, 2007). Empirical evidence about circular economic implementation in Indian industry and cases of industrial symbioses are limited. Previous examination in India revealed the potential for industry-driven eco-industrial park development; empirical evidence on extant resource exchanges (Bain et al., 2010; Unnikrishnan, Naik, & Deshmukh, 2004) and case studies (Erkman & Ramaswamy, 2000), with suggestions for future possible exchanges (Singhal & Kapur, 2002). In recent years, dynamics of eco-industrial development in India are limited in number and scope

The research gaps identified raise critical questions on the practicability of developing nations to pursue traditional material, energy, water and waste intensive strategies to sustain long-term growth. Instead, rigorous strategies to decouple economic development from environmental damage by expanding circular economy pursuits can offer international competitive advantages. Such strategies have the potential to circumvent "pollute-now, cleanup-later" actions to catapult the growth trajectory for developing economies (UNIDO, 2017a). As previously stated, India has not yet formalised a national circular economy agenda; still, ample evidence points to persistent efforts through a wide array of resource efficiency projects, acceleration of renewable energy production capacity, sector-specific targets and investment in waste infrastructure. This thesis argues that the ongoing and planned projects at various levels of the Indian economy exhibit strides in the greening of industrial activities in a slow but determined shift towards the circular economy. The following general research questions guide the inquiry, in the context of India's manufacturing sector.

What prospects does the circular economy hold in India's developmental plans? How does the Indian industrial sector compare in circular economy adoption vis-à-vis global counterparts? Is current policy an enabler or disabler for long-term circular economy attainment?

- The research aimed to assess India's decoupling strategies as a means of greening the industrial sector, with the following specific research objectives:
- To review theoretical perspectives and map inter-disciplinary conceptual links for circular economy, across diverse geopolitical and economic contexts.
- To collect, analyse and present empirical data on circular economy practices and stakeholder roles in Indian industry.

- To test literature findings in a novel context, and to examine hypotheses that link industrial symbiosis as a subset of circular economy.
- To add to existing knowledge on ISNs in terms of emergence characteristics, internal and external requisites, and capacity building.
- To consider prevalent ecological perspectives on the circular economy by combining economic and management dimensions, to deepen qualitative understanding in the field.

3.2 Research design

A multi-pronged research design was created to ascertain the circular economy progress at various levels. Macro nation-level performance was quantified using secondary data from reputable national and international statistics agencies. Industry implementation was examined using qualitative research methodologies and secondary data. Firm-level adoption of circular economy was studied at two spatial scales: industrial parks and individual firms. For the study of industrial parks, the theoretical lens of industrial symbiosis was applied and case studies formulated based on established methodologies. In-depth interviews with key stakeholders and field visits helped ascertain network characteristics in terms of emergence, internal and external requisites, and capacity building activities. Furthermore, circular economy applications in individual firms are reported using current conceptual frameworks and inter-disciplinary perspectives on the circular economy. The findings will be extrapolated with literature insights to identify gaps and opportunities for circular economy in India.

3.2.1 Macro-level data collection and analysis

Quantitative methodologies were adopted to study material performance indicators like domestic material consumption (DMC), material intensity (MI), IPAT identity, for India, in comparison with leading industrial hubs. Databases published by International Resource Panel (IRP), Organisation for Economic Co-operation and Development (OECD), India's National Institution for Transforming India (NITI) Aayog, and various United Nations (UN) agencies were mined. Timeseries data were used to compute macro nationwide trends, and to identify the direction of decoupling for India.

Material Flow Accounting and Analysis (MFA) is one of the core methodologies to study resource flows, both for national economy-wide assessment (Dittrich, Giljum, Lutter, & Polzin, 2012; IGEP, 2013; Mutha, Patel, & Premnath, 2006; Singh et al., 2012), and worldwide decoupling (Bringezu, Schütz, Steger, & Baudisch, 2004). To examine India's material use performance, economy-wide material flows were studied for the period 1970-2015. The following metrics were analysed: *Domestic Material Consumption* (DMC, the difference between Direct Material Inputs and exports), *Material Intensity* (MI, the ratio of DMC and GDP) and *Resource Efficiency* (inverse of MI, also referred to as Material Productivity). Direct Material Inputs (DMI, the sum of raw materials extracted and imports) and Domestic Material Consumption (DMC) are important metrics for the assessment of nationwide material flows (Eurostat, 2001; UN, 2016a, 2016b). DMC measured in tonnes per capita indicates average material consumption of the economy and is a useful indicator to assess impact of population growth on material use and consumption.

The IPAT identity formulated by Commoner (1972) and Ehrlich and Holdren (1972) was used to quantify environmental impact as a factor of three macro indices: population (P), affluence (A) and technology (T). Waggoner and Ausubel (2002) improvised the IPAT identity to extend its use for the study of dematerialisation progress in a country. Martinico-Perez, Fishman, Okuoka, and Tanikawa (2017) adopted the IPAT methodology to compute material impacts in the Philippines from 1985 to 2010. The IPAT identity is a valuable metric to identify the direction of resource use for economic growth and as a measure of the nation's environmental impact from material, energy and emissions.

To investigate material use impacts, IPAT for India was computed for the period 1970-2015, following the methodological approaches of Commoner (1972), Ehrlich and Holdren (1972) and Martinico-Perez et al. (2017). Metadata from the International Resource Panel's *Global Material Flows database* (IRP, 2018) and India's economic planning data were used to calculate India's material flows alongside other macro-economic indicators. Trend analysis of the IPAT identity is useful to study the degree of impact of individual factors over a longitudinal period.

Second, changes to India's energy mix were evaluated to assess macro shifts in principal energy sources. Specific focus was placed on India's renewable energy capabilities, in comparison to international counterparts, to ascertain the direction of India's green energy shift as an overarching indication of the circular economy. Time-series data from domestic and international agencies like India's Central Electricity Authority (CEA) and the International Energy Agency (IEA), were examined to quantify shifts in India's energy mix. Energy capacity and generation statistics were used to study longitudinal trends.

The overarching theme of the macro analyses was to evaluate key resource performance metrics for India, namely, materials and energy consumption. Together, these insights will enable thorough understanding of the nation-level drivers for greening India's industrialisation patterns. The established metrics are designed to present collective insights on various macro-economic trends which are closely linked to a nation's economic growth.

Some of the methodological challenges included incongruencies between national and international statistics, for data collection and reporting techniques, measurement and reporting. To address these gaps, complex databanks were used collectively in line with methodological assumptions and recommendations (Dittrich et al. 2012; Eurostat, 2001; Martinico-Perez et al. 2017; UN, 2016a, 2016b). News and reports by the World Economic Forum (WEF), OECD, World Bank, International Monetary Fund, were used to address discrepancies between data collection methodologies and reported results. For India, the Ministry of Statistics and Programme Implementation (MOSPI), Central Statistics Office (CSO), Ministry of Finance, Central Electricity Authority (CEA), Central Pollution Control Board (CPCB), and The Energy and Resources Institute (TERI) all publish rigorously tested and updated statistics for national and state-level indicators; these were valuable in computing longitudinal indicators.

3.2.2 Meso- and micro-level data collection and analysis

The manufacturing sector was chosen as the focus of analysis owing to its generally high resource dependence and intensive emissions impact; concomitantly, the sector's increasing share in the Indian economy made it the appropriate choice to present forward-looking prospects for circular economy in India. Previous research had demonstrated examples of ISNs, at the level of an industrial park or region, where case studies demonstrated inter-firm exchanges, material/energy/water flows and varying actor roles at different stages of the network's evolution (Chertow & Ehrenfeld, 2012; Mathews & Tan, 2011, 2016; Shi, Chertow, & Song, 2010; Yu, de Jong, & Dijkema, 2014). This research adopted case study methodology in order to analyse the phenomenon in detail and to enable critical analysis based on existing events (Yin, 2014). To obtain meso-level insights, case studies of industrial parks were generated using field visits, participant interviews and secondary data publications.

Additionally, interviews with firm managers and secondary data from news, reports and publications were analysed to assess product-innovations in circular economy, intra- and inter-firm circular exchanges. In order to review wide-ranging resource exchanges for materials, water, and energy across manufacturing industries, qualitative insights and quantitative data helped decipher the closure of material loops and institutional support systems. These results are graphically represented throughout the case study chapter and offer an introspective view of key developments. The next section details the industrial parks field study design which consisted of multi-stakeholder interviews, site visits and quantification of key metrics.

3.3 Field study design

Manufacturing industrial parks were shortlisted based on news reports and secondary information on the main manufacturing regions. Due to the researcher's familiarity with the chemical industry through past collaborations, manufacturing regions engaged in chemical and allied industries were narrowed down. Before arriving at the final shortlist, numerous interactions with government agencies and industry experts were beneficial. The preliminary exchange achieved dual goals – to seek reliable information on actual activities within regions, and to seek introductions with industrial park authorities as a preamble to formaliszing approval for the study. The field study plan received approval from Macquarie University Human Research Ethics Committee in October 2017. The research abided by the University's ethical code of conduct; the ethics protocol for this study is detailed in a later section.

3.3.1 Field study site selection

The preliminary screening process included intelligence gathering and secondary research of government and industry publications, past scholarly work and the investigator's own networks. *Core activity* (manufacturing of chemical or allied products), *operational status* and *expanse* were the main criteria used to select parks. A shortlist of field study locations was then prepared, which was further streamlined by reviewing individual park websites, key industrial activity, tenant firm profiles and major environmental/ resource efficiency projects.

The first site confirmed was Jawaharlal Nehru Pharma City (JNPC) in the southern city of Vizag. JNPC specialises in the manufacture of Active Pharmaceutical Ingredients and has 103 firms of various sizes; primarily, large and multinational firms operate here. Following preparatory talks and email communication, the field visit commenced in November 2017. In addition to visiting the park premises, shared services and multiple entities directly engaged in environmental management of the park, interviews were conducted with varied actors including: park management, representatives of the state pollution control board, environmental agencies, and firm managers.

Due to the lack of a central agency for managing industrial parks in India, involvement of multiple government departments and the active role of the private sector, access to key stakeholders was particularly challenging in the early stages of the study. The researcher relied heavily on the extended network developed at international conferences. Some of the earlier shortlisted parks could not be pursued due to lack of access, response, or interest from the component firms. A compelling research design and action plan were instrumental in seeking stakeholder endorsement. Physical presence for meetings and flexibility in daily schedules was vital to benefit from snowballing effects.

Following the field study at JNPC and external interviews with experts, introductions to two new industrial parks followed. The two parks, Naroda and Nandesari, are located on India's western border, in the state of Gujarat. Both, Naroda and Nandesari are mature industrial parks and home to mainly small and medium enterprises engaged in the manufacture of chemicals, dye and dye intermediates, pharmaceuticals, textiles, and food. Naroda has 400 chemical firms and Nandesari has 250 chemical firms. Both of these parks have been operational for over 50 years, in contrast to JNPC which only commenced operation in 2006. The maturity level of a park poses distinctive opportunities and challenges for circular economy adoption, these are considered in later chapters.

Within individual parks too, the backing of an influential member or department proved crucial to gain access to individual firms and network-wide bodies. Different actors and government agencies are active across different states and industrial regions within India. For example, in Gujarat, cleaner production activities in industrial parks are managed by two key state agencies: Gujarat Cleaner Product Centre and Gujarat Pollution Control Board. However, a third agency Gujarat Infrastructure Development Board dominates the initial phases of park establishment, permissions and land development. Local Municipal Corporations and industry associations are responsible for day-to-day waste and infrastructure management. Thus, a complicated web of roles, responsibilities and accountability unfolded through the study. Previous research has not delved into these composite relationships. Unintentionally, the three field study sites represent multifarious economic, social and policy contexts. They are also examples of young/planned (JNPC) versus saturated/spontaneous (Naroda, Nandesari) parks. These facets are explored in-depth in later chapters.

Interviews and field visits with the Andhra Pradesh Pollution Control Board, Gujarat Cleaner Product Centre, Central Ministry of Housing and Urban Affairs, TERI, GIZ, National

Productivity Council, as well as numerous industry and academic experts, yielded rich and invaluable insights for identifying India's path to greening. To expand the scope of analysis, three industry sectors were explored in the form of case studies – circular approaches in steel manufacturing, bio-products and co-processing in cement. In total, six in-depth case studies are presented in this thesis, to complement the quantitative analysis of national resource flows. The case studies are developed based on exhaustive discussions with stakeholders and the writer's personal observations during field visits.

3.3.2 Interview protocol

Initially, the plan was to conduct face-to-face semi-structured interviews with three main actors: *industrial park management; federal, state, local government agencies; and individual firms* operational within the industrial park. A detailed interview protocol was followed (Appendix 2). The objective was to gain thorough understanding of policies, industrial park setup and implementation experience, evidence of materials/energy/water exchanges, and circular economy plans. After the initial visits, a fourth actor emerged, *industry associations;* these, in the absence of centralised park management, have been fundamental to industrial symbiosis development. The roles of each of these actors, degree of involvement in industrial symbiosis activities and influence over other actors in the industrial symbiosis network are explicated in subsequent chapters. The participant pool included:

Industrial park management: Managers of shortlisted industrial parks were interviewed using semi-structured interviews (Appendix 3) to document their experience of inviting firms to locate within the park; challenges faced and incentives (financial/policy) offered; knowledge of ongoing inter- and intra-firm material/energy/water exchanges; environmental compliance and monitored indices; reporting of environmental indicators and details of workshops conducted to educate stakeholders of latest technology and initiatives to facilitate industrial symbiosis within co-located firms. Data on material flows was sought to ascertain network actors, linkages and economic/environmental/social results.

Federal, state, local government agencies: Interviews were conducted with multiple stakeholders within agencies directly involved in industrial infrastructure development, industrial park policy formulation and implementation, environmental management (Appendix 4). The objectives of these interactions were to discover policies under consideration and to develop links with state bodies and industrial park authorities for further data collection. Industrial policy and incentives have played a critical role in facilitating past cases of industrial symbiosis globally; hence, this was an important group. References for field study sites and databanks were also sought from these participants. The participant set for this group extended beyond government agencies to include allied agencies like: GIZ, an Indo-German entity, which regularly undertakes public-private partnership projects as well as awareness-building workshops for resource efficiency and industrial symbiosis; and The Energy and Resources Institute (TERI), an independent leading voice in India on policy and research for energy, environment, climate change, sustainability.

<u>Individual firms operational within the industrial park</u>: Based on interviews with park management, attempts were made to interview firm participants wherever feasible; especially, firms which had prior experience and/or interest to partake in symbiotic exchange (Appendix 5). Direct access to firm participants was constrained; hence, introductions from park management/government agencies added credibility and helped clarify the research scope. Access to data on firm's material flows, exchange partners and commercial information relating to by-products/exchanges was pressed upon – this information was valuable to identify exact exchanges, firm-level motivations and barriers, and to establish commercial viability and longevity of the exchange. In some cases, potential for future exchanges was identified.

<u>Industry associations</u>: In two of the parks (Naroda, Nandesari), the role of local industry associations in managing day-to-day activities, shared services, waste infrastructure, cleaner production and resource efficiency strategies was distinctive. Data on historical antecedents, park's overall functioning, maintenance and shared activities was sought, in addition to industrial symbiosis initiatives. This actor group added a fascinating dimension to the study, as the association leadership generally represented or owned individual firms, and acted as the main liaison with government agencies. The associations also functioned as the central information repository for a multitude of indicators, not included in statutory disclosures.

The following protocols were executed for participant recruitment:

<u>Participant roles and responsibilities</u>: Interviewees at managerial/ senior leadership positions were recruited with the objective of gathering market intelligence and partner access. Since environmental reporting is usually managed by a select few individuals (large firms would have a dedicated team), participants from these relevant departments were also targeted. Senior management helped direct the investigation to suitable team members. Efforts were made to recruit government representatives holding the ranks of Secretary/ Director (Federal) and Joint

Commissioner (State), in addition to team members responsible for industrial park projects and environmental management.

Age and gender: The basis of participant recruitment was the rank/ decision-making authority; hence, age and gender were not pertinent to the study.

Recruitment method: Appointments with nominated actor groups were invited via an introductory email, detailing the scope of the project and expected involvement from participants (Appendix 6). Based on the response/ wait of one week, follow-up emails or phone calls were made. An attempt was made to elaborate on project objectives, address participant queries and schedule a face-to-face interview. In cases where this was not possible, alternate channels like audio/Skype call or email interview were chosen. The supplemental endeavour from these preliminary discussions was to organise field visits and partner introductions for additional interviews. The investigator relied on snowballing effects to recruit additional participants.

Number of participants: The overarching aim of the project was to develop case studies of industrial park operations and ongoing resource exchanges, to be able to draw comparisons with international cases. Individuals have not been identified or used in the generation of case studies. The interviews were a means of seeking access to data on material flows and policy frameworks; thus, caution was maintained to recruit only appropriate members of each actor group. Emphasis was placed on quality, access to information and networks. In total, 51 participants were interviewed reflecting a mix of different participant groupings: *i) Industrial park management ii) Government iii) Firm in industrial park iv) Industry association v) Ecosystem participant vi) Subject matter expert.* For details of these participants see Appendix 7.

Conduct of interview: In line with the guidelines of the ethics committee, Participant Information and Consent Forms (PICF) were presented before the interview (Appendix 8) and participant doubts or questions clarified. After this, the interview process began. Interviews were conducted in English as it is the prevalent language medium for the participant set. Interviews were audio recorded, with photos and videos filmed for later analysis. Participants were assured that audio and video recordings were to be used only for analysis, decoding of interview transcripts, and later publication; however, where participants objected to audio recording, photos and videos, hand notes were made. Similarly, if use of a participant or firm name was objected to, anonymity was maintained.

Data management: Interview and field visit data are stored safely on the investigator's hard drive, with secure backups on desktop, laptop, pen drives and cloud. Interview files have remained in close circulation of the research team. Hard copies are stored in a locked cabinet on University premises.

Follow-up interviews: In most cases, follow-up interviews were conducted with participants to share findings, verify gaps and seek additional information. This stage was crucial for confirming the accuracy of resource loops identified in the case studies, and to triangulate information collected from diverse actors. In many instances, participants offered supplementary information and feedback to complete diagrammatic flows, and leads to improve data validity. The follow-up interviews were undertaken via phone, email, video calls and personal visits.

3.4 Ethical considerations

Adequate caution was maintained to ensure confidentiality of information collected, anonymity (if requested by participants), and declarations on the use of data. The Participant Information and Consent Form clarified research motivation, design and purpose; along with investigator details; data storage, reporting and publication channels (Appendix 8). Personal or sensitive information is anonymised, and care was taken to ensure participants were not under duress or perceived risks. Wherever requested, published results will be made available to participants.

No human or physical property was harmed during the research; no personal information or qualitative data related to beliefs, culture or motivation were collected. The investigator's prior work experience with Indian industry was beneficial in building familiarity and awareness of cultural nuances, sensitivities and privacy expectations. Concerns regarding the disclosure of firm-sensitive data were addressed and objections to the use or publication of data were noted. Lastly, the investigator declares no conflicts of interest and confirms that the research was undertaken purely for academic investigation and publication.

3.5 Data analysis methodology

Multiple data analysis tools and methodologies were used to arrive at a rounded understanding of circular economy in India. Established tools like MFA and economy-wide MFA were applied to aggregated datasets to compute nationwide longitudinal trends. Direct Material Inputs (DMI, the sum of raw materials extracted and imports) and Domestic Material Consumption (DMC, the difference between DMI and exports) are important metrics for nation-wide MFA (Eurostat, 2001). Statistics from various secondary sources were compiled and extrapolated to derive meaningful metrics for comparison and critical analysis. DMC for India was further disaggregated into key material sources: biomass (wood, food), fossil energy carriers, metal ores (ferrous, non-ferrous), and non-metallic minerals (construction minerals, industrial minerals). Together, these sources help determine the material performance of an economy (OECD, 2016).

Results of the field study and interview data were manually transcribed to design case studies for distinct phenomena, using primary and secondary sources. Implementation frameworks and policy mechanisms were founded on theoretical principles of industrial symbiosis and circular economy. Closed-loop materials, energy and water exchanges in chemical and pharmaceutical manufacturing settings are mapped to identify current and future flows, and also validate data not hitherto reported for the case sites. Stakeholder roles are categorised to identify key influencers and barriers. Institutional capacity building, in the context of industrial symbiosis network development, provided an analytical tool to ascertain the direction of circular economy advancement, enabling critical comparisons between the three field study sites.

Lastly, three industries, namely, steel manufacturing, bio-products and cement manufacturing, were examined to present circular economy applications at the level of individual firms. The cases of Essar Steel, Help Us Green, and Akash Dyes-Geocycle, are reviewed to identify ongoing exchanges, product-innovation and efficiency improvements. Together, the six case studies and quantitative data analyses were useful in mapping the direction of circular economy implementation in India. Such a holistic study has not yet been conducted in India; it’s timeliness and novelty is evident in recent policy declarations.

3.6 Chapter conclusion

The scholarly contribution of this work lies in the originality of data (case study sites) and combination of data sources (actor categories, secondary data) used to enhance understanding of circular economy in India. The absence of a centralised data repository, on industrial symbiosis exchanges, and disjointed mandates of federal and state agencies for industrial park development posed significant hurdles in the early stages. Although secondary data are valuable for macro analysis, detailed understanding of meso and micro drivers is useful to present qualitative insights.

Culturally, face-to-face interactions and personal connections play a significant role in seeking any sort of reliable information in India. The investigator’s local knowledge, biological roots and consciousness of social structures, authority and cultural norms were huge assets to forge relationships. While email and telephonic communication were helpful to build familiarity, physical field visits were essential to access and demystify network characteristics. One of the main challenges was access to stakeholders not bound by formal authority. The writer relied heavily on snowballing methods to connect the dots.

This chapter demonstrates gradual improvements to the research design based on intelligence gathered during the field visits. The inclusion of industry associations as an influential intermediary yielded rich links between formal and informal actors in the ecosystem. The research design evolved depending on the quality of data collection and participant access, which in many instances was restricted due to the lack of a formal structure for industrial symbiosis implementation in India. The six case studies emphasised the diversity of experience in industrial park implementation and circular economy prospects in Indian industry. Chapter 4 follows on with quantitative assessment of resource performance.

CHAPTER 4. QUANTITATIVE ASSESSMENT OF INDIA'S RESOURCES PERFORMANCE FOR MATERIALS AND ENERGY USE

4.0 Introduction

Traditional industrialisation patterns, indicative of linear economic growth, rely on augmented use of virgin materials, fossil fuels and mounting emissions (SERI & WU, 2010). In the wake of the manufacturing sector's prominence to India's economic development, the study of resource use impacts is essential. This chapter uses established quantitative methodologies to compare resource metrics for India with leading industrial hubs. For holistic assessment of resources performance, *materials and energy metrics* were studied using longitudinal trend analyses. Metrics like domestic material consumption (DMC), material intensity (MI), IPAT identity, in conjunction with shifts in India's energy mix and underlying drivers were assessed.

Databases published by national and international agencies such as the International Resource Panel (IRP), Organisation for Economic Co-operation and Development (OECD), India's National Institution for Transforming India (NITI) Aayog, various United Nations (UN) agencies, the International Energy Agency (IEA), and India's Central Electricity Authority (CEA), were mined. Timeseries data were used to compute macro nationwide trends, and to identify the direction of decoupling for India.

This chapter is divided into two parts: the first part examines material performance indicators like material consumption (DMC), material intensity (MI), IPAT identity and decoupling of material use with GDP growth. These metrics are analysed for India and comparative insights for international industrial hubs are presented. The second part of the chapter evaluates shifts in India's energy mix, observing key sources of energy capacity and electricity generation, as well as the renewable energy shifts driving green growth in the economy.

PART I: Material performance of the Indian economy

India's industrial sector comprises large, medium and small enterprises, with government incentives and digital programs channelled towards formalising small and medium enterprises (SMEs). A large proportion of SMEs are clustered within industrial parks and regions, which allows them to gain resource and knowledge advantages, for increased competitiveness. India contributed 5% to world manufacturing output in 2017, and ranked as the fifth largest manufacturing nation after China, the USA, Japan and Germany (UNCTAD, 2020). India's surge in manufacturing is likely to accelerate with a 25% contribution to GDP expected by 2025 (IBEF, 2019b). Complex interdependencies between economic growth, augmented resource use (land, materials, water, energy), mounting waste and emissions, present dichotomous challenges for the manufacturing sector. These challenges merit thorough examination of the nation's material use trends, to identify enablers and impediments for India's green industrial shift.

The most recent evaluation of India's resource consumption and efficiency trends was presented Shah, Dong, and Park (2020) who compared the trade, material flows and resource efficiency indicators for Bangladesh, India and Pakistan over four decades from 1978 to 2017. The analyses showed that India's reliance on material imports was rising as a result of increased domestic demand, shifting the nation's status from a resource-neutral to a resource-deficient country. Although India's domestic economy accelerated in recent decades, the authors underscored the importance of trade policy incentives and technological innovation to achieve dematerialisation from economic growth (Shah et al., 2020).

This section compares India's materials performance with leading industrial hubs like Australia, China, Europe, India, Japan, and the USA. Timeseries data published by the International Resource Panel (IRP), Organisation for Economic Co-operation and Development (OECD), India's National Institution for Transforming India (NITI) Aayog, and various United Nations (UN) agencies, are used to ascertain India's decoupling progress.

4.1 India's material use trends

Material Flow Accounting and Analysis (MFA) is one of the core methodologies to study resource flows, both for economy-wide assessment (M. Dittrich, Giljum, Lutter, & Polzin, 2012; IGEP, 2013; Mutha, Patel, & Premnath, 2006; Singh et al., 2012), and worldwide decoupling (Bringezu, Schütz, Steger, & Baudisch, 2004). To examine India's material use performance, economy-wide material flows were studied for the period 1970-2015. The following metrics were analysed: *Domestic Material Consumption* (DMC, the difference between Direct Material Inputs and exports), *Material Intensity* (MI, the ratio of DMC and GDP) and *Resource Efficiency* (the inverse of MI, also referred to as Material Productivity). Direct Material Inputs (DMI, the sum of raw materials extracted and imports) and Domestic Material Consumption (DMC) are important metrics for the assessment of nationwide material flows (Eurostat, 2001; UN, 2016a, 2016b).

Domestic material consumption (DMC) provides an aggregate estimate of a nation's material use; longitudinal analysis is beneficial to ascertain trends and sources of consumption. India jumped to second place in 2015, superseding the USA in aggregate material demand, and a 81% increase since the year 2000 (IRP, 2018). The rise in India's material consumption can be ascribed to increased consumer spending, rising affluence, expanding housing, infrastructure and transport sectors, as well as growing domestic manufacturing and exports. China's total material consumption (DMC) was the highest among 168 countries, with the rate of increase levelling off to around 4% in the last few years (IRP, 2018).

Deeper review of India's material use sources explains the upsurge in biomass, fossil fuels, metal ores and non-metallic minerals (Figure 12). Together, these sources form the material basis of an economy (OECD, 2016). Typical patterns of fast-industrialising economies are emergent, with increases in fossil fuels (74%) and non-metallic minerals (66%) over the decade 2007-17 (Figure 12). Construction, industry and agriculture were dominant sectors for non-metallic mineral use in India, bolstered by ongoing investments in infrastructure building, residential and commercial development, and expanding manufacturing output. While the aggregate DMC for India showed an upswing, its per capita material consumption is still way below global per capita demand. In 2015, India's DMC per capita was 5.34 tonnes, lagging Australia (38.38 tonnes), China (23.65 tonnes), and the USA (21.14 tonnes) (Table 4).

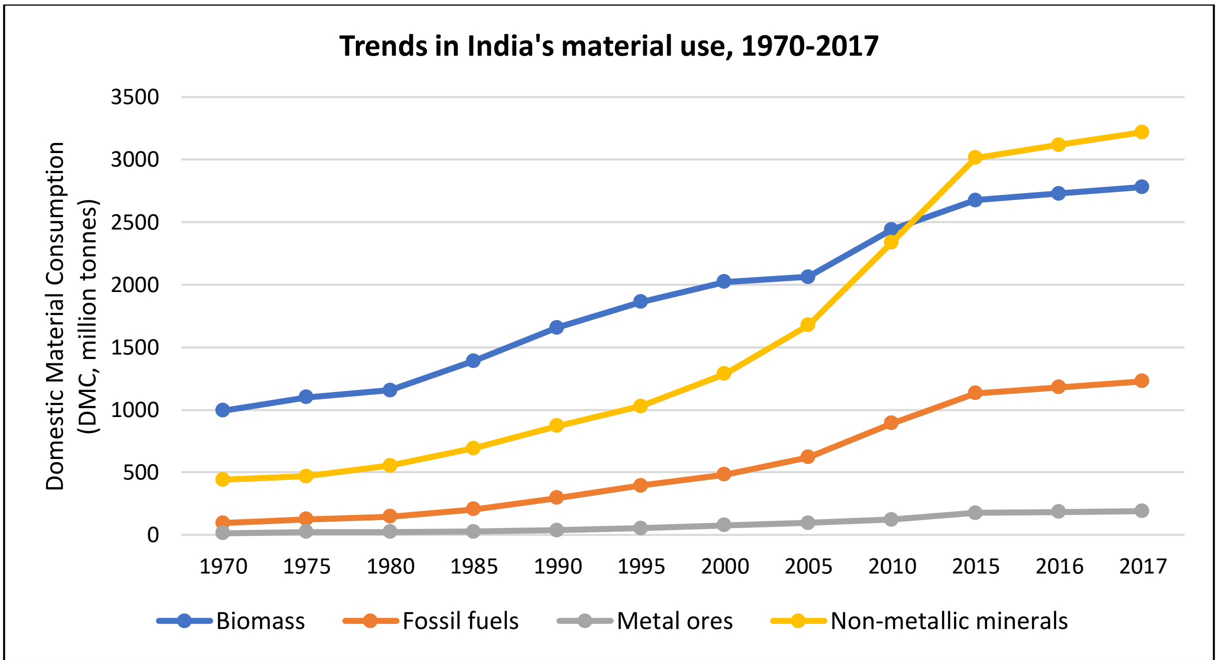


Figure 12: Trends in India's material use, 1970-2017

Source: Author, based on Global Material Flows database (IRP, 2018).

Table 4: Domestic Material Consumption trends for top industrial regions

Country	DMC per capita in 2015	CAGR 25 years (1990-2015)
Australia	38.38	-0.07%
China	23.65	5.92%
United States of America	21.14	-1.01%
Europe	13.84	-0.05%
Japan	9.38	-1.37%
India	5.34	1.96%

Source: Author, based on Dittrich (2014); IRP (2018); OECD (2016)

4.2 Comparative assessment of global material use trends

4.2.1 Per capita material consumption

DMC measured in tonnes per capita indicates average material consumption of the economy; it is a useful indicator to assess impact of population growth on material use and consumption. This section compares changes in material use for 6 leading industrial regions. Figures 13 and 14 compare per capita material consumption for the periods 1970-2015 and 1990-2015, respectively. Continual rise in DMC was witnessed in Australia and the USA until 2004-05, after which a downward shift in material consumption began. China's DMC at 23.65 tonnes in 2015, surged over the period, no doubt owing to the manufacturing boom and infrastructure development. Material consumption in Europe has remained fairly steady, due to the region's diversity, stable economic profile and mature infrastructure. Concomitant with other developed economy trends, Japan's DMC too declined over the analysis period; yet, was almost double of India's DMC in 2015 (Table 4) (Figure 13-14).

Unsurprisingly, material use increased over the decades since 1970, led by India and China. Between 1990-2015, material consumption rose considerably for both India and China, in contrast to the other developed regions, which witnessed declining growth in DMC (Table 4) (Figure 13). The year 1990 was significant to India's industrialisation history, marked by economic liberalisation and participation in international trade markets. Although compounded annual growth rate (CAGR) for India was less than 2% and it had a significantly lower per capita material consumption by 2015, India's DMC rose exponentially by 42% between 2005-2015 (IRP, 2018). The surge in India is an inevitable consequence of intensive industrialisation and infrastructure development; similar patterns were witnessed in China, where DMC grew at almost 6% annually (Table 4).

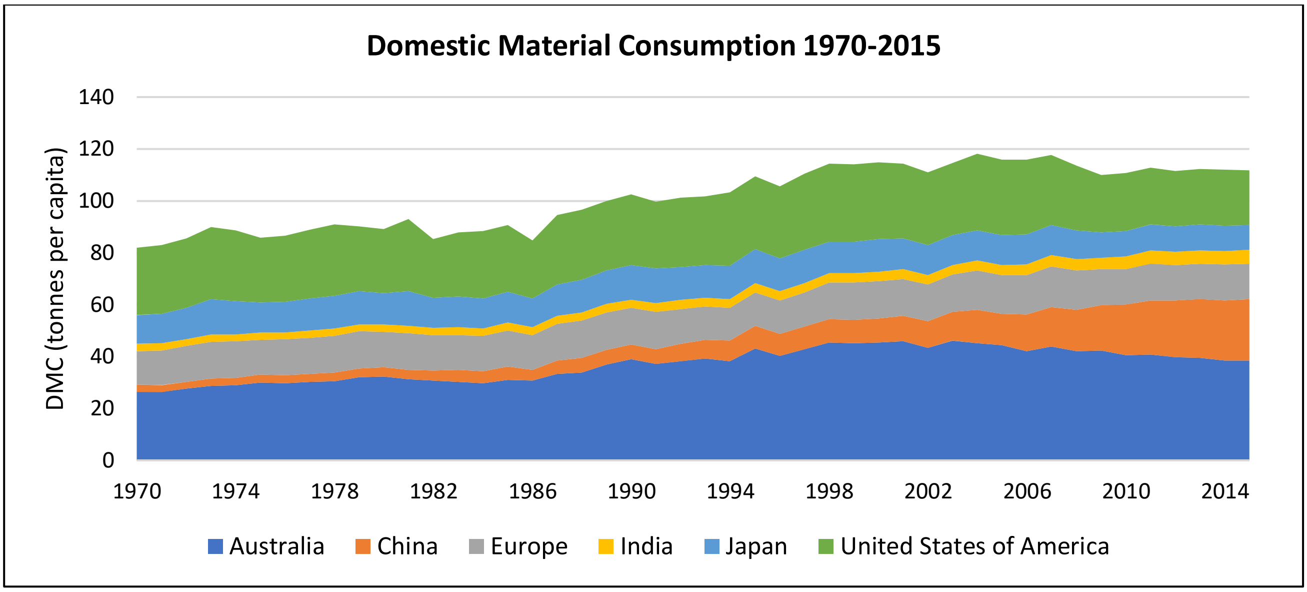


Figure 13: Total Material use for 6 leading industrial regions 1970-2015

Source: Author, based on Global Material Flows database (IRP, 2018)

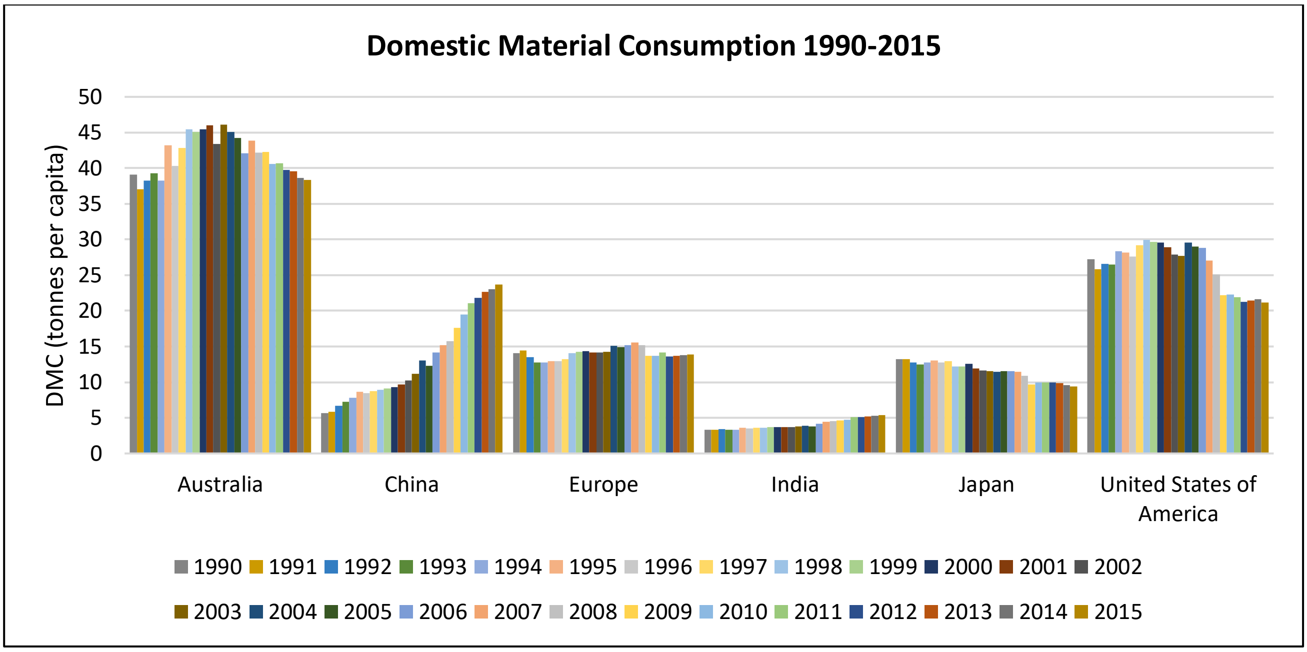


Figure 14: Annual material use for leading industrial regions during the period 1990-2015

Source: Author, based on Global Material Flows database (IRP, 2018)

Note

The shortlist of regions is based top 5 manufacturing nations in 2017 (China, USA, Japan, Germany, India) (UNCTAD, 2020). Additionally, Europe and Australia were included, to reflect major global economies. Germany was excluded from individual analysis, as it is included in the data for Europe.

4.2.2 Material intensity

Material Intensity (MI) is an indicator of the level of efficiency of an economy and signals resources required to produce a single unit of GDP. A decline in MI indicates increase in resource use efficiency and vice versa; MI is calculated as the *ratio of DMC to GDP.* A declining trend in MI generally implies relative decoupling of the economy (Martinico-Perez, Fishman, Okuoka, & Tanikawa, 2017; Talwar, 2016). In contrast to DMC, MI is a relative figure, which measures material consumption as a factor of GDP growth and is useful to determine the direction of decoupling (Eurostat, 2001; GMF, 2018; UN, 2016a, 2016b). Together, DMC and MI facilitate longitudinal trend analyses of the material performance of an economy, in association with changes in macro variables like population and economic growth (UN, 2016b).

Table 5: Material intensity trends for top industrial regions

Country	Material intensity in 2015	CAGR 25 years (1990-2015)
Australia	0.84	-1.84%
China	5.12	-2.99%
Europe	0.44	-1.36%
India	3.78	-2.77%
Japan	0.21	-2.19%
United States of America	0.41	-2.45%

Source: Author, based on Global Material Flows database (IRP, 2018)

MI being a relative figure and since GDP is dynamic, comparisons for MI must be made over a longitudinal period, and not viewed statically for a single year. Table 5 exhibits MI for leading industrial regions in 2015; between 1990-2015, China and India witnessed the highest declines in MI at 2.99% and 2.77% CAGR, respectively, followed by the USA at 2.45% CAGR (Table 5). Figures 15 and 16 trace changes in MI for these regions over 1970-2015 and 1990-2015, respectively. A decline in MI is considered positive, indicating improved resource use efficiency. While this is generally true, the sharp declines in MI for India and China can be ascribed primarily to rising GDP. The material use efficiency for India and China has not improved in conjunction with the heightened material consumption (DMC). Nonetheless, a relative decoupling of the economy is possible and this is examined in more depth in a later section. The next section examines the influences of population, affluence and technology through India's IPAT identity.

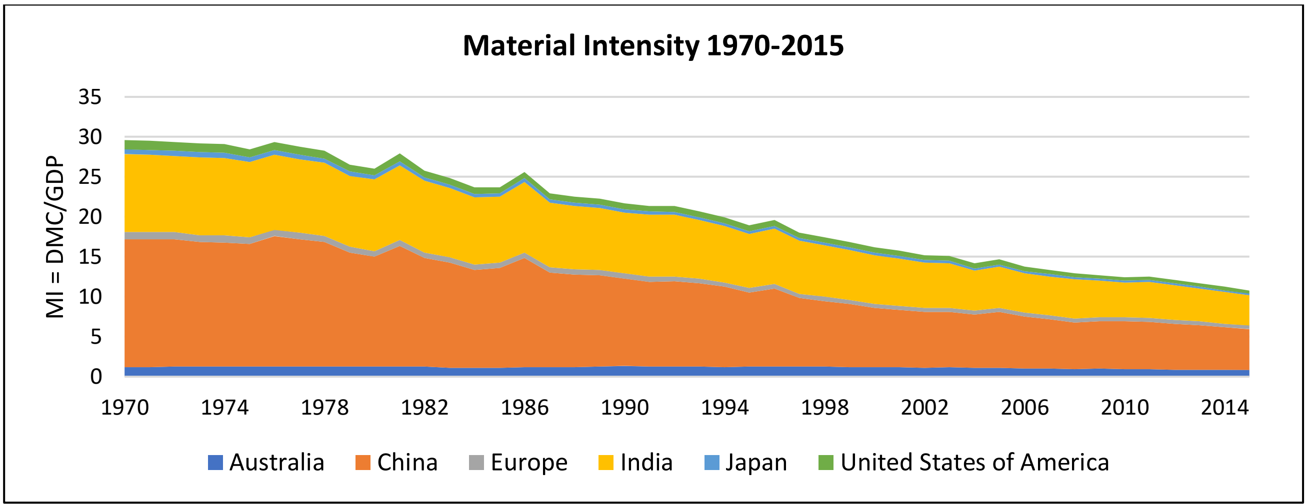


Figure 15: Material intensity for leading industrial regions 1970-2015

Source: Author, based on Global Material Flows database (IRP, 2018)

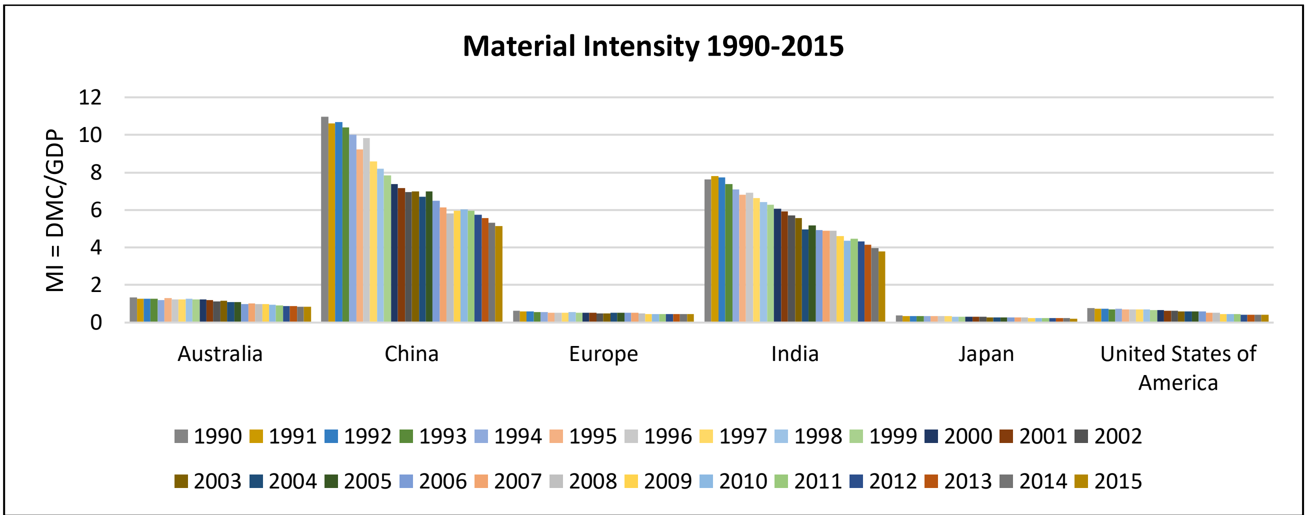


Figure 16: Annual material intensity for leading industrial regions 1990-2015

Source: Author, based on Global Material Flows database (IRP, 2018)

Note

The shortlist of regions is based top 5 manufacturing nations in 2017 (China, USA, Japan, Germany, India) (UNCTAD, 2020). Additionally, Europe and Australia were included, to reflect major global economies. Germany was excluded from individual analysis, as it is included in the data for Europe.

4.3 India's IPAT identity

The IPAT identity formulated by Commoner (1972) and Ehrlich and Holdren (1972) quantified environmental impact as a factor of three macro indices; environmental impact (I) which is calculated by factoring in effects of population (P), affluence (A) and technology (T). PAT are influenced by various political, social, economic and technological developments. Waggoner and Ausubel (2002) improvised the IPAT identity to extend its use for the study of dematerialisation progress in a country. The suggested ImPACT identity incorporated consumption metrics by calculating the intensity of resource use as a versatile measure to assess different environmental influences (e.g. material use intensity, energy use intensity and emissions intensity).

The IPAT identity is a valuable metric to identify the direction of resource use for economic growth and as a measure of the nation's environmental impact from material, energy and emissions. Trend analysis of the IPAT identity is useful to study the degree of impact of individual factors over a longitudinal period. Martinico-Perez et al. (2017) adopted the IPAT methodology to compute material impacts in the Philippines from 1985 to 2010. Material flows recorded a shift from renewable materials, like biomass, in 1985 to non-renewable materials like construction minerals in 2010. IPAT analysis illustrated population growth and rising affluence as drivers for material consumption (Martinico-Perez et al., 2017).

Ehrlich and Holdren (1971) hypothesised that population control alone was insufficient as a policy measure, to address the challenges of resource consumption and environmental degradation. The authors emphasised that population growth had negative impacts on the physical, human and epidemiological environment, and that analogous solutions were needed to address population control strategies, alongside technological improvements, closed loop resource use, economic opportunity and growth (Ehrlich & Holdren, 1971).

To investigate material use impacts for India, IPAT for India is computed for the period 1970-2015. Metadata from the International Resource Panel's *Global Material Flows database* (IRP, 2018) and India's economic planning data were used to calculate India's material flows alongside other macro-economic indicators. Domestic Material Consumption (DMC, the difference between Direct Material Inputs and exports) is also used to denote the environmental impact (I) of all economic activity during a set period (Martinico-Perez et al., 2017). Population is calculated as *number of persons*; Affluence is defined as the *ratio of GDP and population persons (capita)*; Technology in the study of material use refers to Material Intensity (MI) as the *ratio of DMC and GDP*. These are important metrics for nation-wide material flow accounting and analysis (Eurostat, 2001; UN, 2016a, 2016b).

Figures 17-19 quantify population, affluence and technology changes respectively, alongside material consumption, for India during the period 1970-2015. The period covers the duration of India's five year plans, starting from the fourth plan in 1969 up until the last one, 2012-2017. Over the analysis period, population recorded consistent growth rate of ~2%. The median growth in domestic material consumption, i.e. environmental impact, was higher at 3%, in comparison to population growth (Figure 17). In 1972 and 1979, DMC recorded negative growth rates, but most of the plan periods witnessed a steady rise of 15%. This increase was expected, given the rise in economic activity and improved GDP growth rates, since liberalisation. Annually, 1981, 1988, 2006, 2007 and 2011 witnessed abnormally high growth rates (>7%); but, since the last plan period 2012-15, the increase has not exceeded 3.5%. This shows a significant drop in DMC after the average 5% increase in the previous decade. Simultaneously, GDP growth rates for India steadied at 6% over the entire period; since 2003-2015, median GDP grew at 8.3% (Appendix 9). Please refer Appendix 9 for detailed calculations on percentage growth rates.

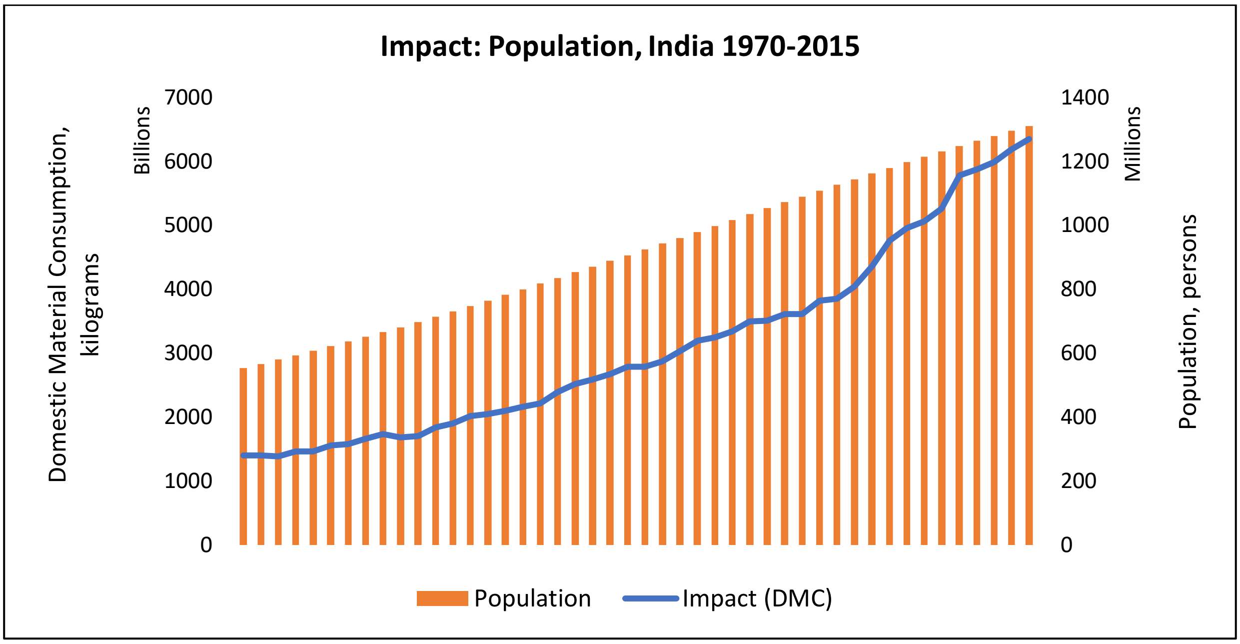


Figure 17: Domestic material consumption as a factor of *population*: India, 1970-2015

Source: Author, based on Global Material Flows database (IRP, 2018; NITI, 2020)

Affluence, the ratio of GDP to population, rose only slightly higher than DMC in percentage terms; average rise in affluence was 3.7% and DMC rose at 3.5% (Appendix 9). In absolute terms, affluence almost doubled in 1998 at $512, from $260 in 1970. Since 1995, post liberalisation of the Indian economy, affluence consistently grew at an average 5.4% (Figure 18) (GOI, 2013)[8]. The steady growth indicates that increasing affluence did not have an extraordinary effect on the country's resource consumption. This pattern can also be ascribed to

[8] Mint. (2019, August 14). A short history of Indian economy 1947-2019: Tryst with destiny & other stories, e-article. *Live Mint*. Retrieved from https://www.livemint.com/news/india/a-short-history-of-indian-economy-1947-2019-tryst-with-destiny-other-stories-1565801528109.html

the fact that India’s per capita resource consumption was one of the lowest among industrial nations at 5.26 tonnes per capita (Dittrich, 2014; IRP, 2018; OECD, 2016).

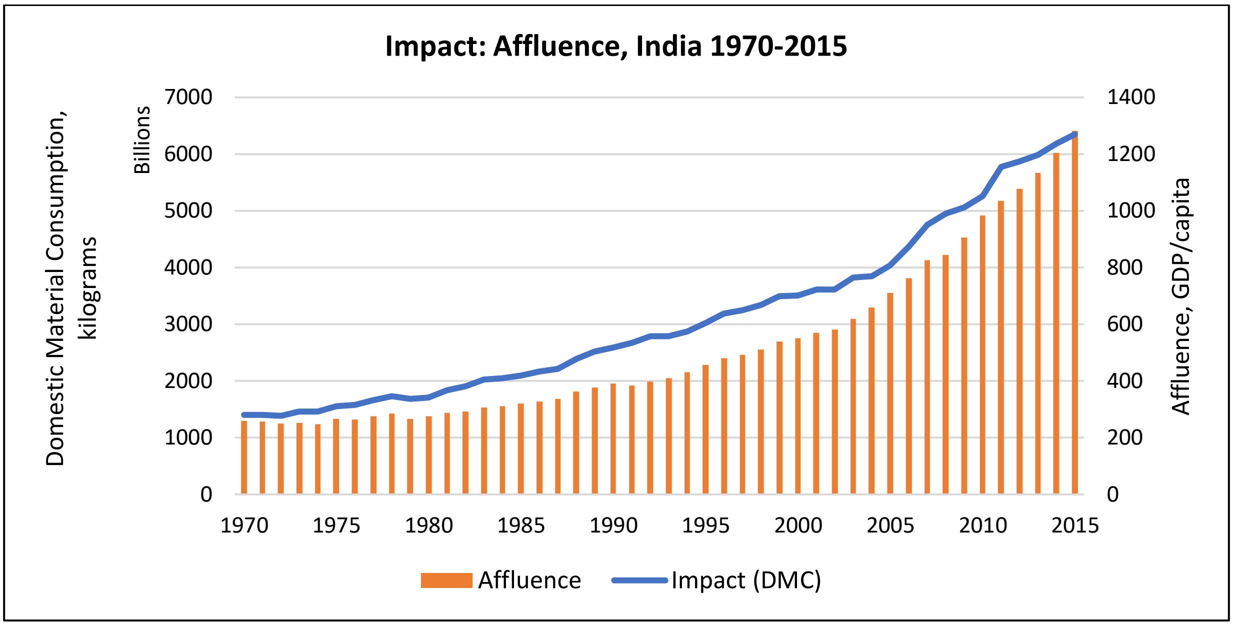


Figure 18: Domestic material consumption as a factor of *affluence*: India, 1970-2015

Source: Author, based on Global Material Flows database (IRP, 2018; NITI, 2020)

<u>Note for Figures 17 and 18</u>

Different scales used to measure DMC and Affluence do not permit direct comparison. The charts are plotted merely for visual representation of trends in India’s IPAT identity. Holistic analysis is possible only when changes in IPAT are viewed simultaneously, as explained via Figure 20.

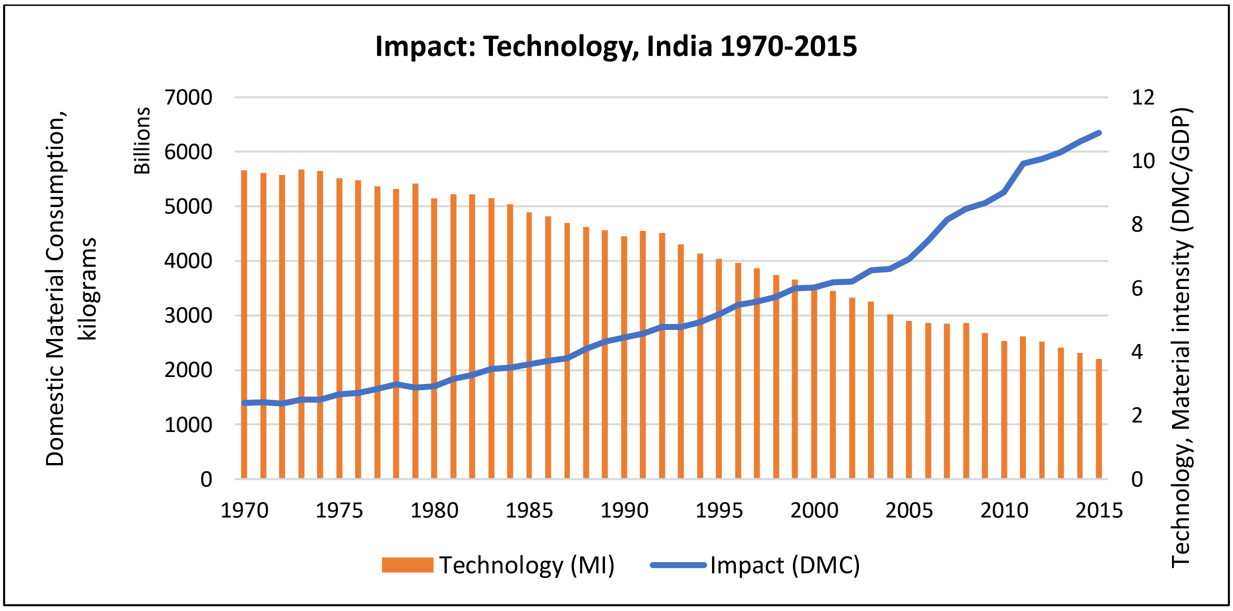
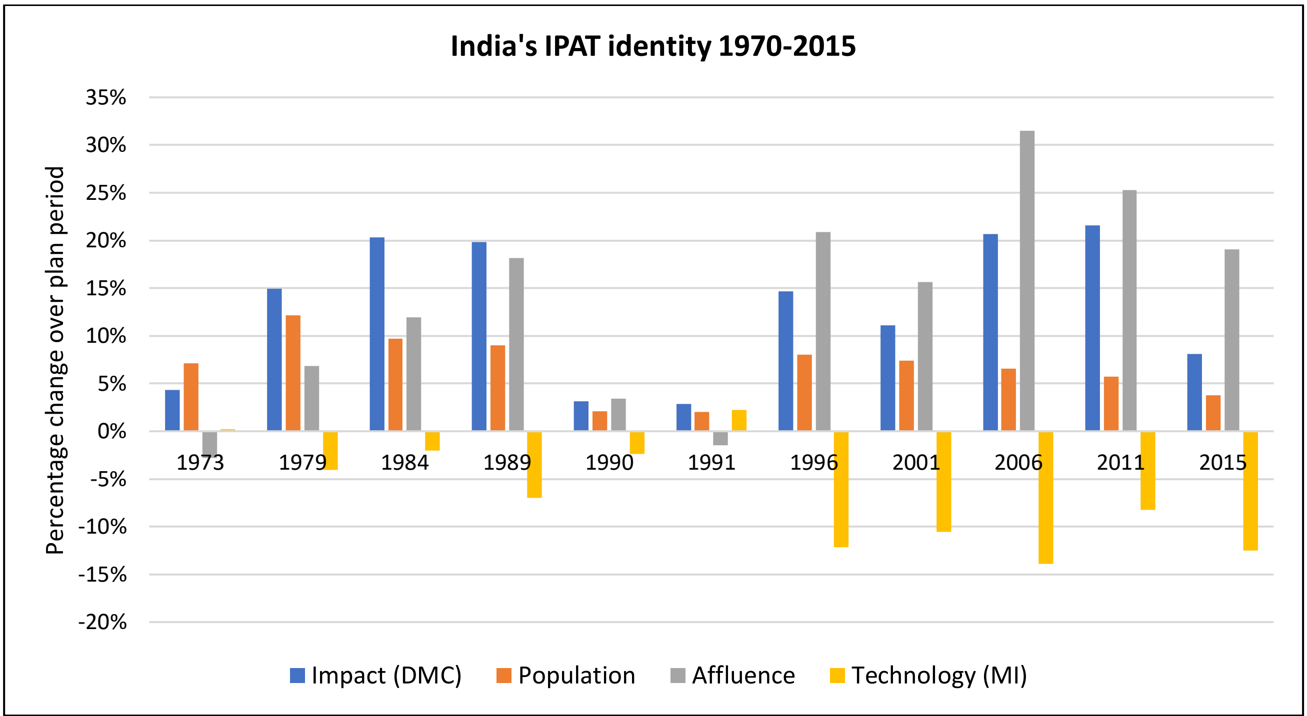


Figure 19: Domestic material consumption as a factor of *technology*: India, 1970-2015

Source: Author, based on Global Material Flows database (IRP, 2018; NITI, 2020)

India's material intensity, the ratio of DMC to GDP, is useful to assess *technology* effects on resource consumption. Although aggregate material consumption rose, MI witnessed a sharp decline over the analysis period (Figure 19). Over the last five plan periods (1992-2015), an average 12% decline in MI was recorded (Appendix 9). Decreasing MI is generally indicative of increasing material productivity or resource efficiency. While the trend is noteworthy and may suggest a relative decoupling of the Indian economy, rising GDP growth rates could be one of the key factors in driving down India's material use intensity.



Year	4th plan	5th plan	6th plan	7th plan	Annual plan	Annual plan	8th plan	9th plan	10th plan	11th plan	12th plan
	1973	1979	1984	1989	1990	1991	1996	2001	2006	2011	2015
Impact (DMC)	4%	15%	20%	20%	3%	3%	15%	11%	21%	22%	8%
Population	7%	12%	10%	9%	2%	2%	8%	7%	7%	6%	4%
Affluence	-3%	7%	12%	18%	3%	-1%	21%	16%	31%	25%	19%
Technology (MI)	0%	-4%	-2%	-7%	-2%	2%	-12%	-11%	-14%	-8%	-12%

Figure 20: India's IPAT identity, 1970-2015

Source: Author, based on Global Material Flows database (IRP, 2018; NITI, 2020)

Figure 20 offers a snapshot of India's IPAT identity over various plan periods. From 1951-2017, five year plans defined India's national economic agenda with sectoral plans and targets. Until the ninth plan, which commenced in 1997, expansion of public sector investment and agricultural self-sufficiency were central. The sixth plan (1980-85) marked economic liberalisation for India, with programs launched for improving industrial productivity and international trade. Free market reforms were formalised in the eighth plan (1992-97) and the era of *liberalisation, privatisation, globalisation* began with India becoming a member of the World Trade Organisation. The last five year plan completed in 2017, after that the Indian Planning Commission was disbanded to be replaced by the National Institution for Transforming India (NITI) Aayog. Instead of five year plans, India now follows shorter term goals in line with budgetary and economic targets (GOI, 2013).

Between the plan periods, population increases have consistently impacted material consumption; although, its influence is overtaken by rising affluence. Since 1980 (sixth plan), affluence has been the main driver of material consumption in India with annual growth rate of 4.48% (Figure 20) (Appendix 9). Owing to economic growth, changes in consumption patterns and resource intensive industries are evident in rising aggregate material use. Even for per capita material consumption, although still low when compared to Australia (38.38 tonnes), China (23.65 tonnes) and the USA (21.14 tonnes), India almost doubled its per capita material use from 2.83 tonnes in 1980 to 5.34 tonnes in 2015 (IRP, 2018). Negative growth in material intensity since 1992 (eighth plan) countered the influence of surging affluence on material consumption; where DMC increased at a lower rate in comparison to affluence. This trend has continued in recent years, implying continued efficiency gains and economic progress (Figure 20).

4.4 Country-wise decoupling trends

Based on the findings of the UNEP International Resource Panel (UNEP, 2016) and the researcher's own assessment of the Global Material Flows database (IRP, 2018), key decoupling facets for individual countries are examined next. In addition to the countries analysed in previous sections, select European nations which showed interesting patterns are discussed.

India recorded rising affluence since 1990, when population showed linear growth and GDP rose at CAGR of 6.5%. Aggregate DMC doubled in less than two decades, but lowered material intensity on account of rising GDP suggests relative decoupling. Caution is necessary when assessing decoupling of fast-growth economies like India and China, where GDP surges drive down material intensity levels, and may not denote an improvement in overall material performance. Shifts in material use categories explained in previous sections, signify macroeconomic transitions from primarily agrarian to manufacturing-dominant industrial activities in India. Overall material productivity (the ratio of GDP and DMC), showed consistent improvements owing to lowered MI (IRP, 2018; UNEP, 2016) (Figure 21).

4.4.1 *Decoupling trends 1970-2015: India, China*

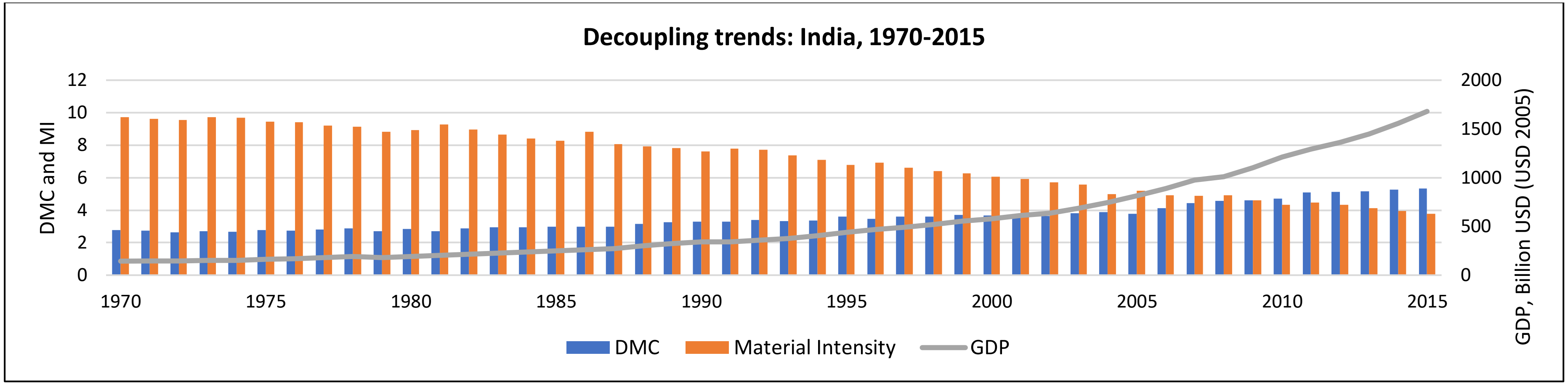


Figure 21: Decoupling trends: India, 1970-2015

Source: Author, based on Global Material Flows database (IRP, 2018)

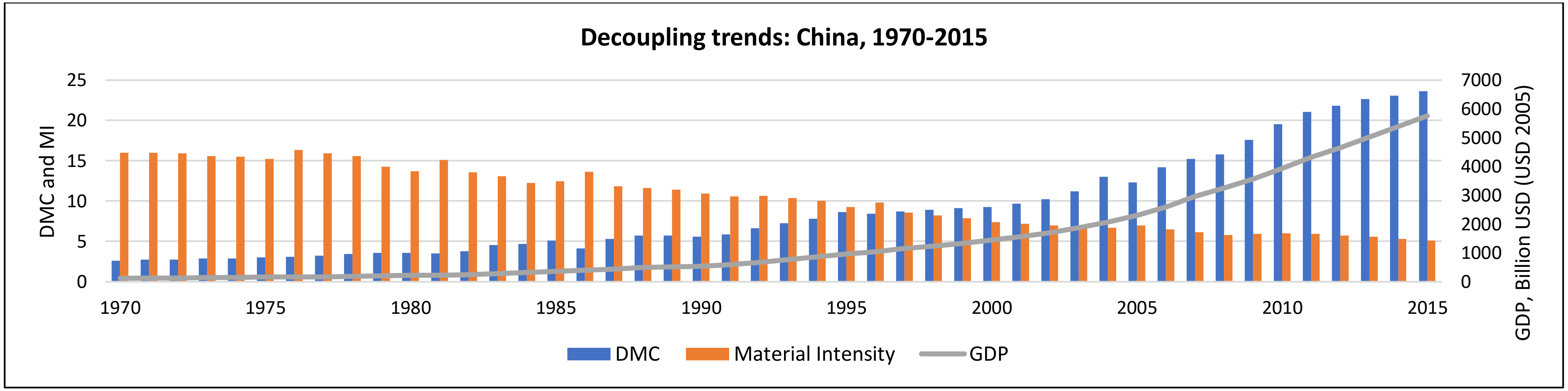


Figure 22: Decoupling trends: China, 1970-2015

Source: Author, based on Global Material Flows database (IRP, 2018)

4.4.2 Decoupling trends 1970-2015: Australia, Europe

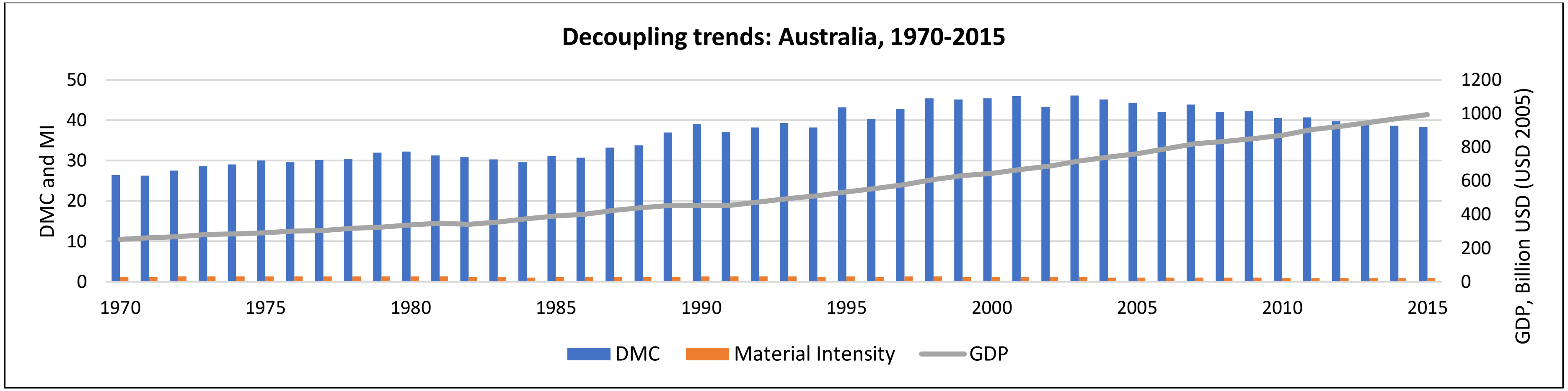


Figure 23: Decoupling trends: Australia, 1970-2015
Source: Author, based on Global Material Flows database (IRP, 2018)

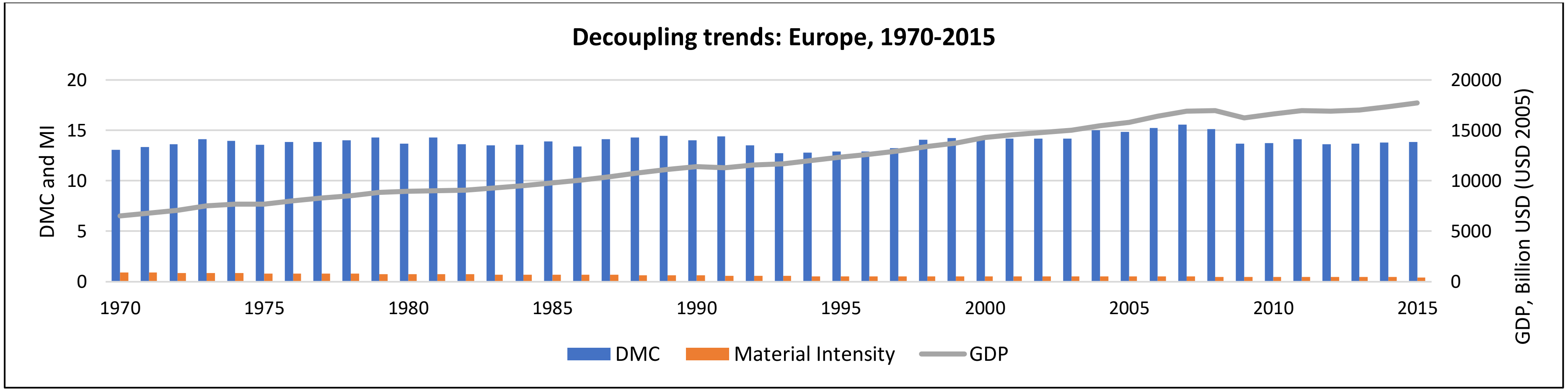


Figure 24: Decoupling trends: Europe, 1970-2015

Source: Author, based on Global Material Flows database (IRP, 2018)

4.4.3 *Decoupling trends 1970-2015: Japan, USA*

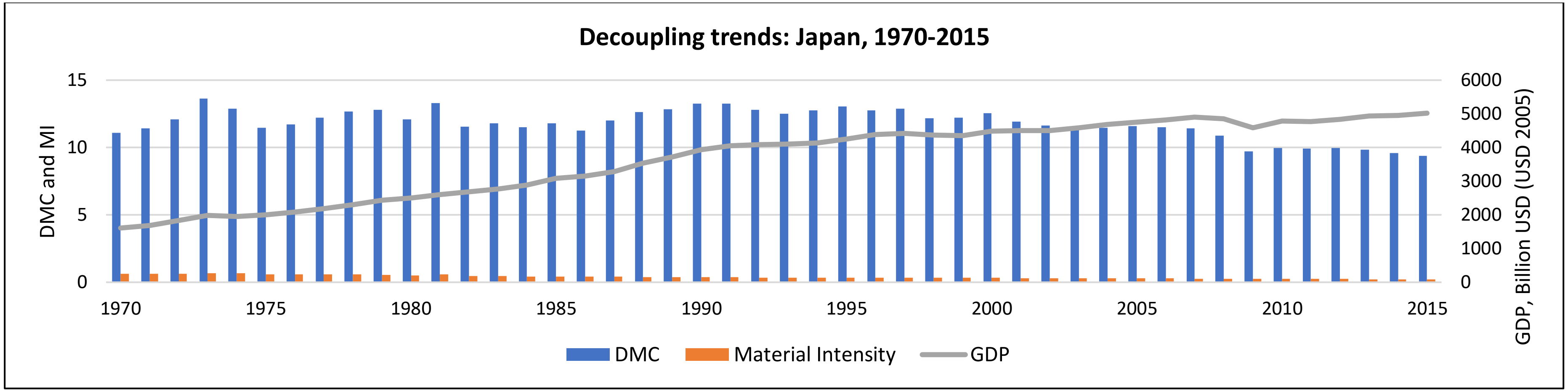


Figure 25: Decoupling trends: Japan, 1970-2015

Source: Author, based on Global Material Flows database (IRP, 2018)

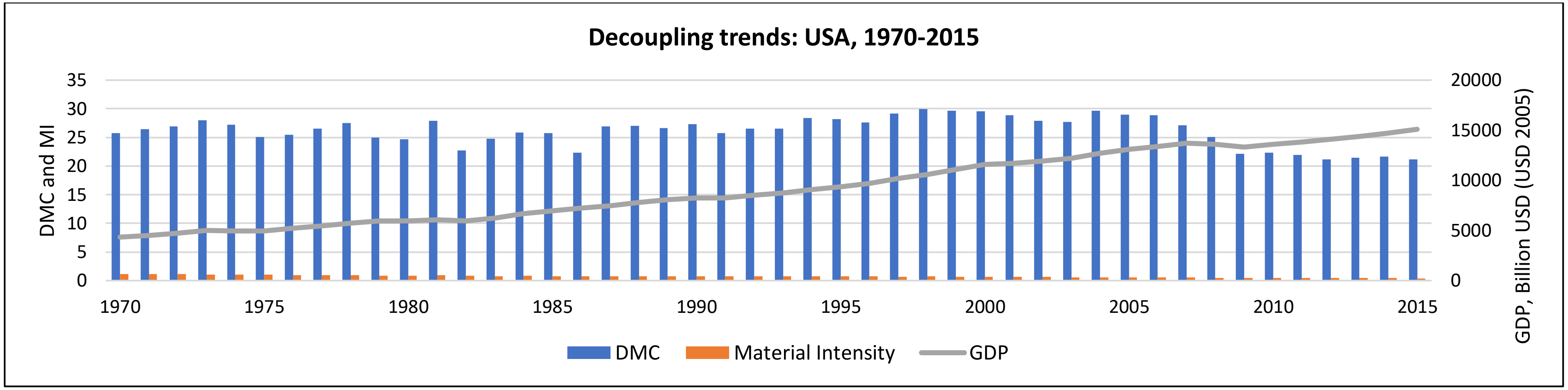


Figure 26: Decoupling trends: USA, 1970-2015

Source: Author, based on Global Material Flows database (IRP, 2018)

China's materials performance showed rapid increases in affluence (GDP >> population) as well as improved material productivity (GDP > DMC) between 1970-2010. Yet, these improvements were undermined by unprecedented surges in aggregate DMC, which increased 13 fold. High import dependencies for net imports of fossil fuels and metal ores marked the increases in material consumption for China (IRP, 2018; UNEP, 2016) (Figure 22). For *Australia*, GDP grew faster than population capita, reflecting a rise in affluence (GDP>population) between 1970 and 2010. Declining material productivity (DMC > GDP) ensued until 2000, due to higher growth rate of domestic material consumption in comparison to GDP growth. A rise in metal ore extraction and consumption contributed to the higher than usual DMC per capita for Australia (Figure 23).

France exhibited strong relative decoupling of GDP from DMC; where per capita DMC resumed 1970-levels, despite a twofold rise in affluence. *Germany* witnessed a rise in affluence (GDP > population) over the period, where GDP-levels doubled as population-levels stabilised. In effect, robust relative decoupling was attained as declining DMC accompanied GDP growth from the late 1990s. The mix of material use transformed, with fossil fuel extraction which was prominent at the start and had shrunken by almost two thirds in 2010, and biomass extraction doubled. In the *Russian Federation*, the impact of political transition from the USSR, on the economy's material use patterns is noteworthy. Rapid and vast declines in GDP and DMC from the early 1990s were accompanied by an unusual decline in population levels. DMC fell at a faster rate than GDP, signifying material productivity improvements (IRP, 2018; UNEP, 2016) (Figure 24).

Japan and the USA both recorded rises in affluence (GDP > population) over the analysis period. Japan's material productivity improvements between 1970-2010 were driven by rising affluence during the first half and decline in total DMC in the second half. However, 1990-2010 marked an interesting two decades of almost absolute decoupling for Japan, with marked GDP growth accompanied by contraction in DMC (Figure 25). The USA recorded a strong rise in affluence; although, material productivity rose more slowly due to increases in DMC, until it decelerated in 2005 with the Global Financial Crisis (IRP, 2018; UNEP, 2016) (Figure 26).

4.5 Environmental Kuznets Curve and dematerialisation

Shah and Park (2021) compared the material consumption and CO_2 emissions intensity for Pakistan with developed nations such as the USA, Japan and China, alongside a multi-country efficiency analysis between Pakistan and its major exporting partners. The longitudinal study measured efficiency improvements for the period 1971- 2015, adopting a novel approach of data envelopment analysis methodology on economy-wide material flow and carbon emission data. The findings showed that Pakistan's national-level efficiency was low, coupled with lowering material intensity and rising CO_2 intensity (Shah & Park, 2021), no doubt owing to the country's fast industrialising economy.

In their examination of the resource metabolism trends for Bangladesh, India and Pakistan, Shah, Dong, and Park (2020) conducted decomposition analysis using the logarithmic mean Divisia index (LMDI) method. This method is useful to identify drivers of resource utilisation and can report variations in absolute DMC values. The authors found that *rising economic affluence* was one of the main drivers for increases in DMC in Bangladesh and India, followed by *population growth*; yet, *technology enhancement* over the analysis period was able to partially offset DMC growth rates. In contrast, population growth rate was an important driver for DMC increases in Pakistan, accompanied with rising affluence; however, the role of technology in mitigating the impact of rising DMC was relatively small (Shah et al., 2020).

Shah et al. (2020) computed the Environmental Kuznets Curve (EKC) for Bangladesh, India and Pakistan, in order to evaluate the trends in dematerialisation. Using three economy-wide material flow indicators (domestic material consumption; domestic extraction; and physical trade balance), alongside socio-economic indicators such as GDP and population, the environmental impact (DMC/capita) was compared with a measure of economic development (GDP/capita). The authors found interesting patterns between economic indicators and dematerialisation, where the EKC inversion points for Japan, the USA and South Korea between 1978–2017 did not show clear correlation with a fixed income range (Shah et al., 2020).

The above finding is noteworthy, especially for developing countries such as India, which may thus be able to decouple environmental impact from economic growth at lower GDP levels. While China might be closer to achieving dematerialisation owing to its high DMC per capita, India is still far away from reaching the EKC inversion point. Yet, the results of the EKC hypotheses by Shah et al. (2020) confirm that developing countries should chart their independent development trajectories, instead of following the erstwhile resource-intensive industrialisation pathways of mature developed economies.

PART II: India's green energy transition

This section investigates India's energy needs, in terms of capacity development and generation. Changes to India's energy mix are evaluated over longitudinal periods to assess macro shifts in principal energy sources. Specific focus is on India's renewable energy capabilities, in comparison to international counterparts, to ascertain the direction of India's green energy shift as an overarching indication of the circular economy. Time-series data from domestic and international agencies like India's Central Electricity Authority (CEA) and the International Energy Agency (IEA), were used to quantify shifts in India's energy mix.

4.6 India's energy mix

As a fast-industrialising economy India's electricity needs are expected to triple by 2040 (from 4926 Terawatt-hour, TWh in 2012, to 15,280 TWh in 2040) (IBEF, 2019c). This demand will be outweighed by construction, manufacturing and transport industries. On the supply side, India's total energy capacity currently stands at 356 Giga Watt (GW), of which coal and thermal sources have a large but declining share at 64% (226.3 GW), followed by the rapidly expanding renewable energy sources (RES) at 22% (77.6 GW) and large hydro at 13% (45.4 GW) (Table 6). Together, RES which constitute solar and wind as the foremost energy sources, along with large hydro are labelled as WWS (Wind, Water, Solar), to imply collective sources of renewable energy (Talwar & Mathews, 2017). WWS had 35% share of India's energy capacity in 2019 (CEA, 2019a).

Table 6: Installed capacity based on source and ownership

Source	Installed capacity* (GW)	Ownership/sector	Installed capacity* GW)
Thermal	226.3	Centre	86.6
Hydro	45.4	State	105.1
RES	77.6	Private	164.4
Nuclear	6.8	**Total**	**356.1**
Total	**356.1**	* as on 31.03.2019	

Source: Author, based on CEA (2019a)

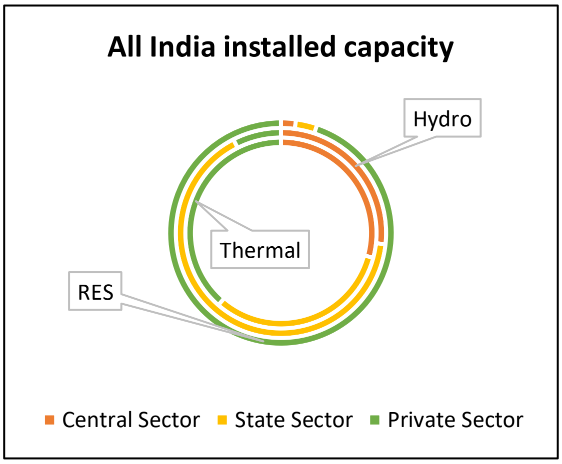


Figure 27: Sector-wise installed capacity

Source: Author, based on CEA (2019a)

Table 6 and Figure 27 illustrate the constituents of major energy sources in India, alongside their ownership between public and private sectors. The private sector is a notable player in both thermal energy and RES ownership. As of March 2019, 39% of thermal capacity belonged to the private sector; while government ownership was dominant, state facilities constituted 32% and the Centre (federal government) owned 29% (Figure 27). Private investment in India's energy sector is continually rising due to sectoral reforms, deregulation, competitive bidding tenders for upcoming projects, especially renewables. Although efforts are underway to make coal more attractive to private investors[9], progress has been slow.

Remarkably, 95% of RES capacity is under the aegis of private ownership (Figure 27). Fast-paced growth and innovative capacity are manifest in the sector's capabilities in charting India's green energy shift. In the case of large hydro, 66% is owned by respective state governments and the private sector is a tiny player with a 7% share (Figure 27). India's nuclear energy capacity had a modest 2% share in 2019 (Table 6). In terms of ownership, 100% of 6.8 GW nuclear capacity was owned by the central government (CEA, 2019a). Nuclear energy has been excluded from Figure 27 due to its minor share in India's overall energy capacity and unilateral ownership.

Before moving on to the next section which presents a critical appraisal of longitudinal shifts in India's energy supply and generation, the following charts synthesise India's energy landscape based on main sources. Figure 28 compares the mix for energy capacity and electricity generation, for the year 2017. Coal, which still has the highest share of capacity and generation, has witnessed a steady decline in capacity addition in the past three decades (Appendix 10). In fact, since 2017, more solar and wind capacity was commissioned, than coal[10] [11]. The nation's Central Electricity Authority (CEA) restricted new coal capacity addition until 2027[12].

For 2017, together WWS constituted 32% of capacity, comprising 18% RES and 14% hydro. RES which had a negligible (<1%) contribution to India's energy mix in 2000, had witnessed a

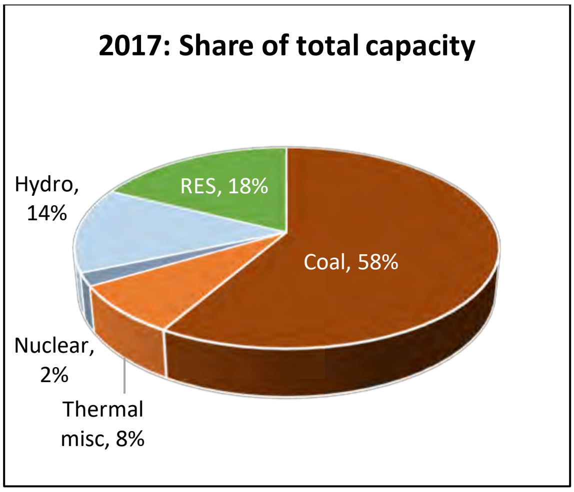
[9] Joshi, P. (2020, June 18). Coal reforms: Fuelling 'atmanirbharta' (self-dependence), e-article. *The Hindu Business Line*. Retrieved from https://www.thehindubusinessline.com/opinion/coal-reforms-fuelling-atmanirbharta/article31853457.ece

[10] Ramanathan, S. (2019, October 16). Renewable capacity additions exceed new coal in India. Blog. Retrieved from https://www.downtoearth.org.in/blog/energy/renewable-capacity-additions-exceed-new-coal-in-india-67269

[11] Sarkar, S. (2020, March 27). Coal power wanes in India despite new additions, e-article. *India Climate Dialogue*. Retrieved from https://indiaclimatedialogue.net/2020/03/27/coals-power-wanes-in-india-despite-new-additions/

[12] Jai, S. (2016, December 13). India does not need more coal-based capacity addition till 2022: Central Electricity Authority, e-article. *Business Standard*. Retrieved from https://www.business-standard.com/article/economy-policy/india-does-not-need-more-coal-based-capacity-addition-till-2022-central-electricity-authority-116121300042_1.html

1000-fold increase in capacity by 2017. The RES share of generation too, which was 8% in 2017, is expanding rapidly. In 2010, RES contributed 3.5% to India's electricity generation from utilities; this had more than doubled to 8% by 2017. Capacity addition and generation from large hydro is steadily declining, supplanted by surges in RES capacity and generation (Appendix 10) (Figure 28). In terms of cost-efficiency, India's renewables tariffs were 31% cheaper than coal-powered utilities (Buckley & Shah, 2020). India's levelised cost of electricity (LCOE), which reflects the upfront capital and development costs, equity and debt finance costs, operating and maintenance fees, was $38 per megawatt hour (MWh) in 2019, making it the lowest renewable energy market in the Asia Pacific[13].



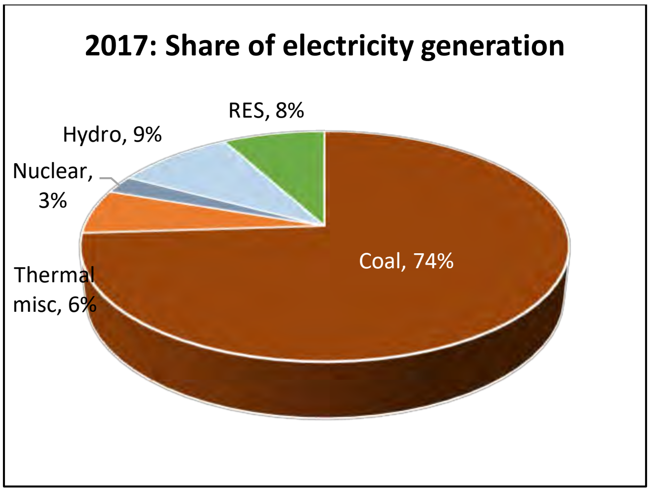


Figure 28: Energy capacity and generation mix: India, 2017

Source: Author, based on CEA (2018, 2019a); IEA (2020)

Note: As on 31st March 2018, total capacity was 344 Giga Watt; total generation was 1532.2 Terawatt-hour

4.7 Wind, Water, Solar: green shifts in India's energy mix

Figure 29 traces changes to capacity from thermal, RES and WWS in the last two decades. WWS had a cumulative capacity of 25 GW in 2000, which rose to 123 GW in 2019 (400% increase over two decades). Between 2005-2019, large hydro capacity remained stable at an average 3% annual increase. RES from solar and wind had the highest share of increase in absolute terms between 2000 and 2019 (CEA, 2019a). RES grew year-on-year at an average 25%, superseding thermal capacity expansion and creating the path for India's green energy shift (Figure 29). As per the Intended Nationally Determined Contribution (INDC), India aims to generate 175 gigawatts (GW) of energy from renewables by 2022, in addition to reducing its

[13] Samanta, K. (2019, July 29). India's renewable energy cost lowest in Asia Pacific: WoodMac, e-article. *Reuters*. Retrieved from https://www.reuters.com/article/us-india-renewables-woodmac/indias-renewable-energy-cost-lowest-in-asia-pacific-woodmac-idUSKCN1UO0L8

emissions intensity by 20–25% compared to 2005 levels (MoEFCC, 2015). The already sizeable renewable energy target was revised to 450 GW by 2030 during the United Nations Climate Week in September 2019 (Joshi & Jaiswal, 2019). Total RES capacity and generation shares are shown in Table 7 below.

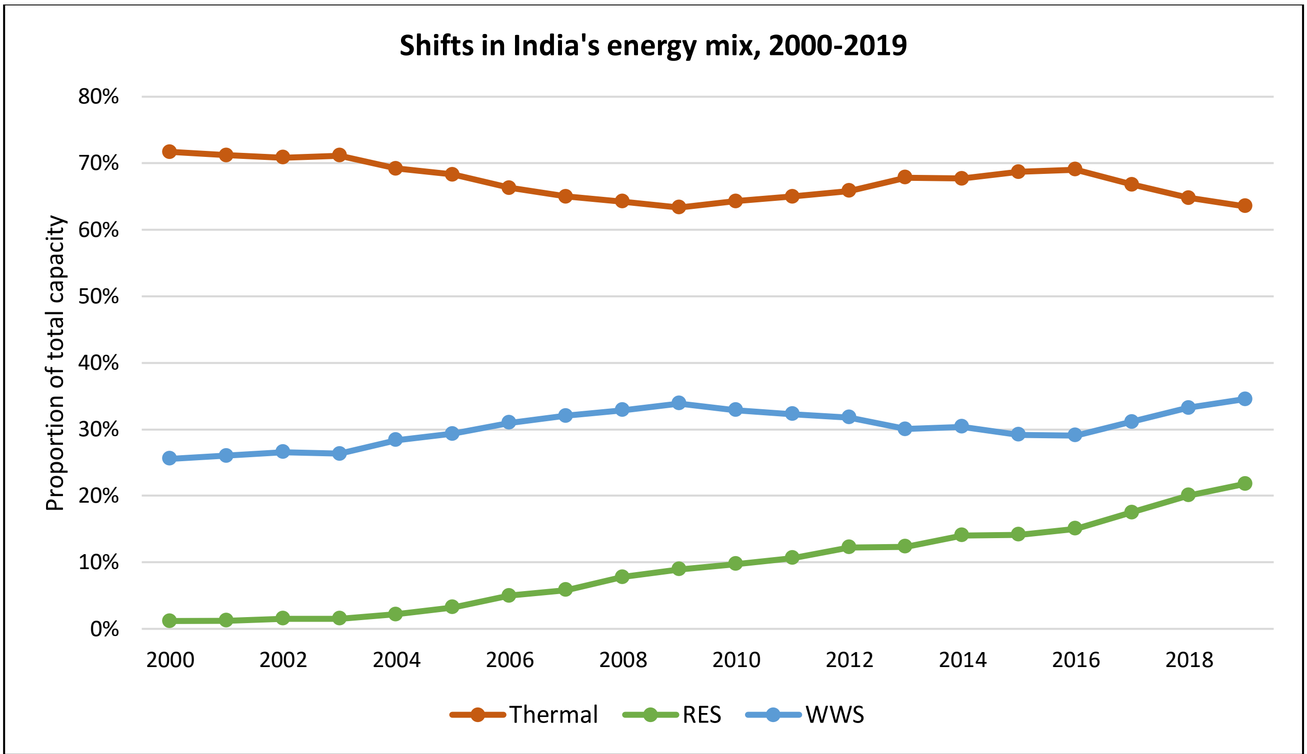


Figure 29: India's energy mix based on installed capacity

Source: Author, based on CEA (2019a)

Table 7: RES total capacity and generation

RES	**Installed capacity (GW)**	**Electricity generation (TWh)**
Wind	37.7	51.1
Solar	34.4	26.0
Biomass	9.9	43.8
Small hydro	4.7	(see notes)
Urban/industrial waste	0.1	1.7
Total	**86.8**	**122.5**

Source: CEA (2020); IEA (2020)

Notes

RES: Renewable Energy Sources; Small Hydro Project (≤ 25 MW); Urban & industrial waste - waste to energy
Units of measurement: Capacity (Giga Watt, GW); Generation (Terawatt-hour, TWh)
Electricity generation from hydro was 142 TWh, this included both large and small hydro. As disaggregated quantities were unavailable, small hydro has been excluded from RES breakdown for generation.
The data reflects *cumulative capacity as of Feb 2020* and *annual generation for 2017-18*.

Since 2007, there has been a striking shift in India's RES activities, owing to the singular direction by the National Action Plan for Climate Change (NAPCC). Three branches of the mission: National Solar Mission, National Mission for Enhanced Energy Efficiency in Industry, National Wind Mission, set the pace for India's green energy acceleration (NAPCC, 2007). Figure 30 tracks RES development between 2007-2018, the most significant decade for the ramp up in India's RES capabilities, both domestically and internationally. Solar witnessed the highest increase in capacity with CAGR of 121%; whereas, in absolute terms, wind energy led total RES at 35.6 GW in 2019, followed closely by solar photovoltaic (28.2 GW) (CEA, 2019b) (Figure 30).

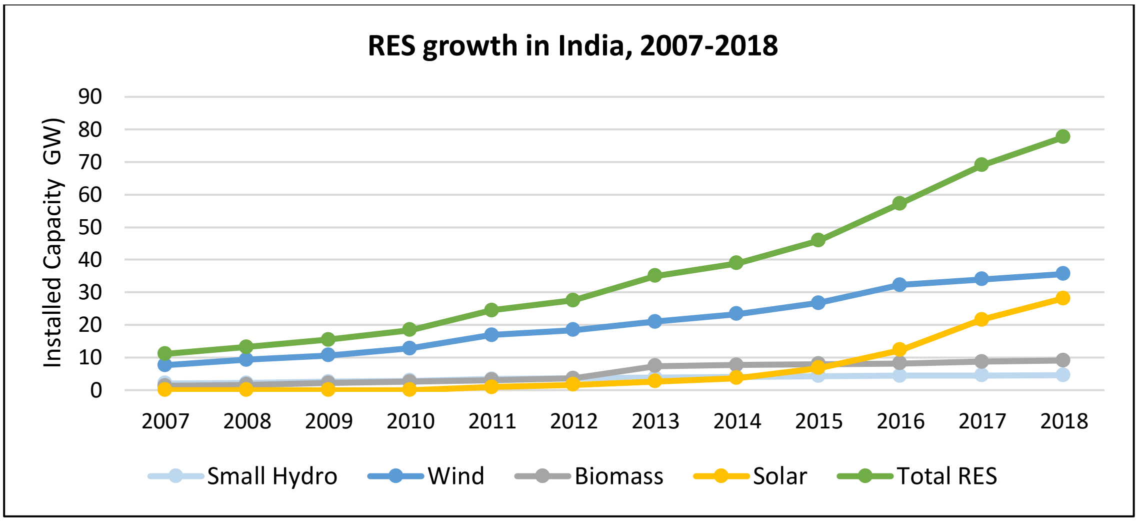


Figure 30: Source-wise RES growth in India, 2007-2018

Source: Author, based on CEA (2019b)

Hydro projects are classified based on captive power capacity; in India, hydro power plants of 25MW or below capacity are under the aegis of the Ministry of New and Renewable Energy (MNRE) and categorised as *small hydro* (micro: 100kW or below, mini: 101kW-2MW, small: 2-25MW) (MNRE, 2020). India's large hydro, which falls under the Ministry of Power (MoP), constitutes the fifth highest capacity globally[14], and has high potential as a renewable energy source. Current estimates are that only 26% of the hydropower potential has been exploited (MoP, 2020). Owing to reporting variations by the Government of India and its huge capacity share, this thesis discusses large hydro independently (as a major energy source) and under WWS calculations; whereas, small hydro which is included in MNRE statistics is represented

[14] ETEnergyWorld. (2020, 29 May). India overtakes Japan with fifth-largest hydropower capacity in the world, e-article. Retrieved from https://energy.economictimes.indiatimes.com/news/power/india-overtakes-japan-with-fifth-largest-hydropower-capacity-in-the-world/76095023#:~:text=New%20Delhi%3A%20India%20has%20overtaken,International%20Hydropower%20Association%20(IHA).

under RES as well as WWS. Thus, RES trends in Figure 30 relate only to small hydro projects as changes in large hydro capacity have been examined previously.

Between 2007 and 2018, small hydro, recorded a 125% increase with consistent 7% CAGR over the analysis period. There was significant expansion in wind power capacity, which also had the highest absolute share of RES at 35.6 GW (46% of total RES in 2018) (CEA, 2019b). Biomass power or biopower has remained steady since 2013 at 12% of total capacity. The most impressive growth was in solar power capacity, which was negligible in 2007 and noted exponential share of RES capacity since 2011. Over the period 2007-2018, solar recorded 121% CAGR and continues to remain a focal area for India's clean energy uptake. The impetus is evident in the steep rise for solar 2014 (Figure 30). The next figure (Figure 31) offers a snapshot of the leading industrial nations in terms of their renewable energy prowess.

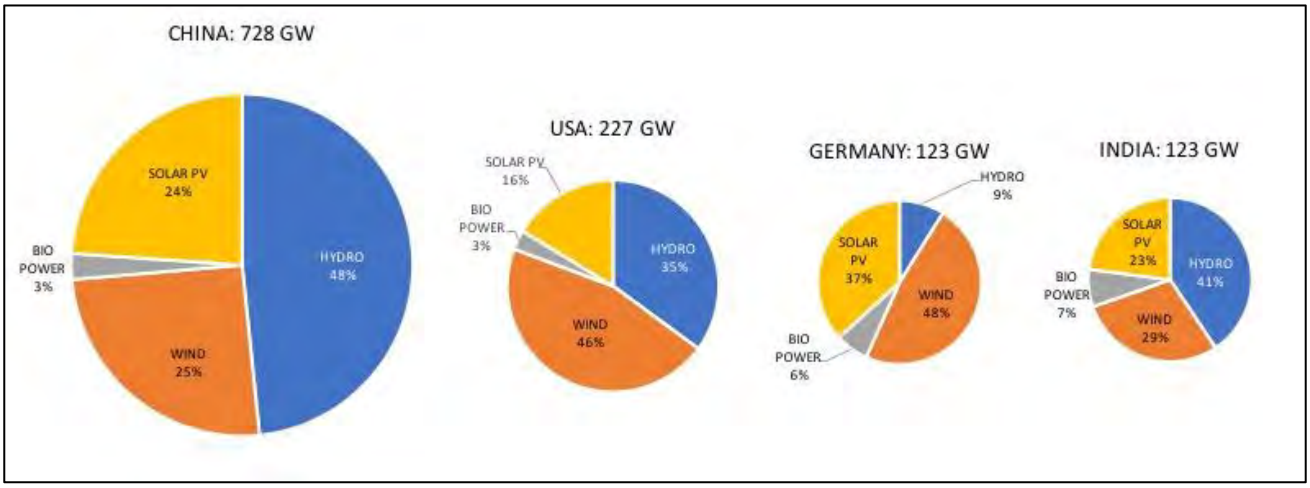


Figure 31: WWS capacity in 2018: China, USA, Germany, India

Source: Author, based on AGEE (2020); CEA (2019a, 2019b); IHA (2020); USEIA (2020); Yuanyuan (2019)

India witnessed early success towards 175 GW target of renewables capacity by 2022, under the Nationally Determined Commitments (NDC) for the Paris Agreement. Although only about halfway to its 175 GW mark (excluding large hydro), significant progress for WWS in India (123 GW) was visible when compared to Germany (123 GW) and USA (227 GW). China is far ahead with 728 GW clean power, including hydro (Figure 31). India's goal for 40% of non-fossil fuel installed power capacity is close to realisation: non-fossil fuel installed electricity capacity which includes large hydro, nuclear, and renewable energy, was at 38% at the end of 2019 (Joshi & Jaiswal, 2019).

4.8 India’s capacity and generation statistics

Total installed capacity in India stood at 356.1 GW in 2018. Between 2010 and 2018, India’s total energy capacity grew 9% year-on-year, indicative of its booming industrial and commercial activity to boost economic growth; especially, in energy-intensive sectors like manufacturing and construction. A closer look at the composition of India’s energy sources, traced since 1990 in Figure 32, points squarely at the green energy shift occurring at a rapid scale. Steady reduction in thermal capacity addition has been recorded since 2012, this has sharply declined since 2017 with modest 2% increases in the last 2 years. India’s thermal sources show a declining share of overall capacity, from 69% in 1990, it rose to 71% in 2000, and was down to 64% in 2018 (Figure 32). Coal had the largest share of thermal energy, and contributed 55% (197 GW) of India’s overall capacity in 2018 (CEA, 2018).

RES gathered momentum only since 2007, with key trends outlined previously. India had 86.8 GW of renewable energy capacity as of February 2020, which included 34.4 GW from solar and 37.7 GW from wind power (CEA, 2020). Among WWS, India’s large hydro capacity doubled between 1998-2018, and was 45.4 GW in 2018. Since 2010, the rate of large hydro capacity expansion has been falling at an average 2% annually. Nonetheless, large hydro still comprises 13% of India’s installed capacity (CEA, 2019a). India’s nuclear capacity has stood at 6.8 GW since 2016, prior to this, nuclear capacity had consistently increased since 2009. Between 2000 and 2016, nuclear capacity rose by 137% (Figure 32).

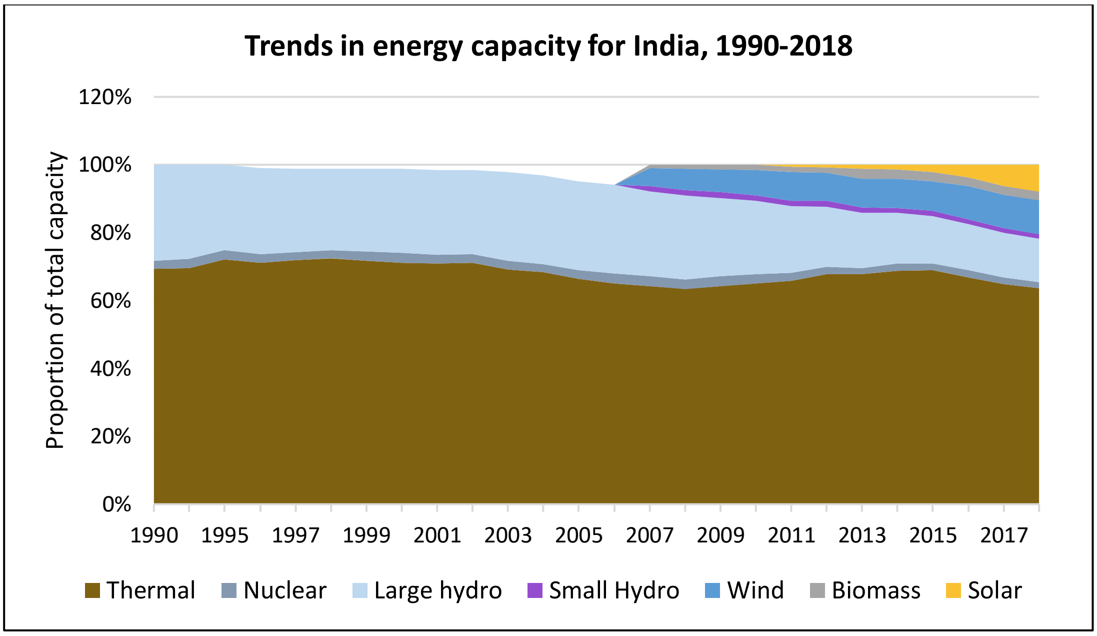


Figure 32: Trends in India’s energy capacity, 1990-2018

Source: Author, based on CEA (2019a, 2019b)

Total electricity generation was 1532.2 Terawatt-hour (TWh) in 2017 (utility power generation, not counting captive power generation in industry); it grew at 6% CAGR between 2000-2017. Figure 33 traces changes to India's electricity generation between 1990-2017. Coal, natural gas and large hydro were primary sources of electricity. The share of renewables has witnessed steep rises since the early 2000s; wind, solar and biomass were main contributors. Coal, which remained a primary energy source, met 70% of India's energy demand between 2000-2017, with an average 7% change YoY (Figure 33). This trend is expected to continue into the next decade in order to meet India's rising demand for energy to support its industrialisation and social development needs. While investments for new coal mines are shifting towards renewable energy infrastructure, imperfect market dynamics have delayed the uptake of renewable power in India; the scale and pace of project implementation has not kept pace with demand.

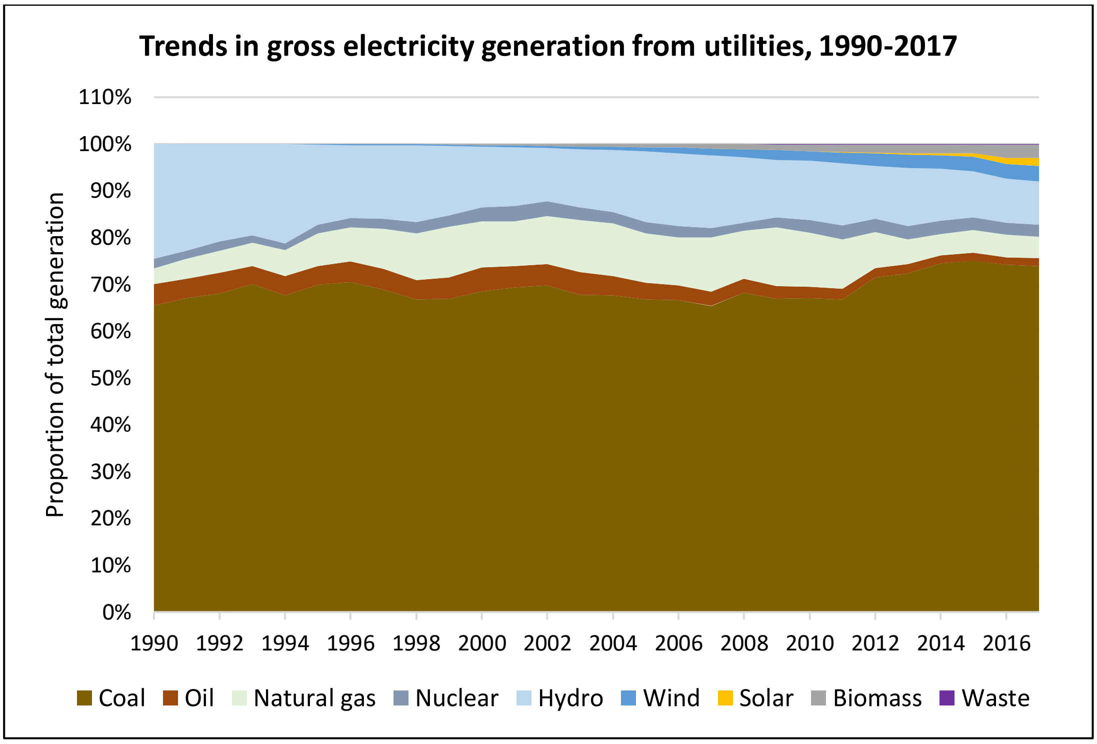


Figure 33: Trends in India's gross electricity generation from utilities, 1990-2017

Source: Author, based on IEA (2020)

Among renewable energy sources, wind power had the highest share of generation at 3.33% in 2017-18, a steep jump from the meagre 0.3% share in 2000-01. Average YoY growth of 22% was recorded for wind power between 2000-2017, indicating the sharp focus to expand renewable energy generation in India. Although capacity increases for large hydro projects stabilised as RES capacity expanded, its share of generation remained consistent at 12.5% between 2000-2017 (Figure 33). Since 2007 when the National Solar Mission was initiated, India has recorded a massive scale-up in solar generation at an average 300% YoY growth. In 2017, solar contributed 1.7% to India's total electricity generation from utilities (IEA, 2020).

Oil had a 5% share of generation in the 1990s, but it has been consistently declining since 2004, with 2% contribution to total generation in 2017-18. Similarly, the generation share of natural gas has considerably declined since 2009; its share dropped to 5% in 2017-18 from 13% in 2009-10. After some early success in building nuclear power capabilities, India's progress steadied at 3% generation since 2010. Biomass as a source of renewable energy had a 3% contribution to total generation in 2017 (Figure 33).

Waste to energy generated 0.11% of India's electricity since 2012 (Figure 33). Waste to energy is an area of focus for many countries to extract value (energy through incineration) from waste through formalised infrastructure and financial incentives. India is piloting many bio-methanation plants to extract energy from bio-waste, some of these initiatives are examined in later chapters. The waste to energy sector has seen slow progress in India, primarily due to the high proportion of organic wastes which are deemed as problematic for incineration. Alternative resource recovery programs for waste and improved recycling rates in India, coupled with challenges for effective energy conversion from high proportion of organic waste from India's municipal waste, have had a significant impact on the growth of waste to energy projects.

4.9 Chapter conclusion

Time-series analyses for *macro* nation-level material and energy performance revealed interesting patterns. India's domestic material consumption (DMC) in 2017 rose sharply by 92% over the year 2000. This surge was led by non-metallic minerals as well as fossil fuel materials and can be directly linked to the expansion of industrial, infrastructure and housing sectors. By contrast, India's IPAT identity recorded increasing affluence as one of the main drivers for material demand, although lowered material intensity due to rising GDP suggests relative decoupling for India's material performance. Material consumption (per capita) of 5.26 tonnes is far lower than in the USA (21.03 tonnes) and China (17.73 tonnes), signalling opportunities to leapfrog traditional material intensive growth patterns.

The International Energy Agency (IEA) placed India as one of the world's foremost nations with renewable energy capabilities, amidst leaders like China and the USA. Acceleration in solar and wind infrastructure in the country coupled with increased generation from WWS sources are driving the nation's green energy shift. India's electric power generation of 1532.2 TWh as of

March 2018 had more than doubled since 2005, placing the nation in the 'super-power' league. Concomitantly, lower dependence on coal sources, especially in terms of new capacity, and the increasing share of private sector investment in renewable energy projects, are promising. With its rising energy needs to foster rapid industrialisation and urbanisation in addition to the massive-scale of rural electrification currently underway, India still has ample potential to strengthen the supply and commercial viability of new RES projects. These initiatives will spur wider industry specialisation and self-sufficiency to manufacture critical components of solar and wind technologies, further expanding domestic and international investment in India's clean energy.

CHAPTER 5. CASE STUDIES OF ECO-INDUSTRIAL PARKS, INDUSTRIAL SYMBIOSES AND CIRCULAR ECONOMY APPLICATIONS IN INDIAN MANUFACTURING

5.0 Introduction

This chapter examines empirical data for the qualitative assessment of circular economy applications in Indian industry. India's industrial park development is traced, to identify policy drivers and emergent pathways to planned industrialisation. India has distinct socio-political features, which coupled with its thriving middle class population, young and skilled workforce, and digital connectivity, are driving economic growth. Traditionally dependent on its vast small and medium enterprise sector, India's industrial trajectory continues to follow a similar pattern as a source of employment and decentralised development. Industrial hubs, which were once located on a city's outskirts are today, nested within residential areas, complicating economic, social and environmental stability. Thus, stringent pollution control, resource efficiency and localised waste management are now at the epicentre of industrial development. In addition to public sector enterprises, private ventures and partnerships are expanding the scale of eco-industrial development in India.

The chapter is divided into two main parts: the first part expands on closed loop circular exchanges for materials, energy and water in three manufacturing industrial parks – *Naroda, Nandesari, Jawaharlal Nehru Pharma City* (JNPC). The second part examines circular economy advances in three industrial sectors; namely, *steel, bio-products* and *cement*. In total, six case studies are designed to evaluate latest developments in India's eco-industrialisation, resource efficiency and circular economy implementation. Field study primary data informed these case studies to gain in-depth understanding of structural and institutional development facets of eco-industrialisation in India. Together, 19 industrial symbiosis networks were found to be operational at the six case sites, involving complex materials, energy and water resource synergies (Table 8). This chapter examines each of the 19 symbiosis networks in-depth, to trace the network's evolution, imperatives and implementation characteristics.

Table 8: Resource exchanges within chosen industrial symbiosis networks

Secondary resource exchanged		Industrial symbiosis network (ISN)	Case site
1.	*Chemical gypsum*	NOVEL – chemical gypsum as alternative material in cement (Figure 41)	Naroda
2.	*High strength acid, colourless acid, alum, ferrous sulphate*	NOVEL – acid reused in dye, chemical and textile manufacture (Figure 42)	Naroda
3.	*Condensate, sludge*	Condensate and sludge recovery from liquid effluents (Figure 43)	Naroda
4.	*Water, biomethane, biofertiliser*	Water, biomethane and biofertiliser from food industry wastes (Figure 44)	Naroda
5.	*Steam*	Inter-firm steam exchange via common boiler (Figure 56)	Nandesari
6.	*Alternative fuel inputs*	Alternative fuels in cement manufacture (Figure 58)	Nandesari
7.	*Water*	Water circularity to replace freshwater use (Figure 59)	Nandesari
8.	*Common infrastructure*; *incremental services, capacity development*	Integrated services and shared infrastructure (Figure 65)	JNPC
9.	*Internal and external by-product reuse, alternative fuels inputs*	Zero waste operations (Figure 67)	JNPC
10.	*Steam*	Heat to steam exchange between co-located firms (Figure 69)	JNPC
11.	*Steam condensate, solvent*	Intra-firm steam and solvent reuse (Figure 70)	JNPC
12.	*Alternative fuels*	Co-processing of alternative fuels from pharmaceutical wastes (Figure 71)	JNPC
13.	*Heavy metals*	Circular economy in end-of-life vehicles through urban mining (Figure 76)	MSTI
14.	*Electricity*	Electricity generation from surplus heat (Figure 79)	Essar Steel
15.	*Micro pellets*	Intra-firm industrial by-product reuse (Figure 81)	Essar Steel
16.	*Briquettes, construction materials*	Inter-firm industrial by-product reuse (Figure 82)	Essar Steel
17.	*Coolant water, reverse exchange of effluent water and clarifier sludge*	Closed loop water exchange between co-located power and steel plants (Figure 83)	Essar Steel
18.	*Incense sticks and cones*; *vermicompost*; *biothermocol*; *bio leather*	Upcycle of biowaste (Figure 88)	Help Us Green
19.	*Chemical gypsum*	Co-processing of chemical gypsum as alternative raw material in cement (Figure 95)	Akash Dyes

Source: Author, based on case study data and analysis

Case site abbreviations

Naroda: Naroda chemical industrial park; Nandesari: Nandesari chemical industrial park; JNPC: Jawaharlal Nehru Pharma City; MSTI: Maruti Suzuki Toyotsu India; Essar Steel: Essar Steel Complex, Hazira; Akash Dyes: Akash dye and dye intermediates

Naroda and Nandesari case sites exemplify mature chemical manufacturing parks; whereas, the third site at JNPC is positioned as India's first greenfield eco-industrial park, and is a relatively new and planned estate. UNIDO (2010, 2017b) identified Naroda and Nandesari as pilot sites for park-wide resource efficient and cleaner production assessments. The two parks were enlisted by UNIDO as exemplary eco-industrial parks, owing to the environmental, economic and social benefits accorded through the setup and implementation of these parks (UNIDO, 2017b). Implemented by GIZ and GCPC, firm-level efficiency improvements and several material and energy recovery opportunities were identified at Naroda (UNIDO, 2010); however, no evidence of actual exchanges is reported so far. JNPC, began as a public-private-partnership, and specialises in the manufacture of Active Pharmaceutical Ingredients (API) drugs. The occupant firms at Naroda and Nandesari are mainly small and medium enterprises, with limited capital and technology assets for resource efficiency projects. In contrast, JNPC houses mostly large bulk drug manufacturers with advanced research, development and financial capabilities.

All three industrial sectors, *steel, bio-products* and *cement,* are known to be materials- and energy-intensive, with high waste creation and landfill disposal. Issues also persist with the hazardous nature of manufacturing by-products, for example in steel manufacturing, which limit possibilities for effective recovery and reuse. In the case of bio-products, mounting volumes of degradable fresh flowers, the discards of worshippers in Indian temples, are clogging fresh water rivers at alarmingly high rates. The ingenious solutions by a social enterprise to *upcycle* these holy yet discarded bio-products, are remarkable in circular economy realisation. Lastly, opportunities for co-processing in India's cement industry are determined through the use of alternative fuels and raw materials in the cement making process.

5.0.1 Industrial park development in India

The Rakesh Mohan Committee Report (1996) was instrumental in outlining widespread infrastructure reform for India. India's industrial park experience, too, follows the recommendations of this report to offer "self-contained island providing high-quality infrastructural facilities.… industrial, residential, and commercial areas with developed plots/ pre-built factories, power, telecom, water and other social infrastructure" (GIDB, 2020; IIR, 1996; NITI, 2008). Industrial parks are geared towards a variety of roles, including: Growth Centre, Export Processing Zone, Free Trade Zone, Export Promotion Industrial Park, Software Technology Park, Electronics Hardware Technology Park (GIDB, 2019). Apart from mixed zones, many are divided into sector-specific zones (engineering, textiles, food processing, chemical). In total, 2589 industrial zones are recorded in India, of which engineering zones had the highest share (24%), after mixed zones (50%) (Figure 34) (DPIIT, 2019).

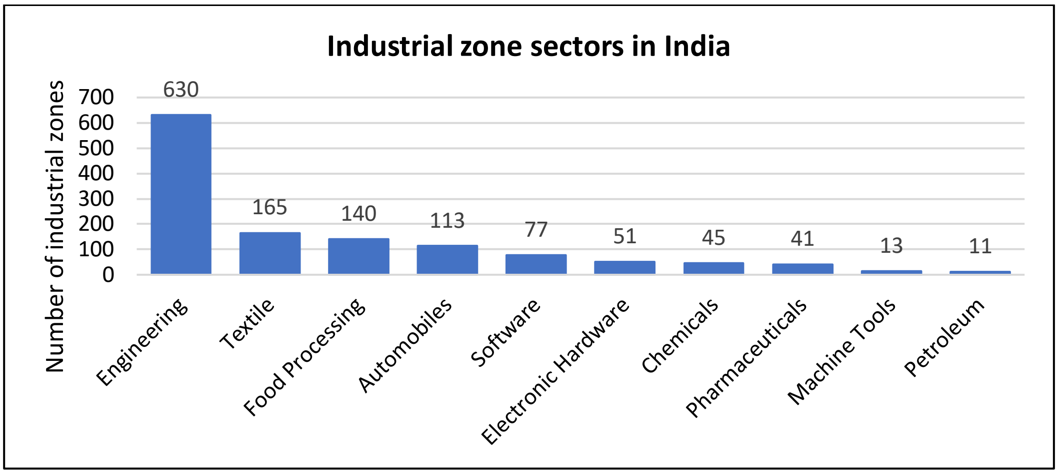


Figure 34: Types of industrial zones in India

Source: Author, based on DPIIT (2019)

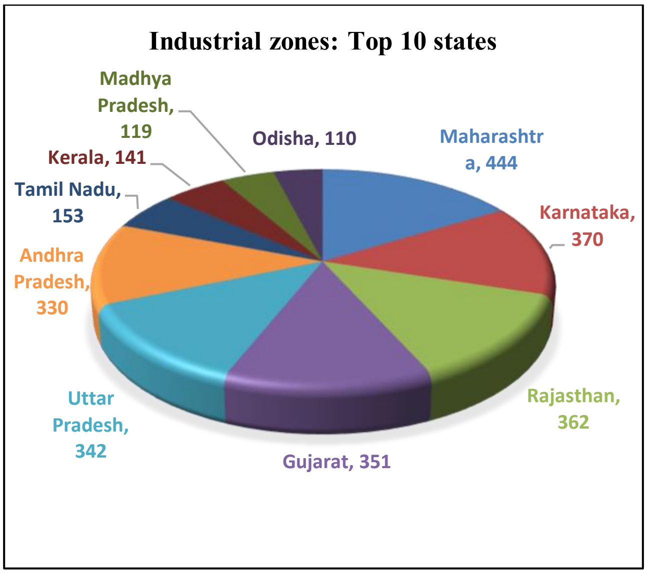
Note: Mixed zones are excluded from the chart

India's micro, small and medium enterprise (MSME) sector is integral to its industrialisation, contributing 8% to national GDP and 45% to the industrial output[15]. The sector which was highly unorganised, is witnessing tremendous agglomeration benefits by locating within industrial regions. Planned industrial parks offer a host of shared benefits like transport infrastructure and connectivity to major ports and roads networks, access to power and water at subsidised rates, tax incentives, ready availability of labour and customers. Additional benefits accrue due to industrial activity being centred around specific sectors like automobiles in Maharashtra, pharmaceuticals in Himachal Pradesh and textiles in Tamil Nadu. Supply chain linkages within industrial parks enable MSMEs to scale up core business by reducing operational costs and benefitting from specialisation.

Together Maharashtra, Gujarat, Tamil Nadu, Uttar Pradesh, Karnataka and Andhra Pradesh constituted 62.46% of India's manufacturing output (Talwar, 2016). These states have successfully adopted centralised industrial park development (Figure 35). Maharashtra, Karnataka and Rajasthan recorded the highest number of industrial zones spread across a variety of sectors and purposes. In terms of land area under industrialisation, Gujarat state had the highest share at 30% with 127739 hectares under industrial zones, followed by Maharashtra at

[15] Raheja, A. (2018, June 5). How industrial parks can help MSME sector reap benefits of 'Make in India'. *Financial Express*. Retrieved from https://www.financialexpress.com/industry/sme/how-industrial-parks-can-help-msme-sector-reap-benefits-of-make-in-india/1194241/

16% (Figure 35) (DPIIT, 2019). The data breakdown exemplifies the intensity of industrial activity in India and the shift towards agglomeration economies, where industrial activity is being consolidated through zonal and regional specialisation. The expansion of planned industrial parks and clusters has strong potential for circular economy practices to be embedded in site master plans, and for older estates to adopt brownfield development, similar to the scaled transformation to eco-industrial parks in China (Mathews, Tan, & Hu, 2018).



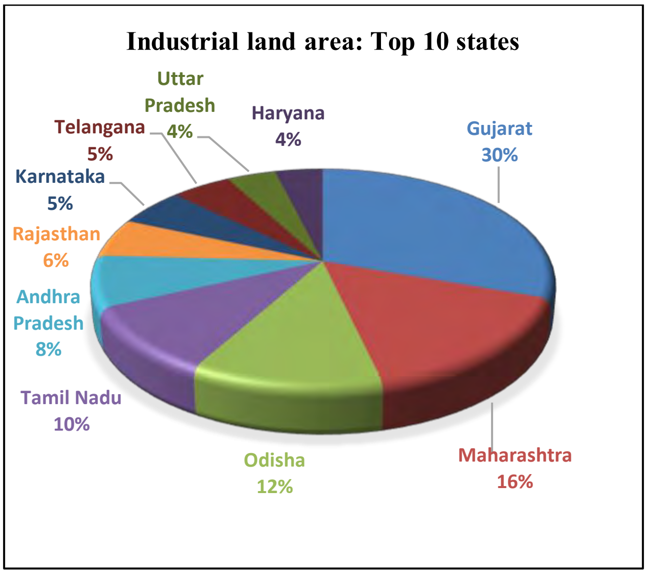


Figure 35: Number of industrial zones (left); Percentage land area (right) – Top 10 states, India

Source: Author, based on DPIIT (2019)

<u>Note</u>: Highest to lowest clockwise

5.0.2 The process of industrial park setup

Multiple layers of central and state government agencies are responsible for industrial estate establishment in India (Figure 36). Structurally, the Department for Promotion of Industry and Internal Trade (DPIIT) within the federal Ministry of Commerce and Industry, implements the nation's industrial development policies. DPIIT is responsible for industrial policy formulation, industrial performance, Foreign Direct Investment, technology and intellectual property rights, in addition to directing state-specific industrialisation plans. The state infrastructure development body initiates industrial park setup, land allocation, sectoral specialisation and capital outlays. Alongside, the state industrial development corporation (SIDC) plans, approves, develops, and regulates project implementation (Figure 36) (DPIIT, 2020; GIDB, 2019; Singhal & Kapur, 2002). Once a lengthy and expensive process, legislative and regulatory reforms have improved its ranking on the World Bank's 'ease of doing business' indices; digitisation has reduced licensing bottlenecks and sped speeded environmental clearance (GOI, 2018).

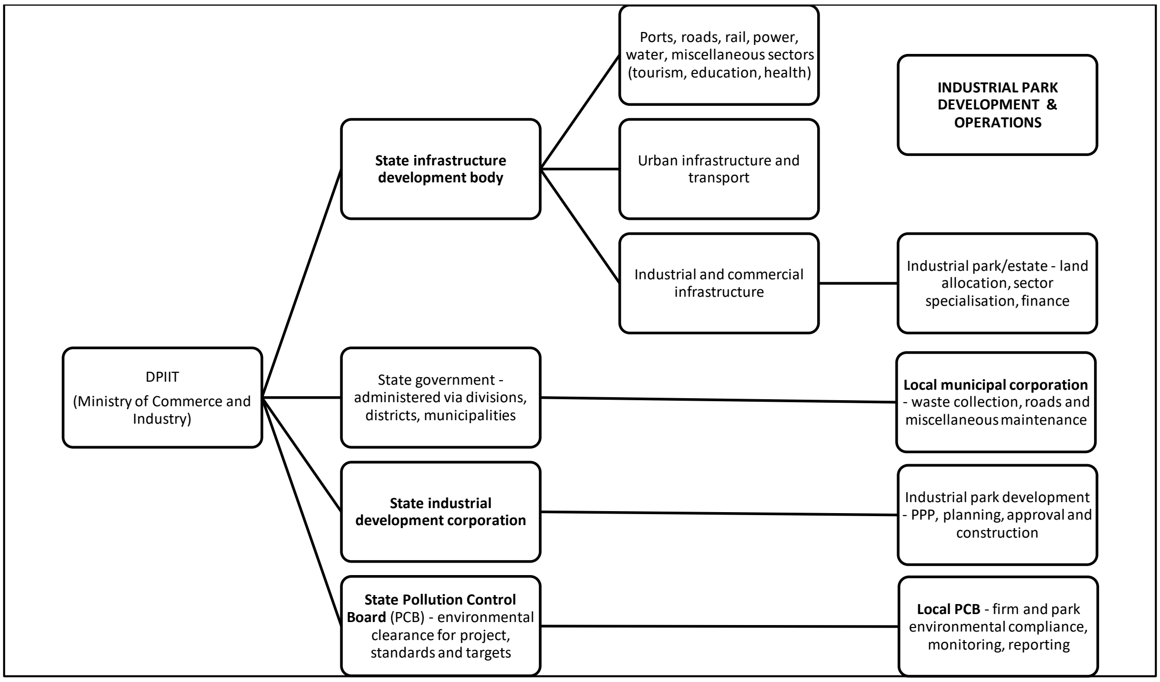


Figure 36: Summary of stakeholders in the standard industrial park setup process in India

Source: Author, based on field visits, DPIIT 2020; GIDB 2019; Singhal and Kapur 2002

At the planning and construction stages for an industrial park, private sector involvement is usually minimal; however, novel ventures for public-private-partnership are emerging in many states. In such a partnership, the state authority maintains control of land, power, water and resources, while the private partner undertakes land rehabilitation, construction, and in certain cases prospecting and maintenance. A later case of Jawaharlal Nehru Pharma City in southern

India explicates this model. Information Technology parks are another successful avenue for private sector participation in development. Subsidised land allotment in industrially backward regions is possible due to nodal control by the state industrial development corporation, which is able to reinvest revenues from thriving regions.

Industrial park setup, administration and regulation varies between states, depending on political and developmental ambitions. Traditionally, the state industrial development corporation, jointly with the *local municipal corporation*, administered day-to-day affairs, shared infrastructure creation, repairs and maintenance. This centralised management has seen a shift in recent decades, with private actors and industry representative bodies assuming administrative duties, due to public sector inefficiencies in housekeeping and maintenance. Inadequate maintenance, lack of specialised services and delays are common issues where government agencies continue to administer beyond the developmental stages. The cases of Naroda, Nandesari and JNPC will elaborate on hybrid operational models for industrial park administration in India.

The Industrial Park Rating System launched in 2018 by the DPIIT, is an impressive tool to measure industrial park performance and seek geographic information system-enabled data on: internal infrastructure; external infrastructure; business services, facilities and environment; as well as safety management. Currently in beta testing, this rating system maps 3354 industrial clusters in terms of land area use, infrastructure and amenities, and employment (DPIIT, 2019); it can be useful for circular economy pursuits. It will also streamline data reporting and monitoring using standardised metrics, a massive gap in India's present industrial scene. Multiple benefits accrue to firms by locating within industrial parks and special zones, like sector specialisation, supply chain connectivity, labour availability, knowledge and technology transfer effects, as well as fiscal and monetary benefits like tax incentives, subsidised land, energy and capital costs. In addition, access to shared services like common roads, transportation and commercial services, lighting and infrastructure, health and housing is also available.

The aforementioned benefits are especially favourable for micro, small and medium enterprises (IBEF, 2012). The Indian Ministry of MSME classifies enterprises based on investment in plant and machinery, and annual turnover. *Small* manufacturing enterprises value plant and machinery investment at up to USD 1.34 million (INR 10 crore) and annual turnover up to USD 6.68 million (INR 50 crore). *Medium* enterprises value plant and machinery investment up to USD 6.68 million (INR 50 crore) and annual turnover at up to USD 33.4 million (INR 250 crore) (MMSME, 2020). The size of operations limits SMEs' access to capital, credit and human resource talent, productivity and efficiency challenges due to low investment in technology and automation. Despite these limitations, manufacturing SMEs contribute 45% to India's industrial output and are a mass employer, generating upwards of 1.3 million jobs annually[16]. For these reasons, operating within planned industrial zones has shown immense benefits for the growth of SMEs in India.

Another important stride is the funding support for Common Effluent Treatment Plants (CETPs), with up to 50% of costs being funded through federal and state government grants. A CETP is a centralised facility for liquid effluents and hazardous waste management, it allays the need for individual firms to invest in onsite treatment and disposal equipment. The reduction in number of waste discharge points in an industrial estate, due to CETP installation, is beneficial to monitor illegal disposal and irregularities in environmental compliance. As of 2012, 193 CETPs were installed across 212 industrial estates in India (CPCB, 2018; GOI, 2010); few of the CETPs were shared across multiple industrial estates. Centralised CETP infrastructure within an industrial park is a specialised service which is promoted for scientific and efficient waste management at an estate level. The common infrastructure also eases pressure off individual enterprises who would otherwise be burdened with high capital investment for decentralised effluent treatment with less satisfactory environmental results.

Eco-industrial parks are designed to improve resource flows and efficiency between co-located firms, as a means to advancing circular economy in manufacturing industries. Two pilot eco-industrial park projects were implemented in the state of Gujarat as part of UNIDO's global resource efficiency and cleaner production initiative (Vadodara-Ankleshwar industrial area, Dahej Petroleum, Chemical and Petrochemicals Investment Region). The project expanded to five Indian industrial parks with the commissioning of the Gujarat Cleaner Production Centre (GCPC) to undertake a comprehensive study of Nandesari and Dahej PCPIR in 2016 (UNIDO, 2017b). To better understand India's emergent circular economy pathways, the next section presents an overview of Gujarat state as one of the leaders in India's eco-industrial development.

[16] Chakraborty, S. (2017, June 2). Indian SMEs more bullish on growth prospects: Survey, e-article. *Business Standard*. Retrieved from https://www.business-standard.com/article/economy-policy/smes-more-bullish-on-growth-prospects-than-firms-in-china-japan-study-117060200656_1.html

5.0.3 *Gujarat state: exemplar of eco-industrial park development in India*

5.0.3.1 *State industrial profile*

Together, the states of Maharashtra, Gujarat, Tamil Nadu, Uttar Pradesh, Karnataka and Andhra Pradesh constituted 62.46% share of India's manufacturing output (GOI, 2014). Referred as India's Guangdong, the western state of Gujarat is one of India's leading commercial centres and third-largest state economy, contributing 7.6% to the National Gross Domestic Product in 2015-16. The state had a USD 172.63 billion economy in 2016-17, in which manufacturing, construction, electricity, gas and water were the fastest growing sectors (GoGSDP, 2017). With 45 ports, 18 domestic airports and an international airport, Gujarat state is well-located on the country's western border and has a 1600 kilometre coastline. Total handling capacity of ports in Gujarat was 466 Million Metric Tonne Per Annum (MMTPA) in 2015-16; this is expected to double by 2020. Pipavav, Mundra, Kandla, Hazira, Sikka, Dahej ports in Gujarat are prominent in India's petrochemicals, gas, cement, and steel trade.

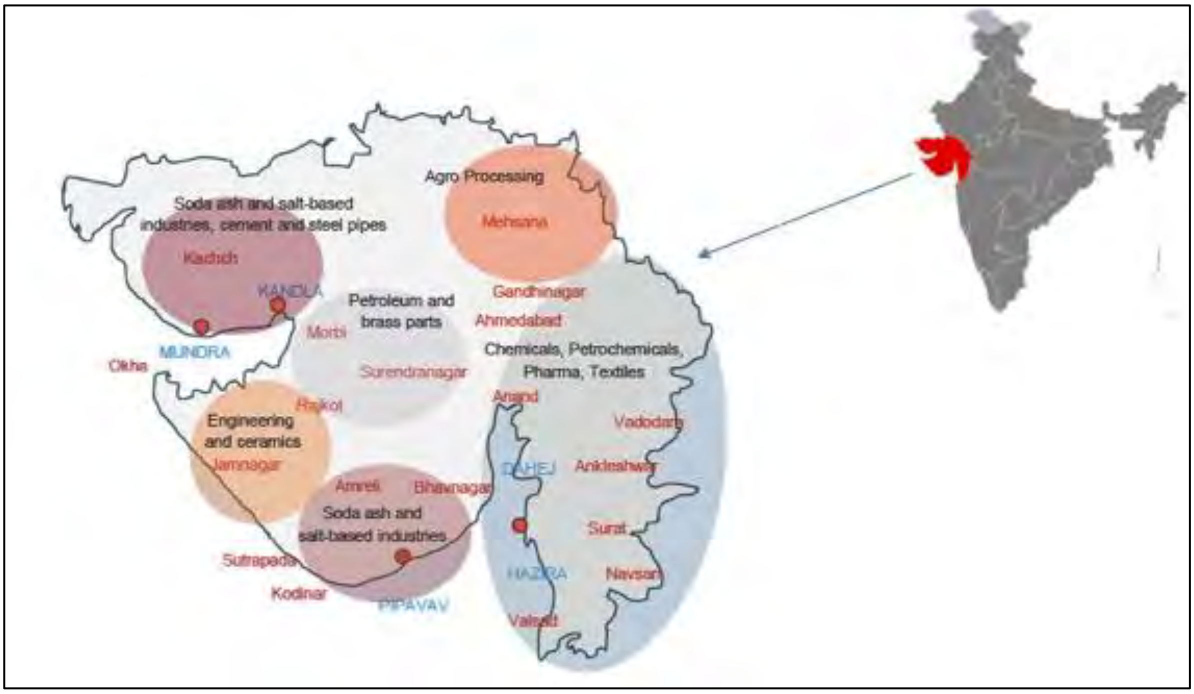


Figure 37. Product clusters in Gujarat, India (left); Gujarat within India (right)

Source: Government of Gujarat Compendium (GoGCompendium, 2012)

As a petrochemicals hub with a total refining capacity of 101.9 MMTPA, Gujarat accounts for 41.54% of the nation's capacity. The cities of Ahmedabad, Ankleshwar and Vapi are home to industrial centres producing pharmaceuticals, agro-chemicals, specialty chemicals, dyes and pigments (GoGCompendium, 2012). MSMEs constitute a large share of the state's industrial landscape. The state is home to 1200 large enterprises and 345,000 MSMEs. Gujarat manufactures over 35% of India's chemical output and fulfils 98% of soda ash demand (GoGCompendium, 2012). Industrial clusters – groups of firms manufacturing identical and/or complementary products with a critical mass of 50 firms and located within a 10 kilometre radius, are visible throughout the state (Figure 37). The state also had the highest land area under industrial activity (Figure 35).

5.0.3.2 Developmental facets of Gujarat's industrial parks

The state of Gujarat, located on India's western frontier, was the forerunner in formalising an industrial park development policy, outlined in the Gujarat Industrial Development Act, in 1962. Since 2009, the Gujarat Special Investment Regions Act has overseen the creation of state-of-the-art industrial areas. In addition to the setup and maintenance of multi-product estates, sector-specific industrial parks facilitate scale economies and supply chain efficiencies. Examples are: the electronics estate in Gandhinagar; ceramics estates near Bhavnagar; and chemical estates at Vapi, Ankleshwar, Panoli, Nandesari, Naroda. As of 2019, there were 204 industrial estates, 83 product clusters, 60 Special Economic Zones and 12 Special Investment Regions in Gujarat, varying in size, core activity and sector specialisation (GIDB, 2019).

Some 13 key industries account for 82% of total factories, 96% of total fixed capital investment, and 90% value of output in Gujarat's industrial economy; agro and food processing, dairy, chemicals and petrochemicals are the most prominent. As one of India's chemicals and petrochemicals hub, Gujarat houses 8 chemical clusters, 13 industrial estates and three SEZs for chemical and petrochemical production (IBEF, 2018a). The state also has the highest land area of 6,819 hectares for special economic zones (SEZs).

The state government is a major investor in industrial infrastructure. In 2018-19, USD 682.2 million was allocated for industrial development, especially for industrial parks, logistic parks and defence manufacturing. In 2015, Gujarat's New Industrial Policy extended financial assistance for private investment in industrial park development, to extend the manufacturing sector's presence which primarily operates within state-run Gujarat Industrial Development Corporation (GIDC) industrial parks. In the decade from 2006-2015 alone, 375,130 new MSMEs registered bringing investment of USD 27.32 billion and generating 2.83 million jobs (IBEF, 2018a).

5.0.3.3 Policy and administrative context for industrial parks in Gujarat

Gujarat Infrastructure Development Board (GIDB) is the statutory body founded under the Gujarat Infrastructure Development Act, 1999, to manage infrastructure projects and policy advice. A significant achievement of GIDB has been the expansion of private sector investment for infrastructure development through a variety of public-private-partnership models. Major headway in capacity building and inter-agency collaboration has created robust networks for industrial parks, transport and logistics, urban infrastructure, tourism, education and health. GIDB also provides viability gap funding for federal and state departments. This fosters industrial ecosystems, multiple Special Investment Regions, Petroleum, Chemicals and Petrochemicals Investment Region; it also ensures that industrial parks and clusters are operational and in varied stages of planning (GIDB, 2019).

Gujarat Industrial Development Corporation (GIDC) operationalises the state government's industrialisation agenda. The key function of the GIDC is to develop land for the setup of industrial estates and associated infrastructure such as roads, power, water, drainage, effluent and waste management systems. Well-established estates also have low-cost housing, amenities and community services like banks, shopping complexes, schools, hospitals, telecommunications centres, police and fire stations. The scale of development positively impacts outlays for firms; costs of setup and manufacture within a GIDC estate is significantly lower than standalone operations (IBEF, 2018a).

Additionally, four implementation agencies work under the state **Forests and Environment Department**: Gujarat Pollution Control Board (GPCB), Gujarat Ecology Commission, Gujarat Institute of Desert Ecology and Gujarat Environmental Management Institute. Among these, GPCB is a state body of the nodal Central Pollution Control Board (CPCB). CPCB is responsible for: laying out guidelines and environmental standards to maintain water and air quality; effluent management; co-ordination with state pollution control bodies to monitor and implement federal statutes; technical guidance; training for government and industry actors; and publication of statistical data and performance metrics (CPCB, 2019). At a state level, GPCB conducts advisory activities on different aspects of pollution and environmental management, and functions as a representative agency for CPCB. GPCB has multiple pioneering initiatives to promote digitisation, live monitoring systems, data reporting and transparency.

Another focal agency is the **Gujarat Cleaner Production Centre (GCPC)**, which operates independently within the state's industries department. Its functions include advisory services for the design of new and current industrial parks, industry dialogue, workshops and educational programs for circular economy, resource efficient and cleaner production (RECP) assessments under UNIDO guidelines, material flow analyses and identification of industrial symbiosis opportunities, funding and financial assistance for the implementation of cleaner production technology. GCPC was a central actor in previous and ongoing industrial symbiosis pursuits within Gujarat, as well as some national and international projects (GCPC, 2019).

5.0.3.4 Chemical manufacturing estates in Gujarat

Gujarat's chemical manufacturing sector comprises 13 formal chemical industrial estates (Table 9) all located in the eastern zone along the *golden industrial corridor* between Ahmedabad and Mumbai. Two of these chemical industrial estates, Naroda and Nandesari, are explored in-depth in this thesis. Operational since 1965, Naroda industrial estate is located in the commercial capital city of Ahmedabad with over 400 chemical firms ranging from multi-nationals to MSMEs. Within chemicals manufacturing, dye and dye intermediates, pharmaceuticals, textiles, and food industries are prominent.

Table 9. Footprint of chemical manufacturing industrial estates in Gujarat

Chemical industrial estate	**Area (hectares)***	**Chemical industrial estate**	**Area (hectares)***
Odhav	135	Ankleshwar	1200
Naroda	295	Panoli	1000
Vatva	690	Pandesara	218
Nandesari	270	Sachin	800
Dahej	4700	Sarigam	400
Vilayat	1000	Vapi	1100
Jhaghadia	1700		
* 100 hectares in one square kilometre; one hectare contains about 2.47 acres			

Source: Gujarat Cleaner Production Centre (GCPC, 2018a)

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The Nandesari industrial estate is located on the outskirts of Vadodara city. About 250 chemical manufacturing firms, a majority of them SMEs, function within the estate. A neighbouring mega-refinery is engaged in discussions to supply used water to chemical estate enterprises. The proximity of these estates to major seaports, as well as road and rail infrastructure facilitates north-south connectivity across India and international trade.

The thesis expands on the criteria utilised for evaluating eco-industrialisation, by examining specific cases of resources sharing and exchange, as central features of eco-industrial development. Site visits, stakeholder interviews and secondary data were collected. This chapter reports on findings of implementation cases and ongoing circular resource exchanges in Gujarat. Both, Naroda and Nandesari, represent established industrial parks in India with distinct motivations and challenges to adopt eco-industrial strategies.

5.1 Case Study 1: Naroda chemical manufacturing industrial park

5.1.1 Overview of Naroda Industrial Estate

Operational since 1965, Naroda Industrial Estate, spread over 358 hectares, is located in the city of Ahmedabad and has a total of 1000 firms. Around 400 firms manufacture chemicals, their sizes range from multi-nationals to micro, small and medium enterprises in the dye and dye intermediate, pharmaceutical, textile, and food industries. Other industries present span engineering, metal and plastics; these are not as material or water-intensive as chemicals manufacture and do not have high volumes of liquid effluents. Notable manufacturers located in Naroda include Reliance Industries, Dishman Pharmaceuticals, Ingersoll-Rand, Havmor Ice Cream, Samrat Namkin.

Naroda industrial estate's proximity to Ahmedabad International Airport (8 km), connectivity with the emerging Gandhinagar-Ahmedabad-Vadodara industrial corridor and two national highways, make it a busy industrial hub. The park houses mainly industrial units, but also has a mix of agricultural land, waste land, residential and commercial dwellings, utilities and green spaces (Figure 38-39). While current expansion is limited due to restricted available land, the co-existence of commercial and residential dwellings attracts a skilled workforce to the region. The estate has been instrumental in social and economic development of the region; however, the environmental burden is high due to the high levels of manufacturing activity in Naroda. Once outside city limits, rapid urbanisation has compounded the eco-industrial development challenges.

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Figure 38: Layout and land use at Naroda industrial estate, Gujarat, India

Source: ENVIS (2020); GIDC (2020)

Figure 39: Naroda industrial estate, Gujarat, India

Source: Author, field visit in April 2018

5.1.2 Park development, management and administration

Typical of other industrial estates in the state, Naroda was set up by the Gujarat Industrial Development Corporation (GIDC) in the 1960s as part of the state's early industrial development. At the time, environmental objectives were peripheral to industrial activity, parks and estates were designed to maximise economic output and spur regional growth. The presence of shared services, ready to use land plots, built infrastructure like roads and pipelines, and centralised waste management apparatus were not envisaged. Individual firms spawned and proliferated in nearby areas, expanding the geographical extent of the estate and obscuring planned eco-industrialisation. GIDC allocated land and basic infrastructure, but operational management and maintenance responsibilities were shared between GIDC and the local council, Ahmedabad Municipal Corporation. The administrative structure at Naroda has evolved since inception, with the majority of its management today undertaken by firm representatives through the Naroda Industries Association.

Naroda Industries Association (NIA) was formed in 1967 to centrally administer park activities. Initial responsibility for infrastructure development lay with GIDC, which passed on routine maintenance to Ahmedabad Municipal Corporation. Confusion between their roles resulted in negligence and poor maintenance. In 2006, legal proceedings by firms ruled in favour of NIA to take charge of infrastructure development and shared utilities management, in addition to being a firm representative body. Today, over 700 firms are members of the NIA. Naroda Utility Services (NUS) functions as a firm under NIA to manage the following shared services: i) Roads; ii) Storm water drainage; iii) Lighting; iv) Security; v) Water supply; vi) Domestic effluent management (planned and in early stages of implementation); and vii) the Green belt, nursery, tree plantation drives (annually 10,000 saplings planted on premises). In addition, operations of the Common Effluent Treatment Plant (CETP) are managed by NIA (Figure 40).

The management of shared utilities by the NIA has ensured consistent upgrading and efficiency in costs and quality. For example, since the inception of NUS (2003), the cost of water has remained unchanged; in contrast, under AMC, annual price increases of over 20% were passed on to industrial customers. Other skill development and community education workshops are hosted at the NIA function centre; these are discussed in a later section. As a means of expanding skilled workforce availability, NIA partnered with Industrial Training Institute (ITI) to design tailored courses with curriculum development and faculty exchange. These courses resulted in upskilling the workforce to match industry demand, and improved employability.

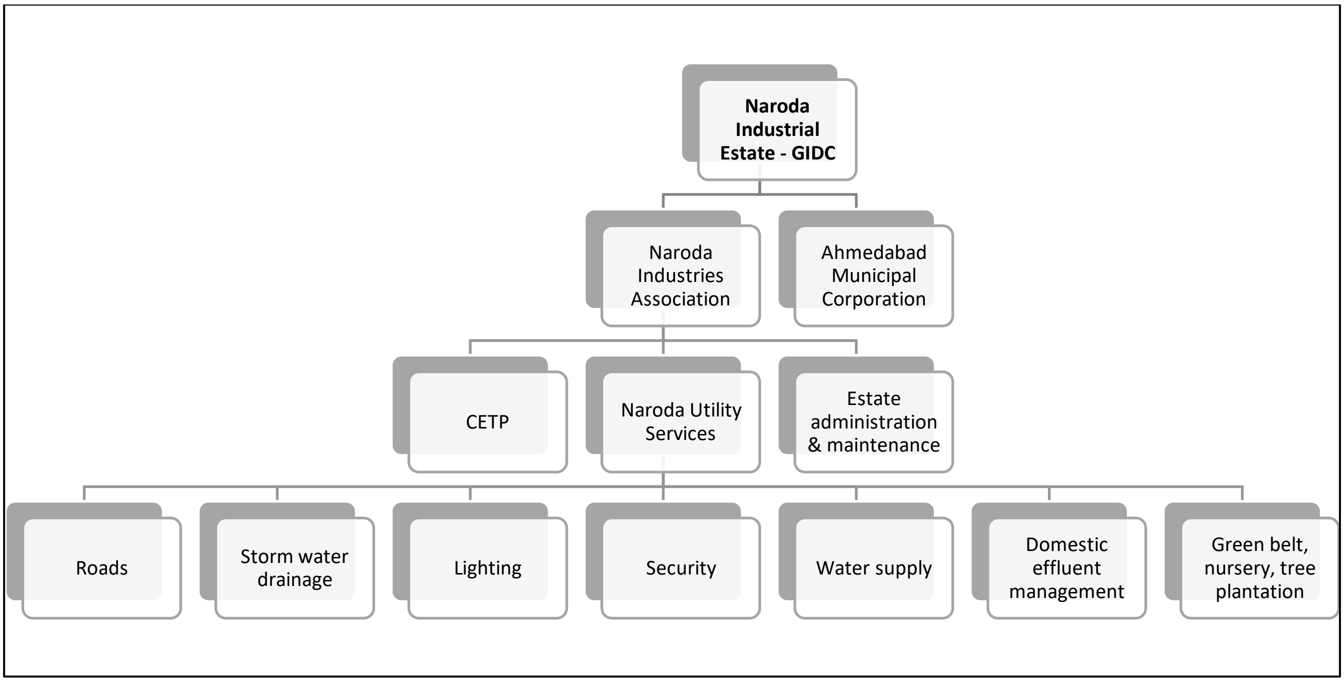

Figure 40: Distinct administrative structure at Naroda Industrial estate

Source: Author, based on field visits and interviews

5.1.3 Industrial symbiosis features uncovered through the study

Naroda was the first industrial park in India to conduct in-depth Resource Efficient and Cleaner Production (RECP) assessment in 2000, in order to quantify and characterise waste streams from every major factory unit (Appendix 11). The UNIDO endorsed project identified 23 major waste categories, of which 8 had recovery and reuse potential. Apart from paper and wood which had direct reuse, five by-product categories had high volumes and recommendations were made to find symbiosis partners for spent acid, gypsum, fly ash, iron waste, and food waste (Bain, Shenoy, Ashton, & Chertow, 2010). The field visits and interviews for this study confirmed closed loop exchanges for some of these by-products; the linkages are mapped below.

5.1.3.1 NOVEL Spent Acid Management: shared facility for spent acid recovery and reuse

Spent acid is a by-product of condensed sulphuric acid and oleum used in dye and dye intermediate manufacturing. Spent acid can be regenerated to relatively pure and concentrated acid for reuse; however, a firm's capacity for reuse varies considerably based on its scale of operation. Many SMEs at Naroda have incorporated spent acid flows back into their manufacturing, resulting in operational efficiency and reduced disposal. High concentration spent acid is reused in these operations, but excess spent acid with 10-30% sulphuric acid concentration is not suitable for reuse. Under GPCB rules, this excess spent acid must be treated by the generating industry, and significant money, space and technical expertise is needed for scientific storage, handling and treatment.

Despite intra-firm recovery and reuse, excess acid was still being generated and without an efficient collection and treatment mechanism, individual firms were forced to dispose of it. For SMEs with limited reuse potential, the costs for disposal are inexpensive in comparison to the investment needed for onsite treatment and recovery of valuable materials. There is also the question of volumes; where low volumes of decentralised spent acid generation do not yield scale economies for individual firms. The problematic management of excess spent acid also occurred in other chemical manufacturing parks in Gujarat. A single effective solution was forged by a cluster of co-located industrial parks through the set-up of NOVEL Spent Acid Management; this was a centralised facility to recover valuable materials from excess spent acid of 3 major chemical manufacturing parks, Naroda, Odhav and Vatva.

Spread over 4.5 hectares with 1.5 million litres daily capacity, NOVEL is co-funded by the Government of India and the three beneficiary estates. NOVEL has 150 registered members. Tankers are used to transport excess spent acid from firms and CETPs in the three chemical estates, located in the city of Ahmedabad, into the centralised NOVEL facility (VIA, 2019). Due to limited volumes at estate level, collection and treatment at a centralised facility standardises quality control from varied sources. This standardised spent acid is then subjected to different treatment and recovery processes to generate secondary materials like chemical gypsum, high strength acid, colourless acid, alum and ferrous sulphate (Figure 41-42).

Two secondary material streams are recovered from spent acid treated at NOVEL, for use in alum, ferrous sulphate, dye, textile and cement manufacture (Figure 41). One of the main applications of spent acid is in the manufacture of *chemical* gypsum for cement. Gypsum, a hydrated calcium sulphate, is a critical input in cement production, used to control the rate of hardening. Around 5% of cement consists of gypsum, added to clinker before final grinding. Naturally occurring gypsum, called mineral gypsum, is the purest form. India mines and imports mineral gypsum to fulfil its domestic demand as a raw material in cement manufacture. Various product testing and market evaluation studies of chemical industry by-products found that chemical gypsum can be a viable alternative to natural gypsum, easing dependence on virgin mining and imports of critical raw materials. Known cases of recovery and reuse of chemical gypsum are sparse in India due to: a poor understanding of the potential; the lack of incentive for waste generators; and insufficient quantities generated at the firm or estate level.

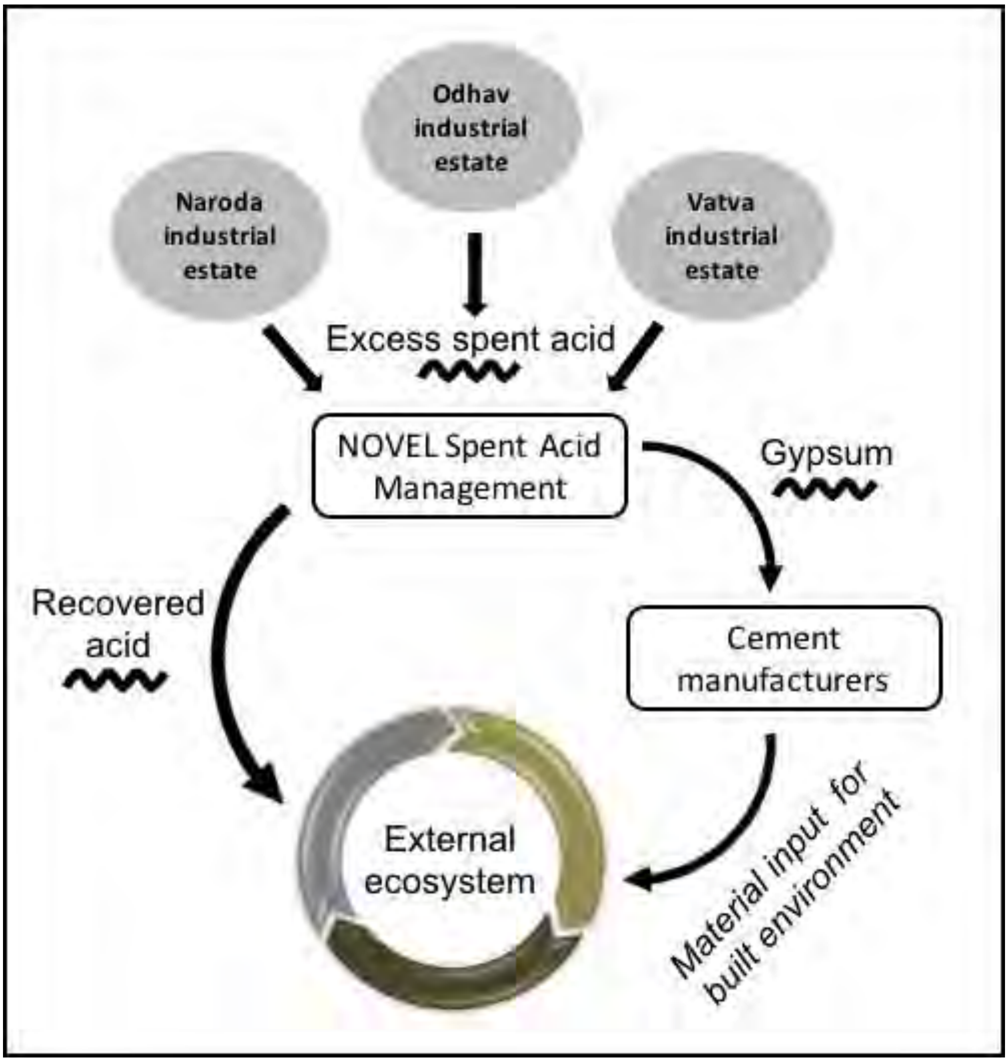

Figure 41. NOVEL secondary materials recovery and reuse

Source: Author generated, based on field visits, interviews and secondary data

denotes by-products

At NOVEL, excess spent acid from three feeder estates is treated to recover chemical gypsum, which is then transported to cement manufacturers for use as material input (Figure 41). Owing to its insensitivity to organic impurities and differing strength, chemical gypsum, made from light coloured spent acid with low chloride content, is suitable for use in cement. The industrial symbiosis network at NOVEL engages multiple actors like firms and CETPs within individual estates, NOVEL and cement industry partners like Geocycle, Ultratech Cement and Ambuja Cement. The now formalised exchange took over a decade of technical testing and financial viability assessment before it was implemented. Key concerns included: the ability of individual firms to generate and supply consistent quantity and quality of spent acid by-product; quality control for cement manufacturers to stipulate mineral gypsum replacement in cement mix; technical and economic modelling for the collection, transportation, storage, treatment and recovery of standardised chemical gypsum suitable for raw material replacement in cement.

The establishment of NOVEL was instrumental in addressing most of the aforementioned concerns, as individual firms were relieved of the responsibility for volume generation and quality control. The technical capabilities, ongoing research and development at NOVEL have ensured that cement manufacturers have found a valuable reuse opportunity to replace mineral gypsum, and also achieve cost economies from the centralised recovery of chemical gypsum. A later example of Akash Dyes, a small scale manufacturer of dye and intermediate products, examines the direct firm-cement model for chemical gypsum exchange; where, the role of an intermediary (e.g. NOVEL) was supplanted due to direct synergies and cost efficiencies established between the by-product generator and cement manufacturer. The industrial symbiosis exchange of gypsum derived from chemical industry by-products, as raw material replacement for the manufacture of cement is a promising example of co-processing through the use of alternative fuels and raw materials (AFRs). The prospects for co-processing in India are explored further in a later case focusing on India's cement industry.

NOVEL enables the reuse of approximately 0.5-0.8 million litres of spent acid daily. Around 0.5 million litres per day are used to make chemical gypsum, and daily gypsum quantities of around 300 tonnes are sold to the cement industry. Additionally, acid is recovered for reuse in alum, ferrous sulphate, dye and textile industries. Figure 42 outlines the material flows for recovered acid in different industry applications. High strength acid is transferred back for reuse in the manufacture of dye intermediates like H-Acid, FC Acid, and DASA. Highly concentrated and colourless spent acid is a direct material input in the manufacture of alum, ferrous sulphate and single super phosphate. Colourless spent acid is sold to the textile industry, where it is used to neutralise alkaline effluents (Figure 42). Leftover wastes including gypsum filtrate and waste water, are treated and disposed of via the CETP of Green Environment Services Co-operative Society Limited (GESCSL). High quantities of dissolved organics in gypsum filtrate undergo biotreatment before being sent to CETP for disposal.

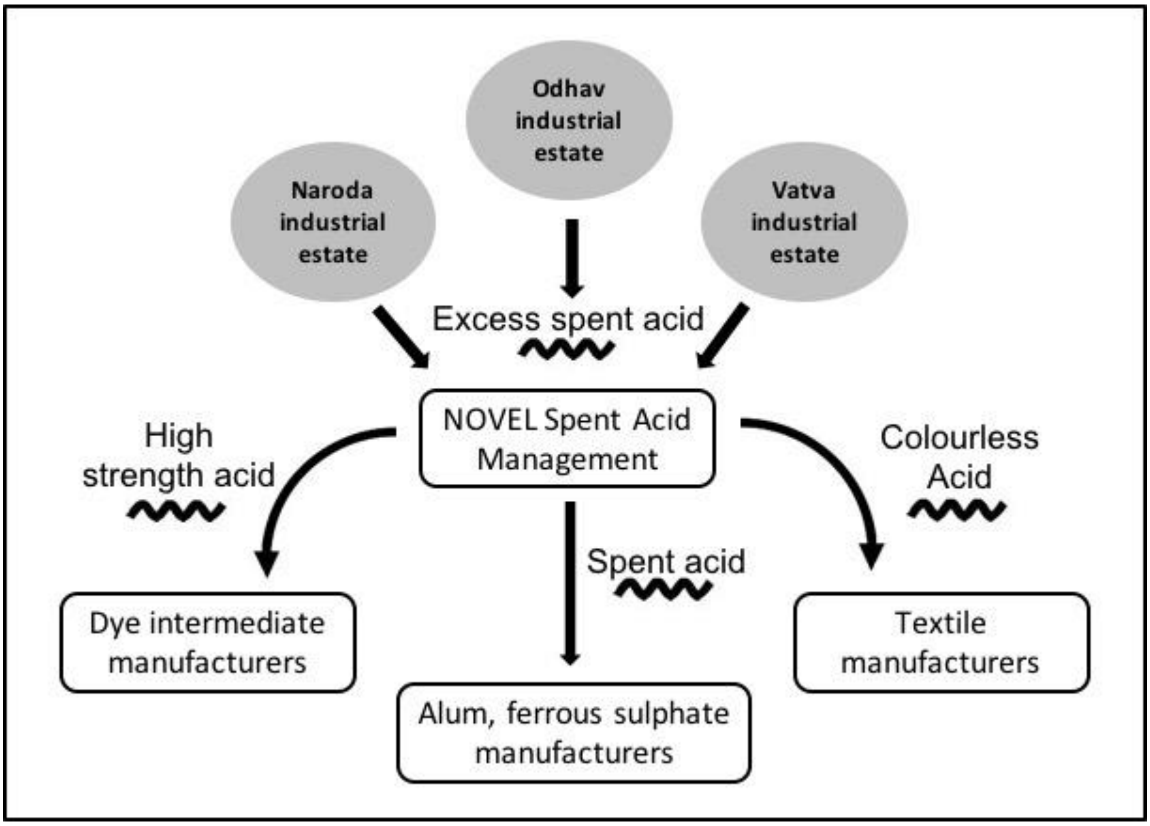

Figure 42. NOVEL acid recovery and reuse applications

Source: Author generated, based on field visits, interviews and secondary data

denotes by-products

5.1.3.2 Condensate and sludge recovery at Naroda CETP

Naroda industrial estate houses an independently functioning CETP which has a capacity to treat 14 millions of litres per day (MLD) of liquid effluent. Of the 1000 firms operational in Naroda, 250 firms, which are bulk effluent generators, are members of the CETP. A majority of these members constitute 200 dyes and dyes intermediate manufacturers; other members include 10 textile manufacturers, 10 chemical manufacturers, 15 food and allied manufacturers, and a few engineering and oil extraction firms (Naroda, 2018). Typically, a CETP is built as a shared resource for centralised effluent collection and treatment, to detoxify hazardous liquid wastes before they can be safely disposed of to landfill. In India, most large and planned industrial parks house a CETP, where state pollution control and industrial development agencies may stipulate mandatory paid membership for firms located within the park. Some small industrial estates may be affiliated to CETPs operational in nearby estates, or multiple estates may pool their resources within a common CETP facility which services multiple estates.

Most CETPs in India perform essential functions of centralised liquid waste collection, chemical or organic treatment and scientific disposal in their own or shared landfill sites. The three case studies of industrial parks at Naroda, Nandesari and JNPC, signified added symbiotic functions which enabled the recovery and reuse of industrial by-products which would otherwise be discarded in landfill. At Naroda, liquid effluents, which comprise large volumes in the dye, chemical and textile industries, are required to undergo primary treatment on firm premises, before they can be transferred to the CETP through underground pipelines. Currently, the Naroda CETP receives upwards of 3 MLD liquid effluents from dye and dye intermediates, chemical, and textile manufacturers. A separate pipeline network transfers organic wastes from food manufacturers, directly into the anaerobic digesters located within the CETP; daily volumes of 0.5 MLD from food industry are processed.

Apart from centralised effluent treatment and scientific disposal, Naroda CETP is involved in the industrial symbiosis recovery and exchange of five important material streams – *condensate* from dried effluent; *sludge* from liquid effluent; *water*, *biomethane* and *biofertiliser* from food industry wastes. Figure 43 traces the first set of by-product flows for hazardous or inorganic liquid effluents at Naroda, which are recovered into valuable materials like *condensate* and *sludge*. Liquid effluent received at the CETP from individual firms, is dried using the spray drying process to recover condensate, which is transferred back for reuse to individual firms within Naroda. Another by-product stream of sludge recovered after the spray drying process is suitable as a fuel input in cement making. This sludge is standardised centrally at the Naroda CETP before it is transported via trucks to cement manufacturers located in Gujarat state (Figure 43).

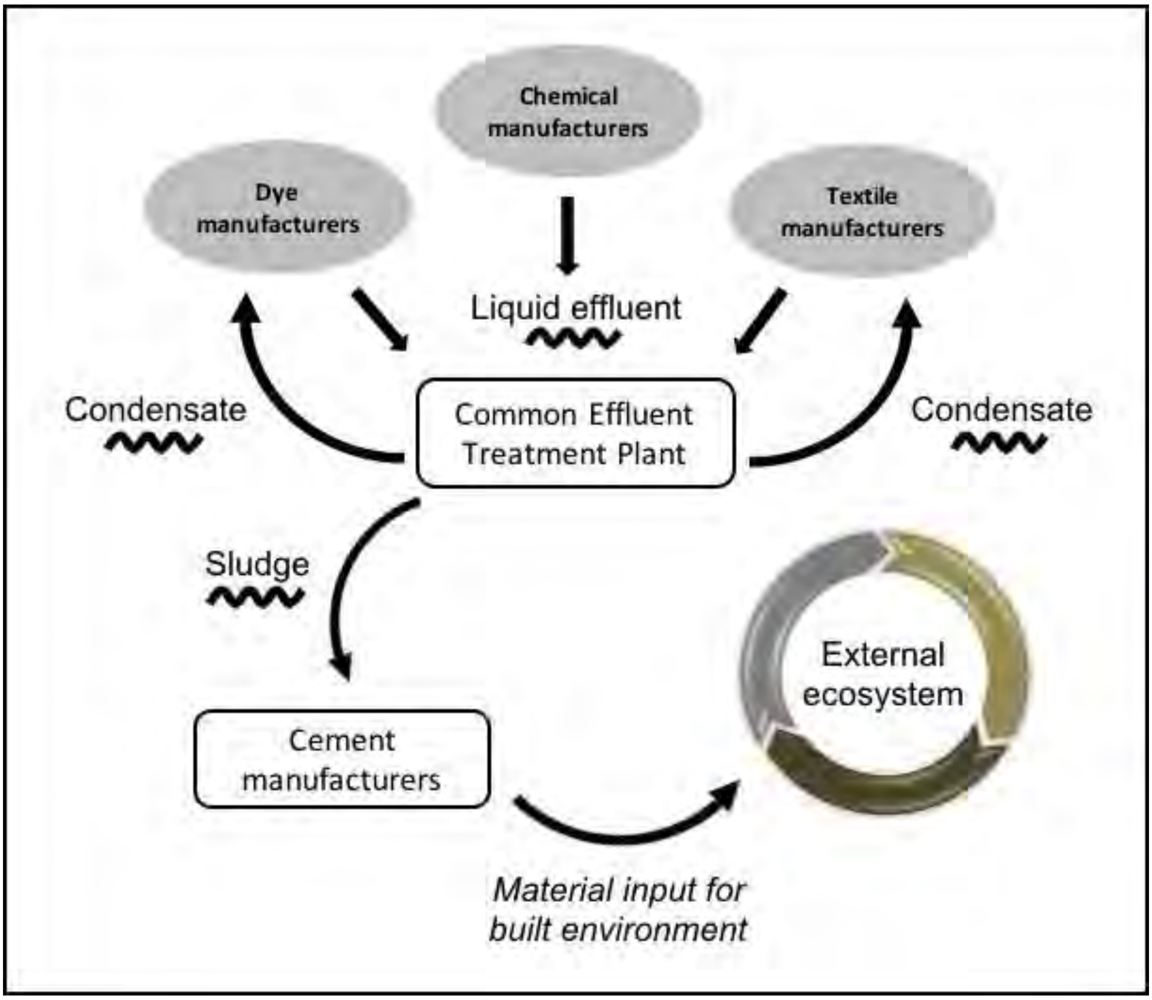

Figure 43: Condensate and sludge recovery at Naroda CETP

Source: Author generated, based on field visits, interviews and secondary data

denotes by-products

The next figure (Figure 44) illustrates flows for *water*, *biomethane* and *biofertiliser* recovered from food industry wastes. Large food manufacturers like Havmor Ice Cream and Samrat *Namkin* (snacks) operate in Naroda, in addition to a few small and medium food enterprises. After many trials, segregated liquid effluents and organic wastes from food manufacturers are now directly transferred to the CETP, independent of other effluent transfer lines for hazardous or inorganic wastes. Segregated effluent inputs into various CETP processes have improved the quality of effluent treatment and by-product recovery. Organic waste through fermentation can be used to produce biogas which is a fuel source for electric energy, heat and fuel. Its applications also include biomethane which can be connected to natural gas grids or used as compressed biofuel in vehicles (Caposciutti, Baccioli, Ferrari, & Desideri, 2020).

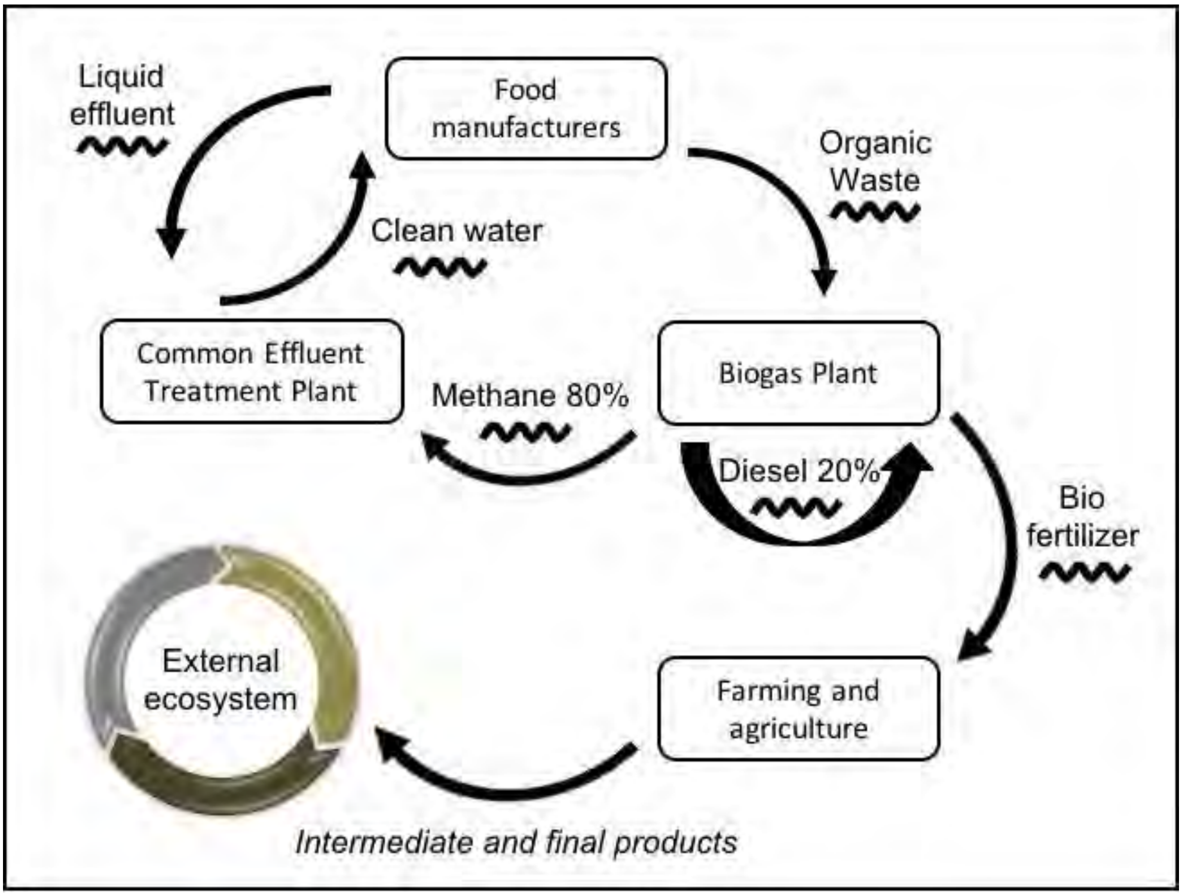

Figure 44: Biomethane and biofertiliser from food industry by-products at Naroda

Source: Author generated, based on field visits, interviews and secondary data

denotes by-products

At Naroda, organic waste streams are directly fed into the biogas plant located on CETP premises. Through the anaerobic digestion process, *bio-methanation* occurs and methane plus diesel are recovered. Some 80% of the recovered methane is used in-house to power the CETP; while 20% of the diesel is recirculated into the biogas plant. Biofertiliser generated from the biogas plant is sold to farming and agriculture users, closing the loop for food industry wastes which would otherwise be disposed of in landfill, or used as compost. Other liquid effluents received by the CETP from food producers are non-hazardous and thus can be treated to recover clean water for recirculation to firms (Figure 44). Additionally, energy efficiency improvements for water supply are in implementation at Naroda; where, drainage pump running costs were optimised and leakages avoided. Reduced power consumption resulted in lowering the average unit from 0.72 per kilolitre to 0.65 per kilolitre. Current plans aim to attain further reduction to meet global average levels of 0.55 per kilolitre.

5.1.4 Supplementary industrial symbiosis initiatives

5.1.4.1 Knowledge and community development by Naroda Industries Association

Functioning industrial symbiosis networks (ISNs) in the EU, Korea and China benefitted from strategic direction by an external body, whose function was to quantify material flows and identify prospective partners, i.e., matchmaking, for implementing material, energy and water exchange loops. In Korea and China, national government agencies with the help of local partners like Eco-TEDA in Tianjin China, expanded ISN creation. Fiscal incentives, subsidies and targeted schemes also encouraged industry uptake of the circular economy in China. In Kalundborg, Denmark, although the initial industrial symbiosis network developed spontaneously between firms with little external support, today, Kalundborg Symbiosis consults on new projects, offering technical and matchmaking advice to prospective participants.

In India, planned approaches for ISN development are evolving. Rather than a nationwide concerted effort, regional and local networks have surfaced as key drivers. At Naroda, various educational and awareness projects develop community engagement among co-located firms. The knowledge and network spill-over effects are evident in close collaboration among actors to adopt novel technologies and environmental solutions. Various events hosted by the Naroda Industries Association include: international delegate exchanges and student training (Figure 45); educational workshops with experts on hydrodynamic cavitation technology for wastewater treatment (delivered by GCPC), membrane filter preparation (delivered by TERI), waste segregation (at Havmor – ice cream manufacturer), communication, entrepreneurship and leadership management (Figure 46); social and environmental engagement with local community (Figure 47).

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Figure 45: International delegate exchange (left); student training (right), Naroda estate

Source: NIA Archives, accessed during author field visit in June 2019

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Figure 46: Educational workshops and environmental training for NIA members

Source: NIA Archives, accessed during author field visit in June 2019

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Figure 47: Community engagement initiatives at Naroda estate

School drawing competition with environment theme (left); plant sapling distribution among local communities (right)

Source: NIA Archives, accessed during author field visit in June 2019

A circular economy necessitates collaboration: either internal – within organisational departments and processes; between supply chain partners and customers; with other firms within the industrial park; and in its most evolved form, with external firms. Ample evidence points to the dynamic links between knowledge resources, relational resources, and mobilisation capacity for institutional capacity building in ISNs (Boons, Spekkink, & Mouzakitis, 2011; Wang, Deutz, & Chen, 2017). The above initiatives of NIA, such as social networks, technical education and knowledge building are contributing to the establishment of formal and informal links between actors. The interviews revealed considerable interest by individual firms to pursue less materials- and waste- intensive, and more energy efficient activities. Further, most small and medium enterprises located in Naroda have been operational for decades and have local ties, so concern for ecological improvement is a personal goal for many firm owners.

5.1.4.2 Naroda waste action centre

To enable easy identification of symbiotic exchange opportunities, Naroda waste action centre was instituted where characterised waste and by-product streams from member firms are on display. Such a shared resource is an important step for information collection and dissemination, as it enables firms to view and assess prospective symbiosis partners. It is also beneficial for the display of active exchanges and quantification of high-volume by-product categories. Most inter-firm resource exchanges do not materialise due to the absence of steady by-product supplies, or the low commercial value for those by-products. Additionally, Rule 9 of India's Hazardous Waste Management Rules (2016) lays stringent pre-approval criteria for any industrial (hazardous) waste exchanges. Thus, a common waste action centre in conjunction with technical assistance on resource reduction, recovery and exchange opportunities is a valuable knowledge resource to formalise circular economy initiatives.

5.1.4.3 Clean energy through solar panel installation

The World Resources Institute (WRI) in association with Gujarat Cleaner Production Centre and NIA, instituted a study on clean energy procurement by firms in Naroda estate (Appendix 12). The energy audit instituted by the Green Power Market Development Group, a partnership between WRI India, Shakti Sustainable Energy Foundation and the Confederation of Indian Industry, launched in India in 2013 (WRI, 2020). The Group was founded to scale up clean energy infrastructure among large commercial and industrial energy consumers in India. The project's goals for India are: to build demonstration cases for setup and cost-effectiveness of renewable energy generation at industrial sites; dissemination of renewable energy technologies and storage; creation of contracting structures; and sector-specific technical assistance for MSMEs, leading to the establishment of self-sufficient marketplaces for green energy in industrial operations (GPMDG, 2020).

Figure 48: Renewable energy initiatives at Naroda estate

280 KW rooftop solar installation at Havmor Ice Cream (top); Rooftop solar installation at Prachin Chemicals (bottom-left); Green Power Market Development Group launch (bottom-right)

Source: Author, field visits in June 2019; NIA Archives

At Naroda, the project concentrated on improving energy efficiency in MSMEs by demand aggregation and renewable energy uptake. One of the pilots was at Akash dyes and intermediates, a dye and pigment intermediate manufacturer, which started in 1994 and today, boasts annual production capacity of 1000 metric tonnes. The operations at Akash dyes were energy-intensive, with most of the energy consumed in the thermopak, thermic fluid heater, dryer and chilling systems. Based on WRI survey findings, compressor modifications yielded 1 hour of runtime savings, culminating in 9KW annual energy savings. Other upgrades planned as a result of the study include increasing efficiency of the cooling tower from the current 60%, and thermopak to improve efficiency to 90% (GPMDG, 2020). In order to scale up renewable energy infrastructure across Naroda estate, NIA has established special guidelines for member industries to access technical guidance, vendor contracts and expert training in regards to solar panel installation on factory premises. Numerous rooftop solar installations were visible throughout the estate (Figure 48).

5.1.4.4 Shared services

NIA manages most of the shared services and common infrastructure in Naroda. Recent LED street light upgrades, road works and domestic waste collection drives have improved energy efficiency and transport systems within the estate. An onsite nursery, developed along with the Forests Department, is responsible for maintaining the green belt and regular tree plantation drives to engage the local community. Additional projects include landfill beautification where a temple and community hall have been built above an old landfill site; training and mentorship for students; employee skill development and education programs. The onsite hospital is equipped for primary treatment and services industrial and residential consumers in the area. Fire safety workshops and installation of hydrant systems on individual units, along with the common fire station, all contribute to health and safety measures to minimise accidents. A fully equipped state of the art training centre on NIA premises is used for park-wide workshops and seminars. The shared space fosters inter-firm collaboration and knowledge sharing through formal and informal networking events (Figure 49-52).

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Figure 49: Workshops and training programs at the NIA function centre
Source: NIA Archives

Figure 50: Green belt (left) and nursery (right) at Naroda estate, managed by NIA
Source: Author field visits in April (2018) and June (2019)

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Figure 51: Community awareness and development programs

Source: NIA Archives

Translation (left image): *Naroda Industries Association*

Figure 52: Shared services and infrastructure – concrete roads (left), hospital (right)

Source: Author field visits in June (2019)

Translation (right image): *NIA Hospital Charitable Trust*

5.2 Case Study 2: Nandesari chemical manufacturing industrial park

5.2.1 Overview of Nandesari industrial estate

To complement the findings at Naroda estate, another mature industrial park in Gujarat was identified for analysis. Nandesari industrial estate is located in the city of Vadodara, around 2 hours' drive from Naroda in Ahmedabad city. Nandesari was one of five Indian industrial parks commissioned by UNIDO in 2016 for the global resource efficiency and cleaner production mission (UNIDO, 2017b). This nomination made Nandesari a logical choice for the current analysis, to possibly demonstrate additional exchange networks beyond the extensive shared services infrastructure already described for Naroda. A similar setup experience, administrative structure and array of industry association leadership and development activities were found at Nandesari. Although, Naroda had achieved higher progress through centralised planning and regular upgrading of shared infrastructure and services. In order to avoid repetition, the following case study of Nandesari industrial estate will focus on specific inter-firm resource exchanges and shared resource utilisation.

5.2.2 Park development and structure

Nandesari industrial estate, one of Gujarat's oldest estates, commenced in 1969 and comprises 250 chemical units: 200 dye and dye intermediate manufacturers, 20 pharmaceutical industries, 4 pesticide makers and a few plasticiser industries. Home to mostly small and medium enterprises, it is highly saturated and constrained by lack of land for further expansion (Figure 53-54). Spread over 214 square kilometres, the estate land was owned by GIDC and followed a similar setup structure as Naroda (Figure 40), with private enterprises invited to locate with some basic facilities built-in by state infrastructure bodies. GCPC conducted RECP assessments at 20 firms within Nandesari to identify ongoing and future resource efficiency measures. Within the first round of RECP assessments, **the annual potential to reduce** 19,427 tonnes of GHG emissions; 45,006 cubic meters of water savings; 4270 metric tonnes of material recovery; 1800 KWh electricity savings; USD 86,014 monetary savings were anticipated, through annual investment of USD 126,367 in Nandesari and Dahej industrial parks in Gujarat (GCPC, 2018b).

Nandesari is located in Vadodara, a pivotal chemical region in the state. The region specialises in the manufacture of dyes, specialty chemicals, agricultural chemicals, pesticides, and pigments. Notable state and private industrial giants are located in the Nandesari-Vadodara industrial belt. Both Gujarat State Fertilisers and Chemicals (GSFC) which generated USD 858.83 million revenue in 2016-17 and the Reliance Group, India's largest private sector conglomerate involved in the business of oil and gas, petroleum refining, petrochemicals, textiles, retail, have multiple facilities within the region. Zydus Cadila, a leading pharmaceutical firm for formulations, APIs, diagnostics, health foods, skin care and animal healthcare has manufacturing units for tablets, injectables, capsules, liquids and APIs in Vadodara (IBEF, 2018a). Massive developmental public-private partnership (PPP) projects are also underway, like the secured engineered landfill facility and water sanitation programs worth USD 4.69 million under the build–own–operate–transfer (BOOT) model. The Nandesari-Vadodara industrial belt is located closer to the commercial city of Mumbai and will be part of the Delhi Mumbai Industrial Corridor (DMIC) road and rail infrastructure upgrades for phase I.

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Figure 53: Layout of Nandesari industrial estate, Gujarat

Source: GIDC (2020)

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Figure 54: Nandesari industrial estate, Gujarat
Source: File photo, Nandesari industries association

5.2.3 Industrial symbiosis features uncovered through the study

5.2.3.1 Common boiler for circular heat-steam exchange between firms

In the final stages of construction, a common boiler will create a system of steam exchange between firms (Figure 55). This will reduce coal consumption in individual firm boilers and allow for common steam generation. Currently, coal will be the primary fuel source for the common boiler for steam generation, which will then be transferred across the estate premises through overhead pipelines. These pipelines will also facilitate inter-firm steam sharing (Figure 56), and in its full form the system will enable heat-steam exchange between firms. Circular heat-steam exchange is a common feature of advanced eco-industrial symbioses like Kalundborg in Denmark, and is central to Nandesari park's transition to becoming an eco-industrial park. The steam transfer at Nandesari will not only reduce primary coal demand but also allow the common boiler facility to function as a storehouse of excess steam, and foster an integrated network for heat-steam exchange.

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Figure 55: Common boiler at Nandesari Industrial Estate, Gujarat

Source: GCPC (2018b)

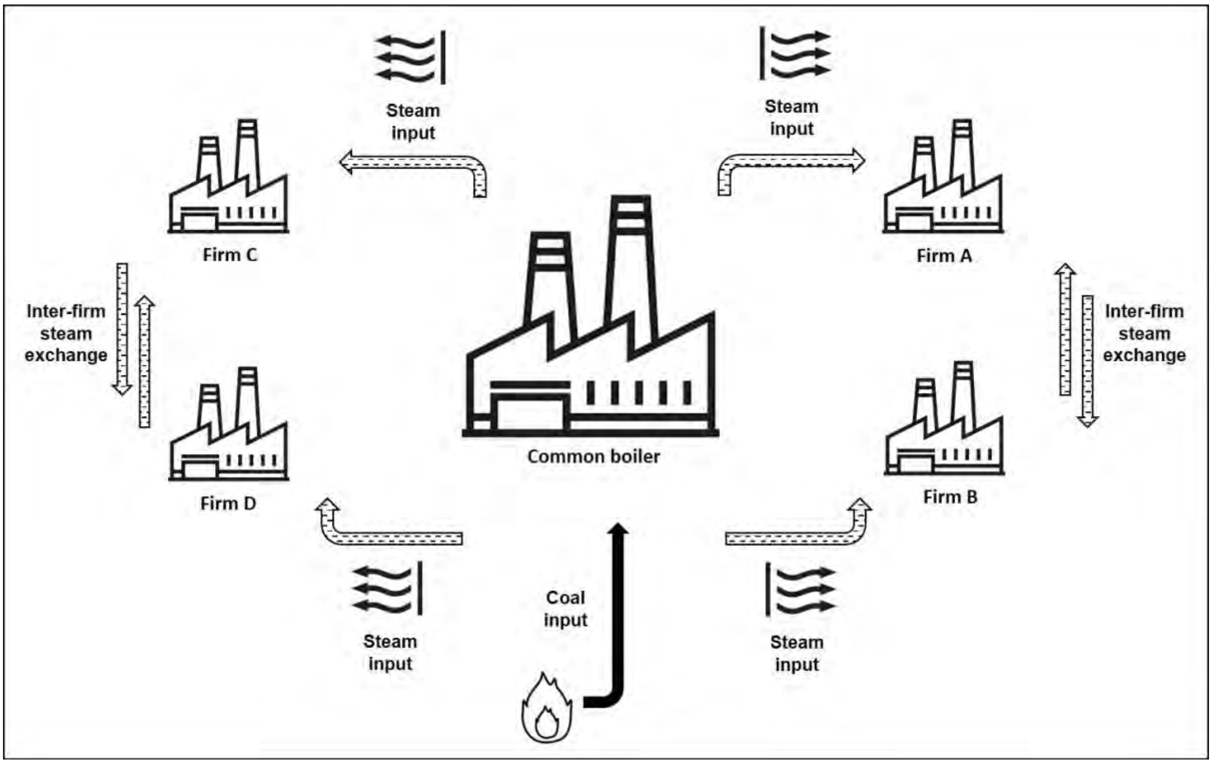

Figure 56: Inter-firm steam exchange via common boiler at Nandesari estate

Source: Author generated, based on field visits, interviews and secondary data

5.2.3.2 *Alternative fuels in cement from chemical industry by-products*

Nandesari CETP is run by the Nandesari Industries Association and is a shared resource for research and development (R&D), effluent treatment, resource recovery and reuse, and safe disposal. The CETP employs 100 people; there is no membership fee and any resident firm can access its services. The CETP processes inorganic wastes like acids, alkalis, chemicals, paints, oil, solvents, primarily from dye, pesticide and pharmaceutical manufacturers. Organic wastes like food industry by-products, ink sludge and biosolids are also treated (Figure 57). Since 2017, after pilot testing, a network of exchange has emerged where inorganic wastes with high calorific value and organic wastes with chloride content (<1.5%) are sent for co-processing to cement manufacturers. Key links in the network are pre-processing facilities like Geocycle, whose role is to standardise fuel input by treating different types and quality of by-products received from chemical industry (Figure 58).

Figure 57. Common Effluent Treatment Plant at Nandesari Industrial Estate, Gujarat
Source: Author field notes from visit in April 2018

Figure 58 explains a typical exchange between chemical industry by-product generators and cement makers; ongoing exchanges at Nandesari estate will be used to illustrate the evolution of co-processing in India. Inorganic wastes produced by pharmaceutical, pesticide and dye manufacturers, as well as organic wastes from food, dye and other chemical industry operators, along with used water are received by the CETP. Nandesari CETP receives 1 million litres of liquid discharge daily; liquid effluents were a key challenge for efficient treatment and resource recovery. Additionally, disposal costs burden industry. Organic and inorganic waste streams are processed with specific technical properties to be reused as *fuel inputs in cement manufacturing*. Inorganic wastes with high calorific value (>2000 degrees Celsius) and organic wastes with low chloride content (<1.5%) are found to be suitable for reuse as alternative fuels in cement kilns. Calorific values refer to the amount of energy produced by the complete combustion of a material or fuel. It is measured in units of energy per amount of material, e.g. kJ/kg. These waste streams are transported to external pre-processing facilities like Geocycle, which aggregate and standardise organic and inorganic wastes from multiple donor industrial estates and firms, before the alternative fuels are sent to cement makers for use in kilns (Figure 58).

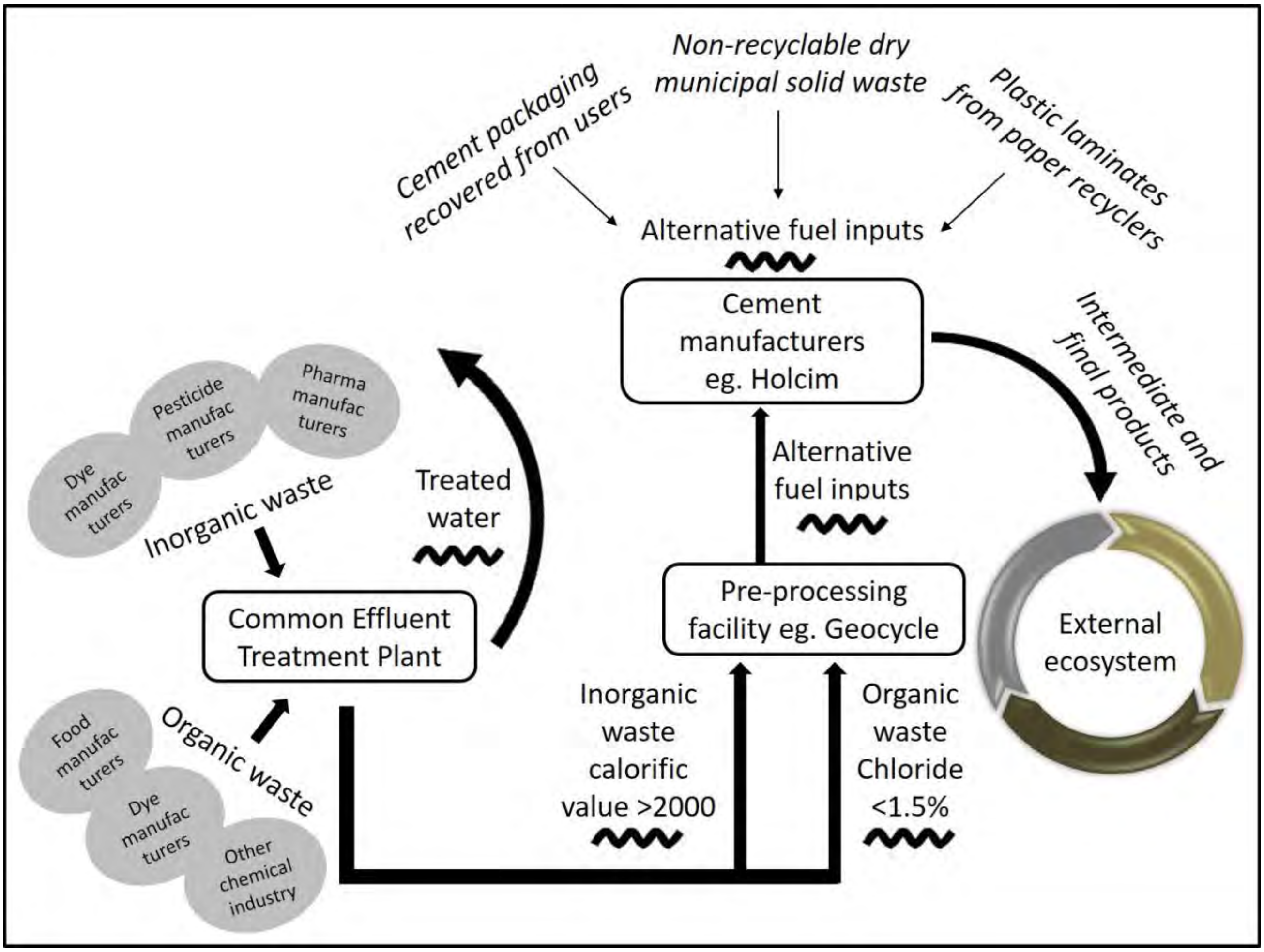

Figure 58. Alternative fuels in cement manufacture

Source: Author generated, based on field visits, interviews and secondary data

denotes by-products

Nandesari Environment Control Limited (NECL) acts as the intermediary between the CETP and the cement industry, and along with pre-processors like Geocycle, is responsible for alternative fuels and raw material (AFR) linkages in the region. Additionally, individual firms which generate by-products >25 tonnes have independent transfer agreements with cement partners, without the involvement of Nandesari CETP or NECL. Cement manufacturers also employ additional waste streams for fuel input in cement kilns; for example, the recovery of cement packaging from end users, non-recyclable dry municipal solid waste, plastic laminates from paper recyclers – efficient and scalable recovery mechanisms are in place to feed such non-recyclable materials as fuel in cement production (Figure 58).

Waste paper recycling is widespread by formal and informal recyclers. Technically-sound recyclers employ mechanical processes to recover plastic laminates from waste paper; removal of plastic is essential when pulp is being made from waste paper, to be reused in newspaper printing or packaging. Previously it was a challenge for paper recyclers to dispose of or reuse the recovered plastic, but the laminates are now being sent to cement manufacturers as fuel input owing to their high calorific value. In addition to using processed waste, reverse logistics are in place to use discarded cement packaging, non-recyclable municipal solid waste as well as plastic laminates from the paper industry, as fuel in cement kilns. Specifically, those materials which have reached the end of life, with no further recycling capacity and with high calorific values, are appropriate for alternative fuel use. This reduces dependence on coal as a primary fuel to fire cement kilns.

The R&D centre located onsite at the CETP offers technical expertise, equipment and technologies for waste/by-product characterisation, matchmaking between donor and recipient firms, and prospecting reuse/ exchange opportunities. The R&D centre is a shared service accessible to all member firms within Nandesari. Unlike most shared services, Nandesari CETP is a profit making entity with USD 0.7 million revenue annually. As there are no membership fees to provide a revenue source for the CETP, firms are required to pay based on volume of discharge. Another novelty is the decision to avoid effluent transfer through underground pipelines; instead tankers are deployed for regular collection and transportation of effluent from firm sites to the CETP. This decision was taken to maximise quality control and minimise nonconformity to environmental norms. Other issues like illegal discharge, parallel discharge of untreated effluent, mixing of effluent streams and data misrepresentation are also circumvented.

The CETP's operations are integral to the industrial symbiosis network at Nandesari. This CETP has received many accolades, including endorsement from industry partners, central and state governments. The project is lauded as a national demonstration site for chemical effluent management, and this CETP model is being replicated at other industrial parks in Gujarat including the upcoming petrochemicals park in Dahej. Chemical clusters across India have also modelled their effluent systems and technologies after Nandesari's singular success.

5.2.3.3 Water circularity to reuse wastewater and replace groundwater

Freshwater is a scarce resource in the region where supply is severely impacted due to excessive groundwater extraction for industrial use and recurrent impacts of recent droughts. Nandesari estate has established reverse osmosis (RO) treatment facilities, to enable wastewater reuse in estate operations. Despite the ongoing reuse of treated effluents, high water requirements for dye and chemical manufacturing still requires the extraction of groundwater to meet current demand. As a solution to expand their supply network for wastewater, the industries association is in the final stages of formalising an underground pipeline exchange with a co-located petrochemicals refinery, Reliance Industries (Figure 59). The refining giant operates on a site next to the Nandesari industrial estate, and initial estimates suggest the generation of 11 MLD volumes of effluent water from the refining operations. Current demand for water at Nandesari is 12 MLD; thus, once operational, the exchange will replace almost all groundwater used in the Nandesari estate.

The ISN will involve the transfer of coolant water from Reliance Industries' refining site in Vadodara, to the wastewater treatment facility at Nandesari Environment Control Limited (NECL). After treatment, the *recovered water* will be supplied to firms within the industrial estate, through the existing distribution network (Figure 59). When fully operational, all the current water demand within the estate will be fulfilled through this exchange, negating the need for further groundwater extraction. Prior to this exchange, some effluent water was being recovered for in-house use at Reliance, but a significant quantity (11 MLD) was still being disposed of at sea – leading to non-utilisation of existing resources (wastewater that can be reused after reverse osmosis treatment), as well as degrading marine biodiversity in the region. In order to close the loop, used wastewater from firms within the estate is already being recirculated back via the CETP (Figure 58-59).

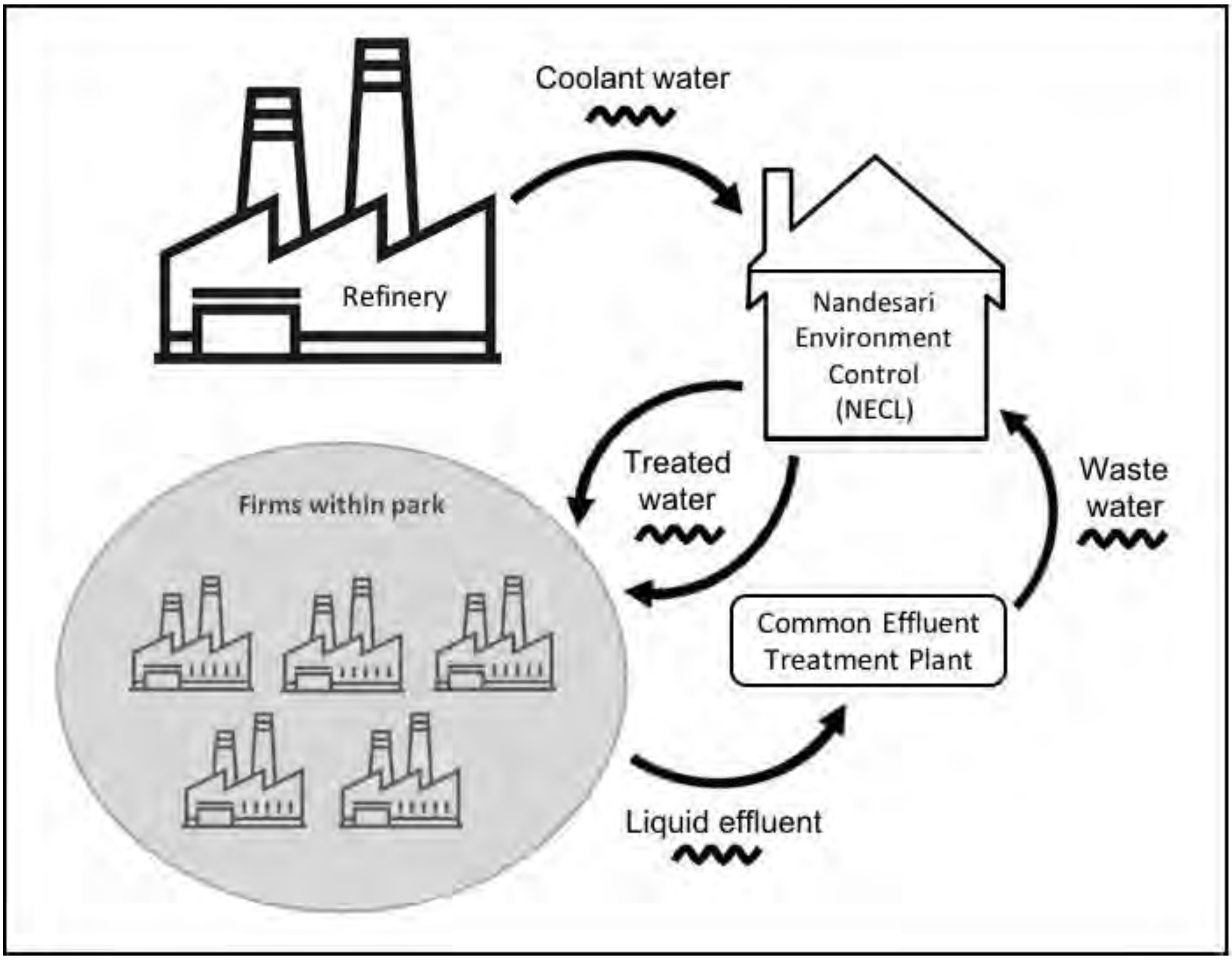

Figure 59: Closed loop wastewater circularity at Nandesari

Source: Author generated, based on field visits, interviews and secondary data

denotes by-products

Wastewater received at Nandesari CETP is treated through a unique advanced oxidation process; where quality treated water is fed back to firms for reuse, in farming and gardening, as well as use in sewage systems and cleaning. The advanced oxidation plant at Nandesari is a global first and has 12 MLD capacity; the treated water is colourless and meets international standards for water audit and reuse. Once formalised, the wastewater exchange between Reliance refinery and Nandesari industrial estate will be a mammoth industrial symbiosis network between two major private operators in India. An otherwise idle resource (for the refinery) will pose an opportunity for Nandesari estate to eliminate precious groundwater extraction. In addition to environmental and social benefits, monetary savings of 13 cents per kilolitre are likely for industrial-users. The current cost of groundwater for industrial users at Nandesari is 47 cents per kilolitre; this cost is expected to fall to 33 cents as soon as the exchange is operational.

5.2.3.4 Scale economies for alternative fuels co-processing at Nandesari estate

The recovery of industrial by-products for reuse as *alternative fuels* in cement making is well-known; yet, limited functional industrial symbiosis networks for this co-processing have been reported in India. The exchange network identified at Nandesari is a promising example of inter-firm and cross-sector synergies for chemical by-products, which may have limited reuse possibilities elsewhere. The interesting facets of this network are the emergent scale economies illustrated in Figure 60, based on co-processing data supplied by Nandesari Environment Control Limited (NECL) for treated inorganic and organic wastes received from the CETP in the period October 2017 to June 2019.

Regardless of their direct involvement, cost and knowledge benefits spill over to all actors owing to formal activities of the Nandesari Industries Association and informal social networks. Moreover, there are a small number of sizeable cement players which are involved in co-processing in Gujarat (Appendix 13). Henceforth, we will proceed with the assumption that all actors involved in alternative fuels transfer at Nandesari bear similar costs and advantages, i.e., cost reduction for volumes transferred by NECL will imply cost reduction for individual firms too. And overall, higher volumes of alternative fuels received by cement producers will lead to greater economic benefit for chemical and cement industry actors.

While the aggregate waste volumes remained more or less steady during the period of analysis (Appendix 14), the share of waste being sent for co-processing has surged (Figure 60). Since August 2018, a monthly average of 25% inorganic and organic wastes were being sent for co-processing. The corresponding decreases in disposal/transfer charges to the chemical industry are significant. Previous costs of USD 195 per tonne have plummeted to a steady USD 59 per tonne (Figure 60). By the middle of 2020, these costs were anticipated to drop to USD 13.32 per tonne. These changes will further encourage chemical producers to participate in co-processing, and present a strong case of the learning curve benefits and scale economies being witnessed in Gujarat's co-processing landscape.

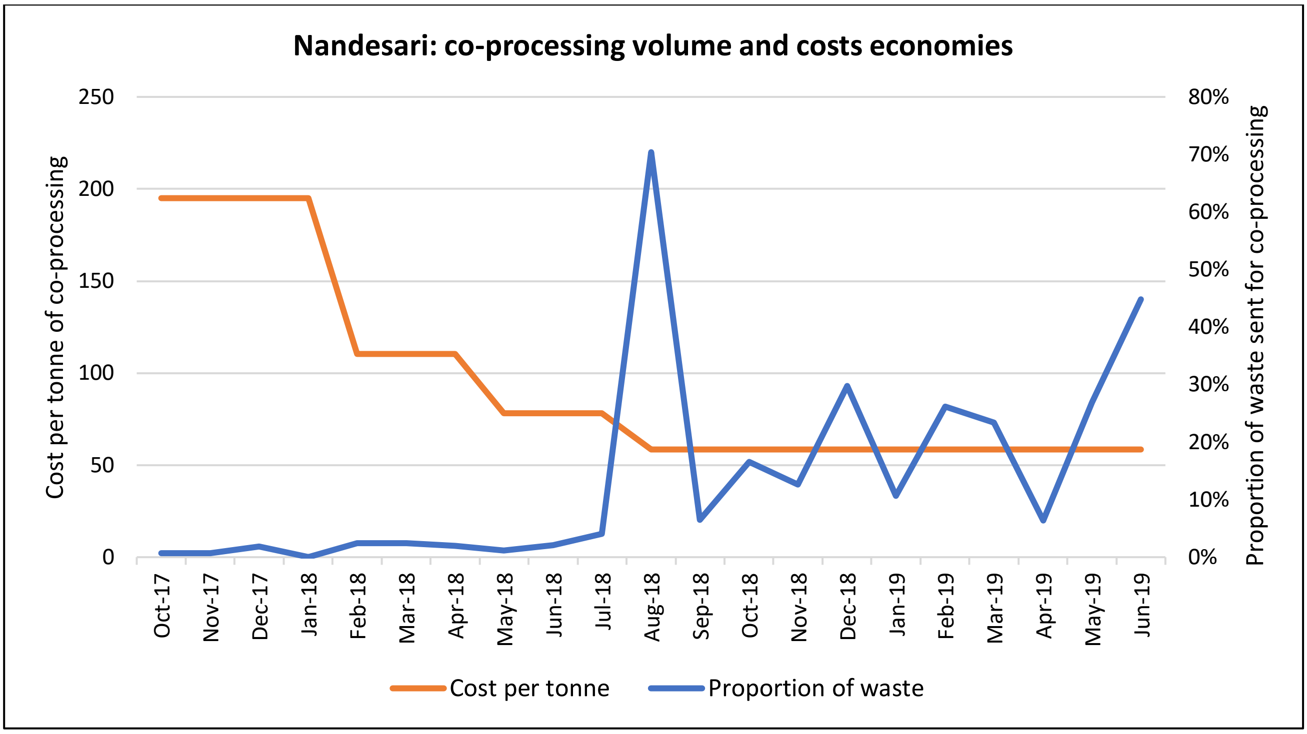

Figure 60: Scale economies for alternative fuels co-processing at Nandesari estate

Source: Author calculations, based on data records of NECL (2019)

By contrast, for cement makers, co-processing is a supplementary revenue source. In addition to replacing the use of coal, purchased at USD 80 per tonne, cement makers can now earn USD 59 for using alternative fuels: a **175% gain in earnings**. The economic imperative for co-processing is robust; in order to increase uptake, timely dissemination of information and use cases are imperative. Efficiency improvements owing to technical improvements, R&D and technology implementation will increase the pace of alternative fuels and raw materials (AFRs) adoption in India. At this stage, the application cases that have emerged have mushroomed organically and no external incentive or financial support is being extended for AFR implementation (NECL, 2019). The industrial symbiosis network for alternative fuels at Nandesari is yielding a viable business model as a means of expanding the share of co-processing in India's cement sector.

5.3 Case Study 3: Jawaharlal Nehru Pharma City pharmaceutical manufacturing park

5.3.1 Indian pharmaceutical industry's prominence in global generic drug manufacturing

The Indian pharmaceutical sector is segmented into Active Pharmaceutical Ingredients (API), Contract Research and Manufacturing Services (CRAMS), Formulations, Biosimilar, and was valued at USD 33 billion in 2017 (IBEF, 2019a). Sun Pharma, Dr. Reddy's Laboratories, Cipla, Lupin and Piramal are all big Indian multinationals. It is estimated that there are 10,500 manufacturing units and 3000 firms operating within the sector; pharma manufacturing clusters are situated in the states of Himachal Pradesh (north), Hyderabad, Andhra Pradesh (south), Gujarat, Maharashtra, and Goa (west) (Figure 61). The high demand for generic drugs in developing markets has made India a key supplier and consumer. India has 20% in global exports of generic drugs and its domestic generics industry is expected to reach USD 27.9 billion by 2020 (IBEF, 2019a).

The 1970 Patent Act was a turning point in India's history for the creation of a dominant domestic pharmaceutical industry. The Act abolished composition patents for food and drugs, giving birth to a vast domestic market for generic drugs manufacturing. The lack of patent protection was detrimental to international pharmaceutical firms operating in India at the time, major global players scaled back Indian operations. This period of flux attracted domestic innovation and led to India's ascendency in reverse-engineering and low-cost generic drug manufacture. In January 2005, India amended the Patent Act for the first time in to include product patents as a means of attracting international pharmaceutical investment, on account of patent protection by the WTO's Trade-Related Aspects of Intellectual Property Rights (TRIPS). The TRIPS agreement offers safeguards for affordable and accessible health care to vast populations in developing countries.

Generic drugs have the highest share (70%, revenue terms) of the Indian pharmaceuticals sector. Within biotechnology, biopharmaceuticals (60%) constitute the largest, bioservices (18%) and bioagri (13%). The sector overall comprises at least 50% Indian firms, this share is higher at 72% for biotechnology. The pharmaceutical sector is a vast employer; Indian firms have an expanding presence in the exploding semi-urban and rural healthcare markets; whereas, international firms are geared towards high-end patented drug manufacturing with 10% market share (IBEF, 2019a). Green chemistry is an opportunity to reduce resource dependence and the environmental impacts of pharmaceuticals manufacture. However, high initial investments and research expenditure are current barriers. A recent conference by Telangana State Pollution Control Board saw participation from by pharmaceutical majors Bristol Myers Squibb India, Laurus Labs, Hikal, Natco Pharma, GVK Biosciences and Pfizer India Healthcare, to design a plan for green chemistry adoption for improved resource and environmental sustainability in API production[17]. Industry bodies like Bulk Drug Manufacturers Association of India, PHARMEXCIL and Pharmaceutical Supply Chain Initiative are also promoting adoption.

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Figure 61: Key pharmaceutical ventures in Indian states
Source: IBEF 2019

This case is a critical examination of the eco-industrial initiatives at Jawaharlal Nehru Pharma City (JNPC), which began as a public-private-partnership to specialise in pharmaceutical bulk-drug and contract manufacturing. Positioned as India's first planned 'eco' industrial park, not much has been reported about the park's operations and accomplishments in circular economy. Most marketing and information targeted large pharmaceutical firms to locate within the pharma city, offering a range of benefits including quick setup and approval, specialised services, skilled labour availability and centralised waste management. In order to gain qualitative information on stakeholder roles and implementation models, the researcher conducted field visits and

[17] Sharma, R. (2019, June 3). India's pharma API industry discusses green chemistry concepts, e-article. *Express Pharma*. Retrieved from https://www.expresspharma.in/market-pharma/indias-pharma-api-industry-discusses-green-chemistry-concepts/407920/

interviews with varied actors such as: the private park management, firms and industry representatives, state pollution control board, waste infrastructure managers, and local community members. A review of JNPC's 'zero waste' goals is presented here, in addition to industrial symbiosis facets uncovered through the study.

5.3.2 Overview of Jawaharlal Nehru Pharma City

Jawaharlal Nehru Pharma City (JNPC) in the port city of Vizag (also known as Visakhapatnam), is home to leading Indian and international bulk drug manufacturers. PharmaZell of Germany, Eisai Pharma of Japan, Biocon and Laurus Labs of India, and US multinational Hospira Healthcare are notable occupants (JNPC, 2019). Spread over 1012 hectares including a 100% export-oriented Special Economic Zone, operations of 75+ bulk drug manufacturers in JNPC range a variety of pharmaceutical and chemical applications. The park offers end-to-end facilities for research, development and production of Active Pharmaceutical Ingredients (API), and a host of shared services align with facets of an eco-industrial park.

Of 103 registered firms, 75 are fully operational and 15 are at various stages of setup. JNPC specialises in attracting firms involved in the manufacture of API, and is home to more than 15 United States Food and Drug Administration (USFDA) approved plants. The employment potential of the park is over 20,000 people, in addition to peripheral employment. Internationally, industrial symbiosis networks have been successful at varied scales: Plant Chicago has 16 food businesses located within a 0.8 hectare facility; whereas, Tianjin Economic-Technological Development Area (TEDA), China, spread over 40,500 hectares, has multiple economic zones and RMB 1.3 trillion (Chance et al., 2018; Mathews & Tan, 2011). JNPC may be classified as a mid-to-large scale industrial park (Figure 62-63).

Firms located within JNPC accrue major advantages in terms of speedy setup, supply chain links and skilled labour availability. Typically, firms need to seek formal Consent to Establish/ Consent to Operate from the Andhra Pradesh Pollution Control Board and Andhra Pradesh Industrial Infrastructure Corporation. A standard approval process can take up to 2 years; for firms within JNPC, this is secured within a few months due to blanket federal approval for all firms complying with JNPC standards. Project setup cost savings of up to 40% and faster returns are possible. Due to strong internal and external supply chain efficiencies, the entire industrial ecosystem at JNPC runs proficiently in one location; thereby, improving productivity, optimising performance and more importantly, reducing environmental impact through lowered resource use and emissions.

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Figure 62: Layout of Jawaharlal Nehru Pharma City, Vizag, Andhra Pradesh, India

Source: JNPC (2019)

Figure 63: Aerial view of Jawaharlal Nehru Pharma City, Vizag, Andhra Pradesh, India

Source: Author field visit, December 2017

5.3.2.1 Internal supply chain linkages in JNPC

The supply chain for pharmaceuticals spans manufacturers of raw materials, intermediates, API bulk drugs and formulation; many of these products are produced on JNPC premises. In pharmaceutical phraseology, if the final product is ‘n’, supply chain partners within the park make ‘n-2’ stage of materials. Plot sizes range from 1 hectare to 20 hectares, allowing for diversity in size and scope of operations. Intermediates manufactured onsite are sent to API manufacturers, who in turn supply to larger pharmaceutical companies. The immediate benefit of such co-located supply chain efficiencies is the reduction in transport and logistics costs, as well as decreased energy/ fuel impact.

5.3.2.2 External supply chain linkages in JNPC

Located on the outskirts of the pharma city are other major pharma players, giving easy access to further materials, manpower, specialised knowledge and resources. It is estimated that by 2022, this zone will contribute $1/3^{rd}$ to India's pharma output. Convenient access to seaport, airport, road and rail networks make JNPC's location a prime advantage. A deeper, more significant impact, is the avoidance of transporting hazardous/ flammable chemicals (liquid nitrogen and liquid oxygen) over long distances. Liquid nitrogen and liquid oxygen production units are located onsite. These benefits have a cascading effect of knowledge and technology transfer between co-located firms.

5.3.3 Park development, management and administration

Historical and political events in the last two decades had a significant role in the formation of JNPC. Until 1999, the capital city of Hyderabad in Andhra Pradesh state was a bulk drug manufacture hub. In 1999, industrial expansion of pharmaceuticals was restricted when state and federal courts issued *bans,* owing to rising pollution levels in Hyderabad. Chief Minister, Mr. N. Chandrababu Naidu (1995-2004, 2014-2019) pushed for alternate sites and Vizag city was suggested as being well-suited for a pharma centre. The Andhra Pradesh Industrial Infrastructure Corporation (APIIC) invited private bids for JNPC with the objective of creating a model public-private-partnership (PPP) project, to serve as an exemplar for industrial parks across the state. The Build-Own-Operate model today, functions as a perpetual contract; the formal letter of intent and concession agreement were cleared in 2004. In addition, 200 hectares of land were set aside and allocated for creation of a 100% export-oriented Special Economic Zone (SEZ).

On commencement, 5 village settlements were to be displaced which raised fears of deforestation, as well as loss of human and ecological diversity. While local employment opportunities, housing and health services have eased these fears, ongoing training and assistance for land and housing loans have been extended. Ramky, the private park management, along with local government are responsible for community and support services; thus, firms are relieved and can focus on their core operations. States like Gujarat undertake rehabilitation of displaced communities by building apartment blocks and creating peripheral services before they initiate the industrial park development. Figure 64 outlines the standard setup process for a firm in JNPC. Multiple actors are involved at various stages, their activities will be examined in detail in subsequent sections.

The role of the private developer, Ramky, in the pharma city's core operations is noteworthy. The group's business includes infrastructure development, environmental management and real estate. Although a public-private-partnership, JNPC had a distinct journey where a large share of land acquisition and development was conducted by the private partner. Unlike the GIDC estates in Gujarat, where basic infrastructure was deficient due to bureaucratic ambiguity and industry associations were compelled to perform road and lighting development and maintenance, JNPC's operations are more streamlined. The private developer, Ramky, continues to run day-to-day operations including: firm approval, land allotment, setup, routine maintenance, environmental monitoring and reporting, as well as circular economy initiatives. Thus, Ramky fulfils the role of formal industrial park management, which is the norm in many countries like China and Denmark, but a very novel setup for India.

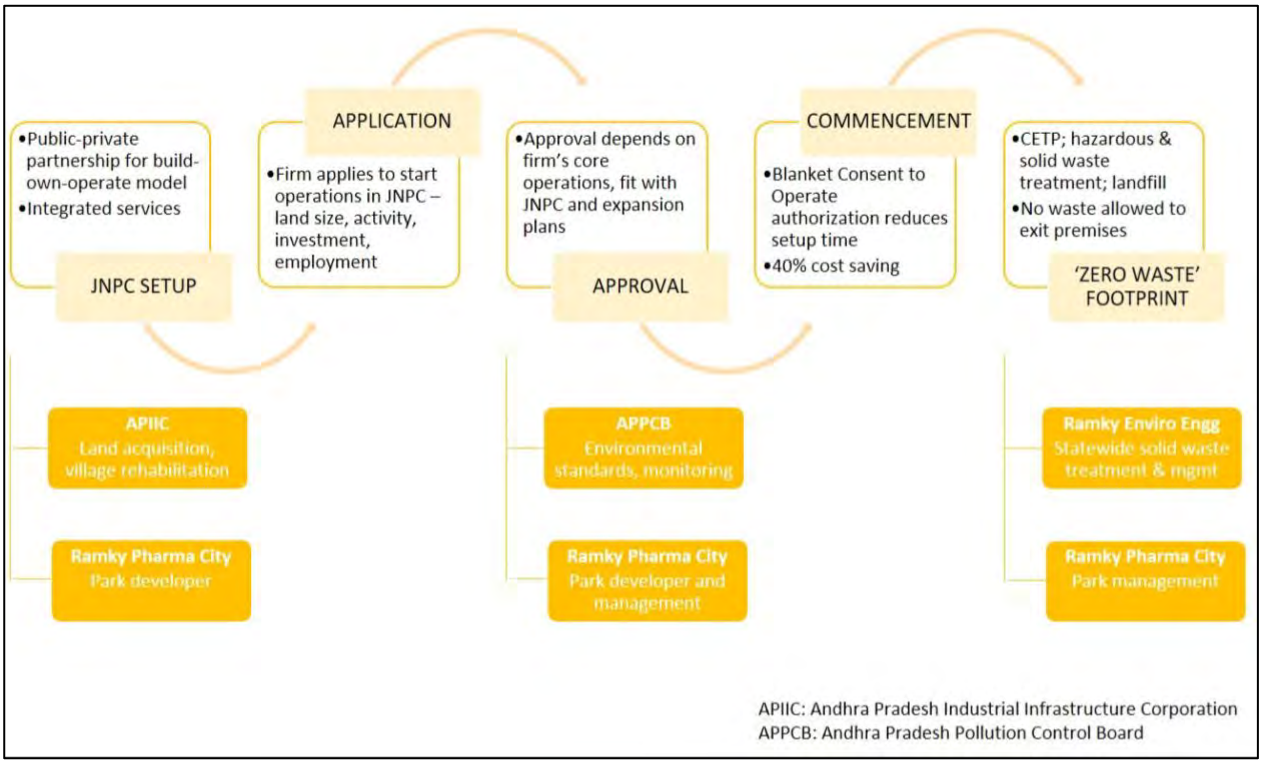

Figure 64: A summary of the firm setup process at JNPC

Source: Author illustration, based on data analysis

As a pilot project in India, the JNPC setup is hugely successful and being replicated in other sites across the country. For example, the Andhra Pradesh state government has initiated similar plans for a multi-product SEZ in Atchutapuram; this proposal will spread over 2000 hectares, of which a big proportion will be dedicated to an integrated pharma city like JNPC. Ramky is also building specialised eco-industrial parks in other states for food processing and textile manufacturing as well as another pharmaceutical park. The business model usually follows Build–own–operate–transfer (BOOT), but in some cases like JNPC, the developer continues to develop and manage park assets in the long term.

5.3.4 Industrial symbiosis features uncovered through the study

JNPC embodies most of the locational benefits for firms operating within an industrial park or cluster. As previously stated, a firm in JNPC saves considerable start-up costs associated with land acquisition, permissions from multiple state and local authorities, plot development, utilities like power, water, sewage, basic infrastructure like roads, lighting, security, and the green belt. The ready-to-go site plan and blanket consent to operate affords considerable time savings for firms. Additionally, the shared research and development incubator is a unique advantage for pharmaceutical start-ups. The initiation of a pharmaceutical plant is an extremely capital intensive venture, and a big barrier for small firms. The ease and flexibility extended to firms for locating within the JNPC incubator fosters entrepreneurship and innovation, making the region a more competitive player in India's contract pharmaceuticals manufacturing sector. A senior official from Ramky defined eco-industrial parks as "…Concentration of energy usage should be low/ energy concentration per unit area should be minimum; use of renewable energy; by-product exchange networks should be developed within park premises to ensure maximum raw material and waste utilisation; sector specific benchmarks would be needed to ascertain eco success; adoption of green chemistry and green solvents". This definition aligns with theoretical underpinnings of industrial ecology and the circular economy. A number of industrial symbioses, uncovered during the field study, are discussed below.

5.3.4.1 Integrated services and shared infrastructure

JNPC offers a host of integrated services and shared infrastructure for firms located within the park. Basic common infrastructure includes: roads, power, lighting, water, central canteen, green belt, health and safety; incremental services include underground pipelines for effluent transfer, a common effluent treatment plant, hazardous waste treatment, water treatment, and scientific landfilling. Fire services, hospital, banks, courier services and a police outpost are available to firms as well as local residents. For knowledge and capacity building, an incubator and common research and development centre operate to get start-up enterprises off the ground (Figure 65-66). Most firms offer bus transfers for employees to and from the city, reducing emissions impact through less reliance on personal vehicles. The resultant efficacies reduce spillages and wastage, cut down transportation costs and linked emissions.

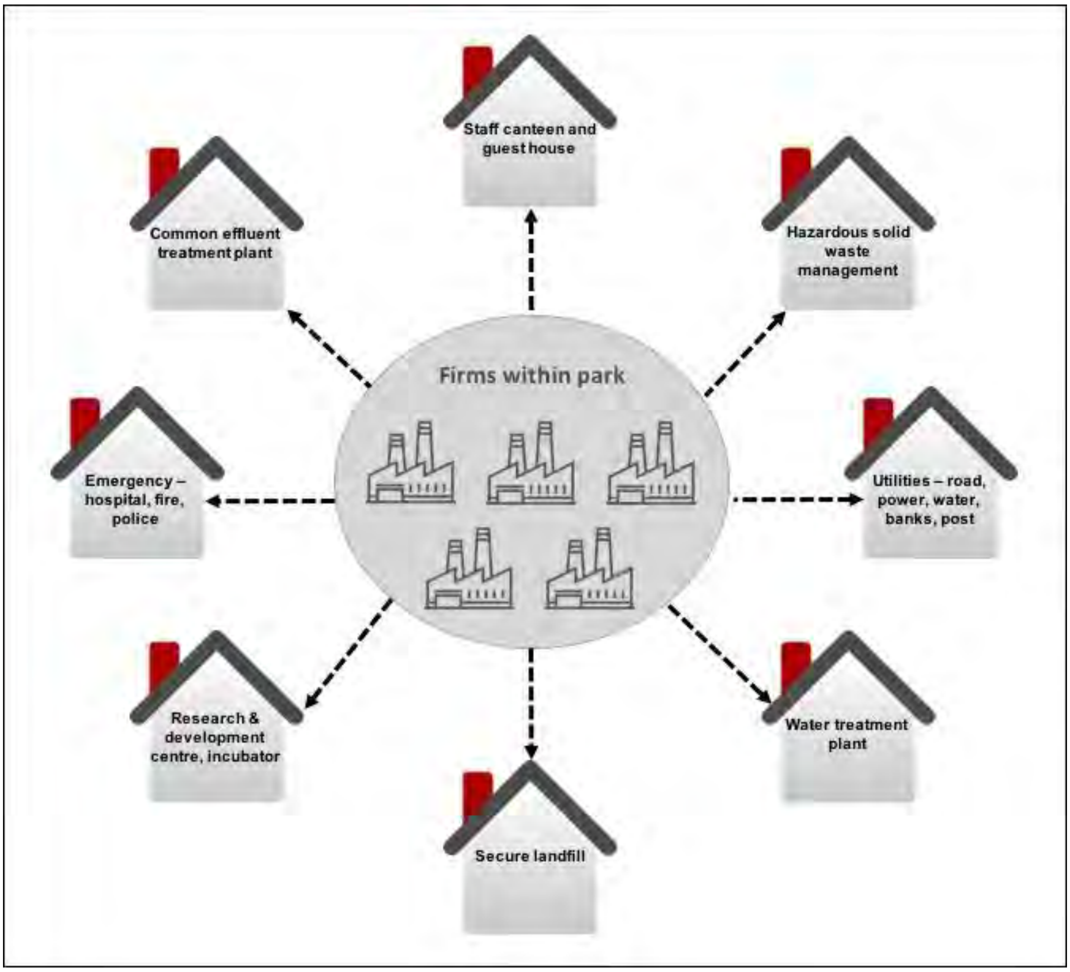

Figure 65: Integrated services and shared infrastructure at JNPC
Source: Author illustration, based on field visits, interviews and secondary data

The shared research, development and incubation centre run by Ramky enables smaller firms during start-up and the early stages of manufacture. The JNPC incubation centre offers financial support and equipment for initiation. Currently, 10 labs operate at the centre in contract research and manufacture, some with USD 1.5 million in turnover. The lab obtained government permission to allow the manufacture of up to 10 kilograms of any molecule for commercial sales. Beyond this limit, the firm is required to register as an independent entity and go through the normal setup process in JNPC. In addition to assisting with faster commercialisation and financial viability, the incubation period also sets off a long production setup period of up to 2 years for independent operations. Short-term barriers like seed capital, lack of market experience and R&D infrastructure are replaced to nurture innovation at JNPC.

Figure 66: Shared services at JNPC
Source: Author field visit, December 2017

Formal and informal interactions owing to the ample shared services and a sense of community create opportunities for inter-firm collaboration and knowledge sharing. Past experiences have shown the virtues of strong inter-firm networks for the building of *institutional capacity* in the context of industrial symbiosis, through *knowledge resources, relational resources, and mobilisation capacity* (Boons et al., 2011; Wang et al., 2017). Air quality sensors across the park feed live data into state and federal Pollution Control Board systems, to measure, track and mitigate emissions. Two secure landfill sites are used for hazardous waste disposal as a final solution; layered outer shells confine leachate and moisture seepage.

5.3.4.2 Zero waste operations

Pharmaceutical manufacturing is also extremely materials intensive: for 1 kilogram (kg) of end product, 10-100 kg of raw material input is required, the remaining excess materials are available for recycling internally or are most likely for disposal. Dependence on the use of solvents like methanol and acetone, toxicity of by-products, and the imbalance between end product/ raw material inputs, position the industry at a comparative disadvantage for resource efficiency programs. To address these difficulties, JNPC initiated a *zero waste policy,* to encourage recovery, reuse or treatment of industrial by-products before safe disposal. JNPC's zero waste policy is geared towards recovering value from material by-products and managing waste onsite so as to have minimal environmental externalities, and in order to encourage firm-level circular innovation.

Recovery and reuse of by-products like spent solvents, salts, organic and inorganic chemicals is encouraged. After internal recovery of solvents and chemicals, excess by-products are transferred to external partners for reuse in industrial operations. These external by-product transfers are closely monitored by the park management of Ramky, and any secondary materials or waste leaving JNPC premises requires formal approval from the Andhra Pradesh Pollution Control Board (APPCB) for reuse plans before they can exit the premises (Figure 67). While the supervision adds an administrative layer and may extend timelines initially, it does ensure accountability of waste generators and improvement in JNPC's environmental footprint.

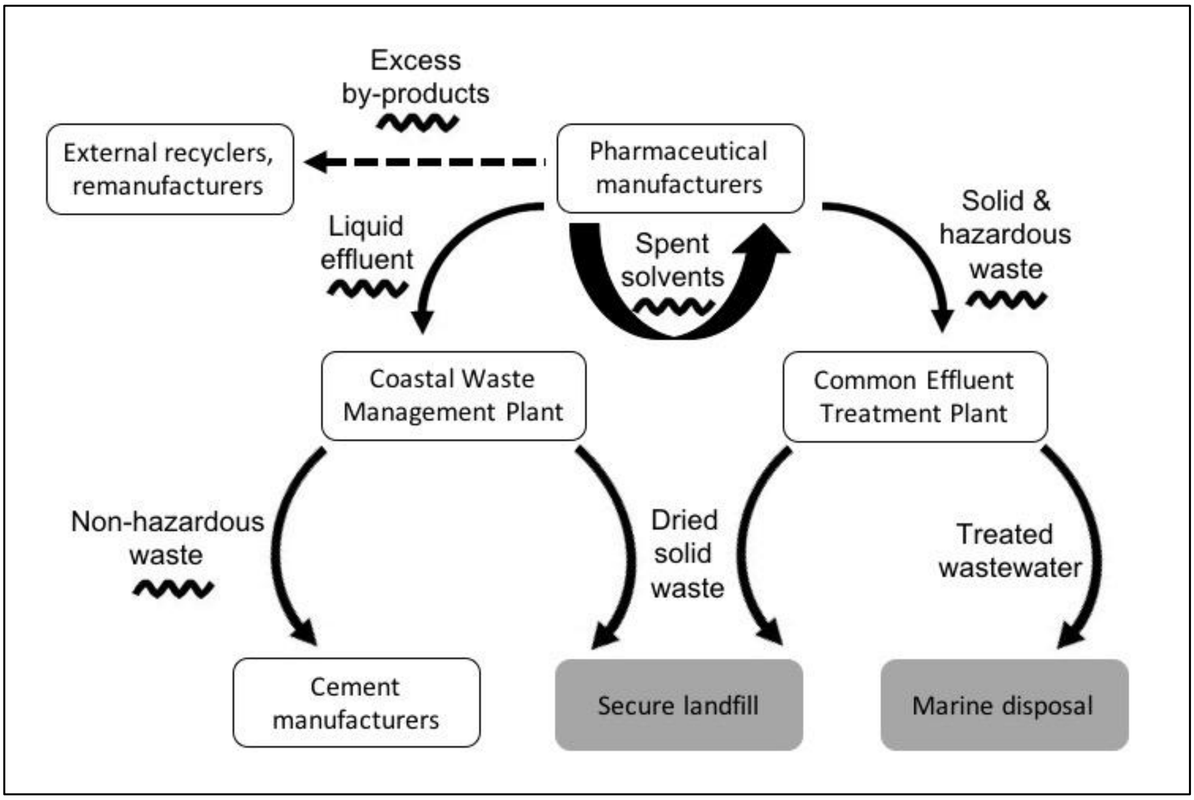

Figure 67: Zero waste initiatives at JNPC

Source: Author generated, based on field visits, interviews and secondary data

denotes by-products

In addition to internal and external by-product recovery and reuse, liquid effluents are transferred from generating sites directly to the CETP via underground pipelines. As per pollution control norms, the treatment of liquid effluents on firm premises in JNPC is restricted due to high toxicity levels, and all liquid effluent must be transferred to the CETP for centralised treatment and disposal. In addition, all hazardous industrial wastes, organic and inorganic solid wastes, as well as organic liquid wastes are transferred to the Coastal Waste Management Plant (CWMP) located on site. This operates independently of the CETP and is a shared resource for firms located within JNPC as well as other state-wide hazardous waste generators (Figure 67). Both the liquid and solid waste treatment plants are managed by park developer, Ramky's environmental management arms.

At present, treated wastewater from JNPC's CETP is discharged through marine disposal in adherence to local pollution control norms. There is an opportunity for reverse osmosis (RO) treatment to recover and reuse wastewater within industrial operations; however, abundant freshwater availability in the region has circumvented wastewater recovery so far. A model similar to Nandesari industrial park is conceivable at JNPC in the near future. Treated and dried solid wastes from the CETP and Coastal Waste Management Plant are sent to secure landfills located within JNPC, reducing exposure and air toxicity from external transportation. Due to highly hazardous content in pharmaceutical wastes, opportunities for recovery and reuse of solid wastes are constrained and so their scientific management and safe disposal is vital. The landfills in JNPC are scientifically designed and controlled through various protection layers to prevent leachates from entering surrounding soils. There are also ongoing industrial symbiosis exchanges between the Coastal Waste Management Plant and cement manufacturers for the reuse of non-hazardous solid wastes as alternative fuels in cement (Figure 67). Detailed recovery and treatment procedures at the JNPC Common Effluent Treatment Plant and Coastal Waste Management Plant are explored in subsequent sections.

Figure 68: Live air quality display panel at JNPC

Source: Author field visit, December 2017

An extension of the Zero Waste policy at JNPC will be to incorporate circular resource and by-product flows within the park's masterplan, as a means of recovering valuable materials and further reducing waste to landfill. In addition to the aforementioned solid and liquid waste initiatives, there is live monitoring of air emissions to check and counteract pollution levels in real time. Live air quality monitoring stations installed throughout the park record anomalies and the system is linked with the local pollution control board for immediate reporting and action (Figure 68). Regular tests are undertaken by pollution control board officials to ensure air emissions remain within limits; deviations face severe monetary penalties.

5.3.4.3 Heat-steam by-product exchange between co-located firms

Kanoria, a chemical manufacturer and Laurus Labs, a pharmaceutical manufacturer are engaged in the exchange of excess heat via underground pipelines, in order to replace the use of coal-fired boilers at Laurus Labs.

Kanoria Chemicals occupies 11 hectares in JNPC and is involved in the manufacture of 3 products:

- Formaldehyde – liquid, main application in plywood industry for moulding (supply locally to SNF India – daily 2 to 4 tonnes, Lupin, Mylan). Fully-automated plant, no-man operation, 300 tonnes produced per day, 6000 tonnes per month – average quantity dispatched.

- Hexamine – powder, some uses in pharma industry and explosives. Semi-automated plant. 200-250 tonnes per month – average quantity dispatched.
- Phenolic Resins – powder & liquid; semi-automated plant. 100-150 tonnes per month – average quantity dispatched.

Although JNPC hosts mostly pharma manufacturers, Kanoria is a chemical manufacturer which supplies within JNPC as well as externally, and to other industries. The interviewees mentioned sea port proximity as the main deciding factor to operate in JNPC, given that methanol, one of their key inputs, is imported from Indonesia. Another advantage was the transport and logistics infrastructure within JNPC. Kanoria is engaged in domestic sales as well as exports. Local buyers within the pharma city and external state-wide sales are supplied by the JNPC plant.

Laurus Labs, a pharmaceutical and intermediates manufacturer, commenced operations in 2007, with their first unit in JNPC. The firm has 6 manufacturing facilities in Vizag city, of which 3 are operational within JNPC and others located in the industrial town of Atchutapuram (30 kilometers from JNPC). Laurus Labs received many prestigious awards for employee health and safety programs; they have a staff strength of 10,000 (permanent + casual) within JNPC, and another 10,000 in Atchutapuram. Proximity to Vizag seaport, was again, one of the key reasons for the firms expansion in JNPC, raw material is procured pan India and imported from China. Additionally, the interviewee's elaborated on the technical expertise, trained labour, supply chain integration, robust infrastructure and effluent treatment at JNPC to be major plusses.

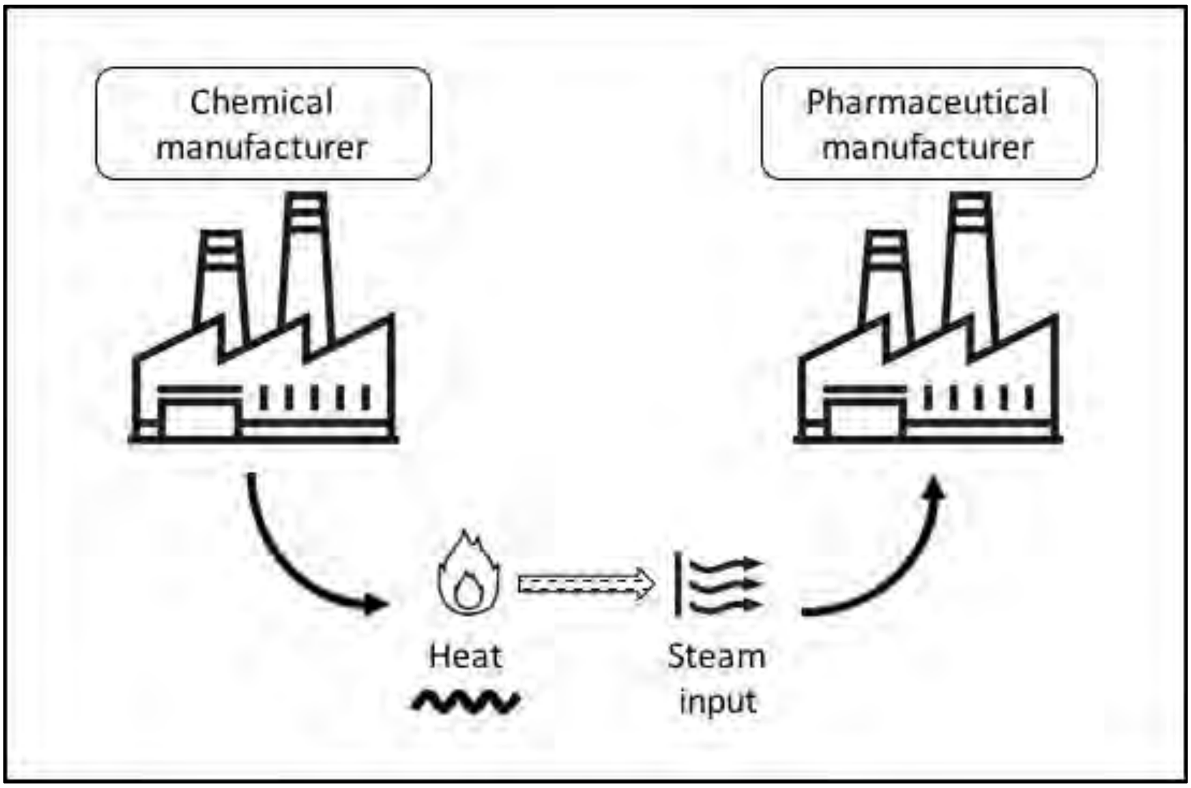

Figure 69: Heat-steam exchange between Kanoria Chemicals and Laurus Labs

Source: Author generated, based on field visits and interviews

denotes by-products

When the heat-steam exchange at JNPC was initiated, Laurus was in search of a reliable supplier of steam, an important manufacturing input. Previously, 4 in-house coal-fired boilers had supplied steam; this was not only expensive but also fossil fuel dependent with high air emissions. In the manufacture of formaldehyde at Kanoria Chemicals, exo-thermic reactions release heat which can be used to create steam. Around 2007, expanded operations at Kanoria Chemicals increased their steam output which was being released into the air (*wasted)*. The co-located firms chanced upon this mutual need through informal employee networks and soon an underground system for heat-steam exchange was established (Figure 69).

The exchange, ongoing till today, was formalised to resolve *practical material challenges*. In effect, it yielded *financial and environmental benefits* to both actors and strengthened collaboration on other projects. Kanoria earns supplementary revenues from heat that was being wasted through air emissions. Risk and impact assessment at Laurus Labs showed a reduction in carbon footprint by meeting 40% of steam demand through this exchange, enabling the retirement of 3 coal-fired boilers. This is a unique by-product exchange and makes a strong case for similar exchanges within JNPC. Globally, planned industrial parks foster a system for heat reuse through underground or above-ground pipelines. For Laurus, cost savings up to 30% accrued by replacing boiler steam with recovered steam from Kanoria.

The heat by-product exchange between Kanoria and Laurus was uncovered as a result of the study. Owing to the localised nature of the exchange and the absence of a circular economy framework at JNPC, this exchange which started in 2007 has remained bi-lateral. The practical solution for co-located firms, Kanoria and Laurus, to share excess heat as steam input, was hitherto unreported, despite the prospects of expanding such symbiotic exchanges to other actors at JNPC. Heat-steam circular loops are an intrinsic feature of advanced symbioses networks at Kalundborg and TEDA. Yet, in India, a planned infrastructure to enable such exchange is yet to be realised. The aforementioned economic and resource advantages of such a by-product exchange will encourage further adoption of circular closed loop operations between previously unrelated firms, fostering deeper connections between various actors within a symbiotic network.

5.3.4.4 Intra-firm steam and solvent reuse

In order to improve production efficiency and resource recovery within its own operations, Laurus Labs has implemented numerous by-product recovery and reuse mechanisms. Steam condensate which is a by-product of its manufacturing processes at multiple locations in JNPC, is recovered at a central facility for reuse in coolant towers. The recovered steam by-product is reused as coolant water; thereby, replacing the use of freshwater in this process (Figure 70). This resource efficiency improvement has directly reduced the firm’s dependence on external freshwater sources and resulted in cost savings. Similarly, excess solvent discharged as a result of the pharmaceutical manufacturing processes, is stored and treated for reuse. Distillation columns are installed within firm premises to decontaminate recovered solvent and make it reusable in internal manufacturing (Figure 70). The internal recovery and reuse of spent solvent has eliminated solvent disposal from landfill, which was a value loss as well as a cost intensive practice earlier.

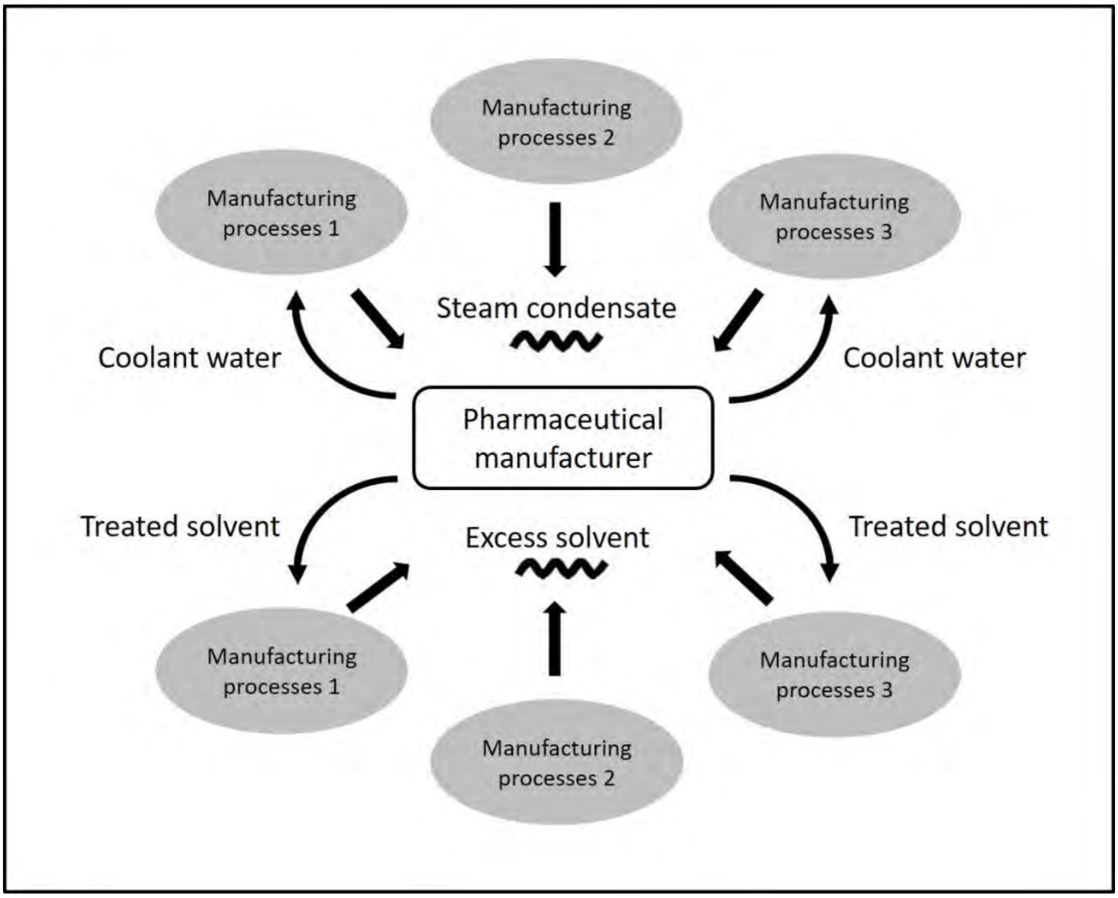

Figure 70: Circular industrial by-product flows at Laurus Labs, JNPC

Source: Author generated, based on field visits and interviews

denotes by-products

5.3.5 Supplementary industrial symbiosis initiatives

5.3.5.1 Hazardous and solid waste treatment at Coastal Waste Management Plant

The Coastal Waste Management Plant (CWMP), managed by Ramky Enviro Engineering, is one of the biggest hazardous industrial solid waste management facilities in the state of Andhra Pradesh, with over 500 member firms. Its services extend beyond JNPC, for the treatment of organic and inorganic solid wastes, as well as organic liquid wastes. As a mandatory clause in the Consent to Operate, firms within JNPC must transfer solid waste to the CWMP for treatment and disposal. Of the 36 industries identified as hazardous waste generators at the Federal level, pharmaceutical, engineering and pesticide wastes are received at JNPC CWMP.

The plant receives 10,000 metric tonnes of hazardous waste per month. The collection process depends on the type and volume of waste: bulk waste generators prefer to keep CWMP containers on site, once filled, these containers are sent to CWMP for treatment and disposal. Alternatively, CWMP sends secure transport for hazardous waste collection. Once on CWMP premises, waste samples undergo comprehensive analysis: 70-80 tests for every new waste stream or every 2 years for ongoing clients. A 7-stage system is in place to check the quality of waste and fingerprint analysis is conducted which includes 15-17 tests on regular waste inflows. Approximately 30-40 variations in waste categories are recorded every month. After testing, permissible waste flows are sent for treatment or safe disposal. Disposal methods include:

- Direct to landfill
- Treatment (stabilizer) → landfill
- Incineration – ash → landfill (organic waste not fit for direct disposal or treatment)
- Waste to fuel in cement-making (circular recovery and reuse)

5.3.5.2 Co-processing of alternative fuels from pharmaceutical wastes

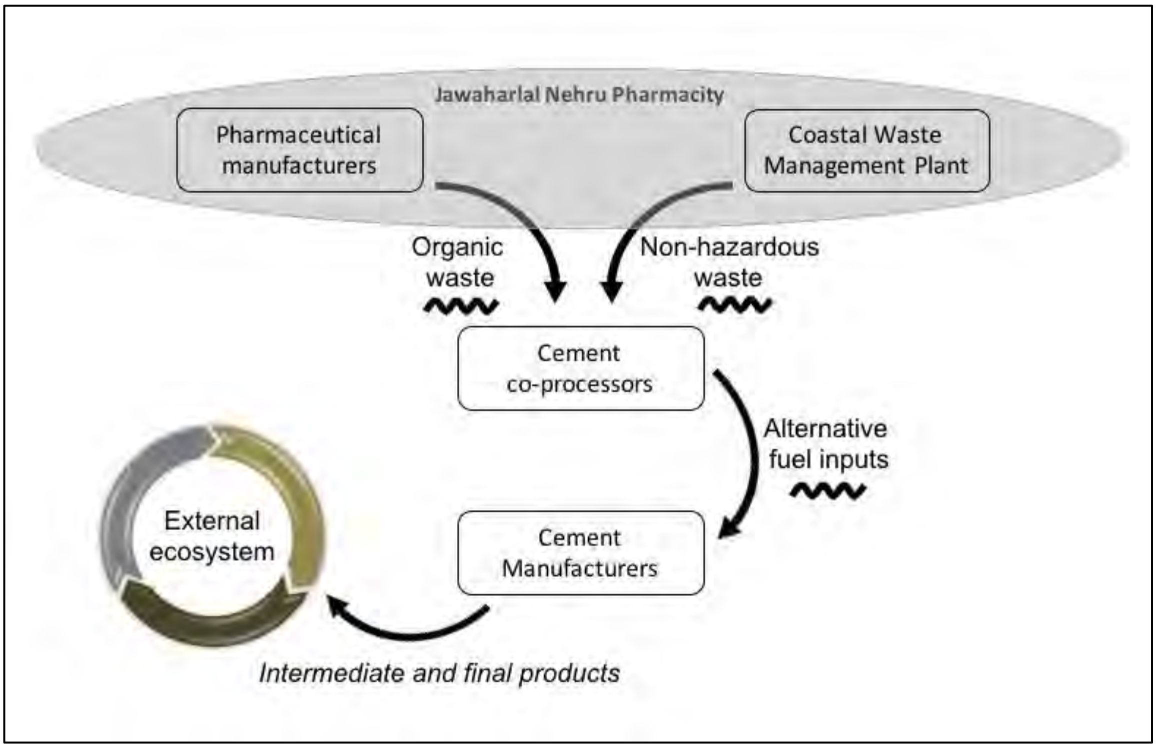

Figure 71: Co-processing of alternative fuels from JNPC

Source: Author generated, based on field visits and interviews

denotes by-products

In the state of Andhra Pradesh, pollution control rules encourage the recovery of high calorific by-products and wastes to be used as *alternatives fuels* in cement kilns. At JNPC, there are two streams of alternatives fuel inputs that are currently being recovered for use in cement manufacture. The first stream involves *direct transfer from individual firm sites* to external aggregators, also known as cement co-processors, who are responsible for common collection and treatment of organic wastes, before standardised by-products are further transported to cement manufacturers as alternative fuels. The second stream involves JNPC's Coastal Waste Management Plant (CWMP), where treated and non-hazardous solid wastes are transported to external aggregators and then cement manufacturers, through independent contracts (Figure 71).

Currently, 80% of organic waste received by the CWMP is being sent to cement manufacturers in neighbouring states. The ISN for alternative fuels from JNPC is now standard practice, especially for individual firms who are bulk generators. The pharmaceuticals manufacturer, Laurus Labs, is a prime example of direct linkages between waste generators and cement manufacturers, without intervention from park management. Organic waste which was earlier incinerated resulting in high air emissions, energy consumption and depletion of valuable materials is now being fully diverted to the cement industry. The Andhra Pradesh Pollution Control Board (APPCB) closely monitors these inter-state exchanges and monthly disposal manifests from cement firms are reconciled with PCB records to ensure compliance and transparency in the network.

5.3.5.3 Centralised liquid effluent treatment

JNPC offers one of the most advanced setups for centralised liquid effluent treatment. Varying grades of liquid effluents comprise a major share of pharmaceutical wastes, which owing to their harmful content, make reuse problematic. Firms within JNPC have access to the underground network for sewage transfer to the centralised treatment facility, which eases the costs and responsibility for operating individual effluent treatment plants. Given the high capital costs to install decentralised effluent treatment and the stringent regulations directing pharmaceutical operations, a specialised central facility ensures scientific treatment, effective management and safe disposal of effluents.

The Common effluent treatment plant (CETP) at JNPC is managed by Ramky in addition to their park management role. The CETP employs 50 full-time staff, in addition to 100 casual labourers, and has 24-hour operations in 3 shifts. Present utilisation of the CETP capacity is around 80%, and planning has commenced to increase total capacity to 12 MLD. Underground pipelines carry two types of effluent – LOW Total Dissolved Solids (LTDS) and HIGH Total Dissolved Solids (HTDS). Average daily volumes of liquid effluents received are 2000 kilolitre of low TDS and 1100 kilolitre of high TDS.

Each firm has clearly stipulated effluent categories and limits, the first point of contact for any digression is the park management, followed by remedial action by the Pollution Control Board.

Surprise audits and ‘lock and key’ systems for disposal ensure compliance, together with regular checks on effluent quality, air and water emissions. Live online monitoring by the CETP and APPCB flags non-compliance and warnings/corrective measures are immediately implemented.

5.3.6 Main actor roles in the industrial symbiosis network at JNPC

Active supply chain interlinkages at JNPC showed potential for advancing synergistic behaviour through higher inter-firm collaboration, information exchange, common goal-setting and knowledge transfer. Four main actors surfaced in the study at JNPC: i) private park developer and management – Ramky; ii) the state pollution control board – APPCB; iii) Firms located within JNPC – especially pharmaceutical and chemical manufacturers; and iv) Waste management firms within JNPC – CETP, dealing in hazardous waste. The standard setup process outlined in Figure 64 highlighted the central role of the private park developer/management in firm approval, induction and day-to-day management. Additionally, the parent company of the developer specialises in industrial waste management and is thus, involved in the operations of the CETP, landfill and hazardous waste management.

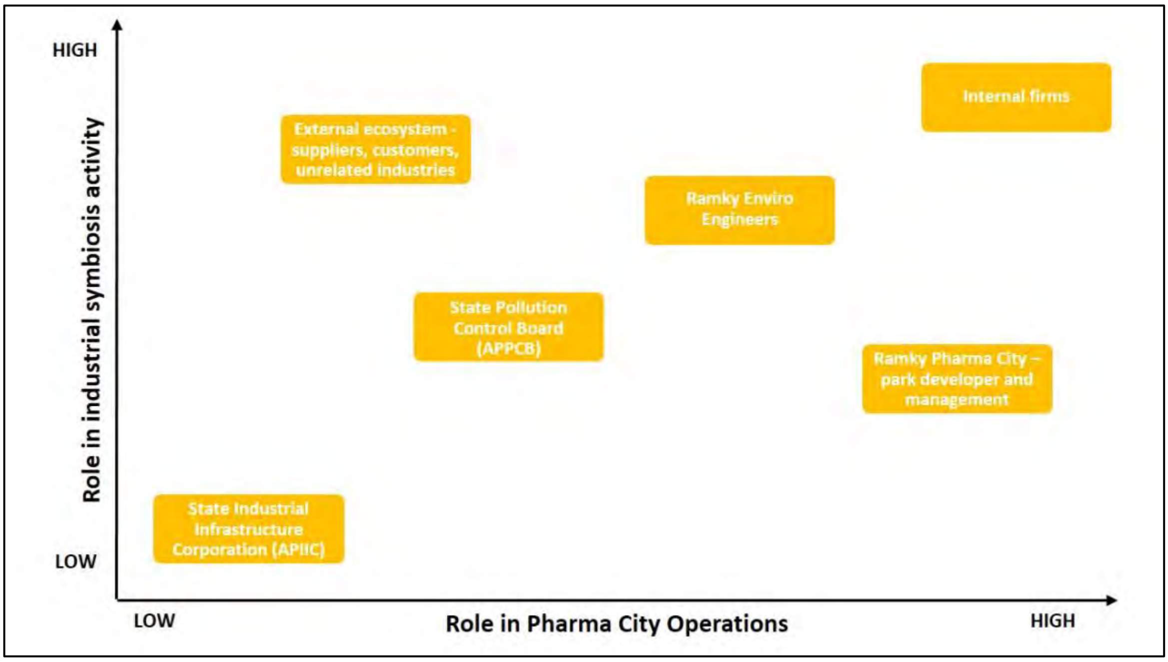

Figure 72: Actor roles at JNPC

Source: Author generated, based on data analysis

The different actor roles in pharma city operations and industrial symbiosis activity are plotted in Figure 72, key actors being internal firms; Ramky Pharma City; APIIC; APPCB; Ramky Enviro Engineers and the external ecosystem. Empirical industrial symbiosis insights negate the notion of symbiotic exchanges limited to park premises, with higher potential for regional symbioses and interactions with external actors. Formal and informal networks amongst actors foster innovation through intra-organisational and inter-organisational learning. Collaborative learning through the sharing of innovative solutions, technical and knowledge capabilities in individual actors, that spill over to the system heighten regional innovative capacity and co-operative behaviour (Lundvall & Johnson, 1994; Mirata & Emtairah, 2005).

Consequently, innovation capabilities of individual firms can translate into region-level progress; regional policies and sectoral roadmaps while assisting localised solutions can also contribute to national strategies for circular economy. At JNPC, internal firms show *high* involvement on both the parameters of pharma city operations as well as industrial symbiosis pursuits. Surprisingly, the participation of APIIC and APPCB in core functions declined after the setup stages, and APPCB is engaged in regulatory roles today (Figure 72). Local government bodies facilitated clustered development through subsidised land and utilities, shared resources for effluent treatment, quality assurance. They did not particularly advance circular economy initiatives in JNPC beyond setup. The low involvement of state and local government bodies in Andhra Pradesh is symptomatic of the lack of a planned approach to eco-industrialisation.

In contrast to leadership by industry associations in Naroda and Nandesari parks, JNPC data showed weak representation of industry associations in ecological projects. Multiple interviewees commented that the JNPC industries association had been involved in managerial and human resource tasks, but limited in response measures. They had not contributed to any dialogue on circular economy prospects at JNPC, a glaring deficiency by an industry representative body. Contrary to the complementary activities of pollution control boards and industry associations at Naroda and Nandesari estates, both these actors are passive at JNPC.

The park developer, Ramky, regulates and enforces environmental directives, resource efficiency and exchange within park premises, affiliated units like Ramky Enviro engineers, manage waste. It must be noted, though, that Ramky does not actively promote by-product exchange, but has the ability and knowledge to facilitate higher inter-firm collaboration, communication and collective goal-setting (Figure 72). The industry's foremost professional body, the Indian Drug Manufacturers' Association (IDMA), excludes knowledge dissemination or resource efficiency initiatives from its objectives. Boasting 1000+ memberships of pharmaceutical companies of varied sizes and scope and a presence in eight regions, IDMA has the potential to become a key driver in putting together a taskforce for circular economy and cleaner production among India's pharma manufacturers (IDMA, 2019).

5.3.7 Future plans for eco-industrial parks

The integrated services at JNPC are a vital attraction for firms; all interviewees echoed streamlined setup procedures and centralised waste management as massive value additions, resulting in time and cost savings for firms. Apart from a source of skilled workforce and knowledge development, specialisation at JNPC can extend the parks industrial symbiosis potential. Bain et al. (2010) found that informal conversations between managers of previously unrelated firms became a platform for collective problem solving and resulted in by-product exchanges as practical solutions, with economic value. The absence of a formal by-product exchange framework at JNPC and its unique operational structure underscore the importance of shared services as an important facet of the ISN.

Nominated as a pilot eco-industrial site by the United Nations Industrial Development Organisation (UNIDO), with future plans to replicate the model at other brownfield/ greenfield sites within India, JNPC was also a test for the APIIC to model public-private-partnership for industrial park development. The successful integration of shared services and localised waste management at JNPC have initiated plans for replicating the model elsewhere in the state. Atchutapuram, an active industrial park with multi-product SEZ and >2000 hectares area, is the next. Within this park, up to 800 hectares be developed as a pharmaceutical hub. Owing to India's rise as a pharmaceutical manufacturer, specialised cluster development is expected to scale up. Innovation parks which foster research and development, and encourage new discoveries especially for individuals or smaller enterprises are being modelled.

To complement current ecological initiatives, JNPC is developing plans to recycle waste onsite, which may result in higher incentives for industrial symbiosis exchange. The main hindrances to adopting closed loop exchange for pharmaceutical wastes are the highly hazardous contents and chemical compositions of by-products. Another barrier is the excessive volume of liquid effluent, which is often discharged illegally into natural water bodies. At JNPC, the close monitoring of liquid effluents, the multi-step treatment at the CETP and the lock-key system for treated effluent discharge are positive steps. A further improvement will be recycling treated water in industrial operations, similar to the current groundwater replacement at Nandesari estate in Gujarat. Plans for a 230-tonne common steam and 100MW power plant have commenced, to supply renewable energy across JNPC.

Other states too are looking to replicate similar parks; for example, the eastern state of Orissa is seeking to partner with Ramky to build eco-industrial parks in 3 cities, each park with an area of 200 hectares (food processing park/ textile park/ pharmaceutical park). There are plans to build 400 hectares of an integrated eco-industrial township in the city of Hyderabad. In addition to these greenfield projects, Hyderabad also has plans to retrofit Nacharam and Mallaram industrial parks with eco-industrial park features.

5.4 Case Study 4: Circular economy in steel through upcycling and industrial symbiosis

5.4.1 Overview of steel manufacturing in India

Steel is a critical component of India's manufacturing sector. The country produced the second highest volume of crude steel globally, when output reached 111.2 million tonnes (MT) in 2019 (IBEF, 2020). India has international competitive advantages of low-cost labour, local availability of iron ore and thriving domestic demand for processed steel. In 2018, India surpassed Japan as the second largest steel producer (WSA, 2018, 2019). The nation is also a net exporter, with 78% rise in exports since 2017, making steel an important contributor to India's foreign exchange earnings. India's National Steel Policy (2017) is geared towards production capacity expansion to 300 million tonnes by 2030. In parallel, the newly announced Steel Scrap Recycling Policy (2019) aims to foster a circular economy in metals while also reducing import dependence for steel scrap demand (MoS, 2020).

India's per capita consumption of steel rose sharply from 57.6 kilograms in 2014 to 74.1 kilograms in 2019 (IBEF, 2020). This increase aligns with the overall increasing material demand in India's manufacturing sector, especially construction, transportation and automobiles. The Indian steel industry can be classified into three main categories: major producers, main producers and secondary producers. Some of the prominent producers include Steel Authority of India Limited (SAIL) – a public sector enterprise, Tata Steel, Arcelor Mittal, Essar Steel, and JSW Steel. The steel industry and associated mining and metallurgy sectors are important foreign investment drivers, in the decade 2010-2020, USD 13.4 billion Foreign Direct Investment (FDI) was received (DPIIT, 2020).

Despite modernisation and energy efficient plants, India's iron and steel industry remains one of the highest industrial energy consumers and emitters. The Ministry of Steel targeted a 14–17% emissions reduction by 2020 (GOI, 2013). Additionally, weak domestic metal recycling infrastructure and the dominance of informal markets impede resource efficiency ambitions in the industry. To fulfil its domestic demand for scrap metal, India imported 5.7 million tonnes of metal scrap in 2016-17 (MoS, 2020). Globally, the metal scrap industry is valued at USD 500 billion. India's current domestic demand for scrap steel exceeds the local supply, exposing the country to geopolitical risks due to price fluctuations, unreliable quality of imports and unstable supply. Reducing import dependence and strengthening local metal recycling value chains are the primary goals envisaged from India's Steel Scrap Recycling Policy (2019).

5.4.2 Steel recycling: a circular economy opportunity

Steel, like most metals is apposite for reuse, due its chemical and physical properties. The primary use and recyclability of a metal depends on whether it is ferrous or non-ferrous. Chemically, ferrous metals like carbon steel, alloy steel, wrought iron, cast iron contain iron and have a magnetic field. Non-ferrous metals like aluminium, copper, lead, zinc, tin, precious metals gold, platinum, silver do not contain iron, and have extended recycling potential. Non-ferrous metals like aluminium, copper, brass are much lighter than ferrous metals like carbon steel, cast iron and wrought iron. Due to strength and weight-bearing capacity, ferrous metals are used to build bridges, skyscrapers, shipping containers, railway tracks, large pipes, tunnels, and automobiles. Heavy electric appliances like refrigerators and washing machines also contain ferrous metals due to their magnetic properties (MRAI, 2019).

Virgin steel is derived from mined iron ore, and is the main component for critical development sectors like construction, transport and infrastructure. Efficient recovery of steel scrap is a strong economic opportunity. In addition to energy saving, each tonne of scrap can replace 1.1 tonne of iron ore, 630 kg of coking coal and 55 kg of limestone inputs[18], reducing energy consumption by 40% and air emissions by 86% (Wübbeke & Heroth, 2014). Present estimates suggest only 30% of steel produced in Australia, Brazil, China and India is recycled (Yellishetty & Mudd, 2014). In 2018, 25 million tonnes of scrap were supplied through unorganised sector activities, and another 7 million tonnes were imported to meet India’s demand (MoS, 2019). India, has succeeded Turkey as the second largest scrap importer[19]. Typically, scrap steel is used in secondary production and does not constitute a vast share of primary steel production.

Steel scrap recycling in India has, so far, been largely unorganised, with fragmented informal sector individuals and enterprises (Figure 73). Well-known marketplaces are Mayapuri in Delhi and Kurla in Mumbai, where scrap metals from end of life vehicles are processed in bulk. Many studies have reported the hazardous practices and environmental damage from these regions, the

[18] PTI. (2019, November 9). Government announces steel scrap recycling policy, aims to reduce imports; scrap centres planned. *Press Trust of India (PTI). The Economic Times*. Retrieved from https://auto.economictimes.indiatimes.com/news/policy/govt-announces-steel-scrap-recycling-policy-aims-to-reduce-imports-scrap-centres-planned/71979106

[19] Iyengar, S. (2019, August 8). India emerges second largest scrap importer, e-article. *The Hindu Business Line*. Retrieved from https://www.thehindubusinessline.com/economy/india-emerges-second-largest-scrap-importer/article28887123.ece#

dangers extend to natural ecosystems and health hazards for workers (CERO, 2018)[20]. Current industry estimates suggest the number of end of life vehicles in India to be around 8.7 million, with a steep rise by 2025 (CERO, 2018); India was also the second largest steel scrap importer in 2018[21]. The exponential increase in demand for steel places the nation at a critical juncture to seek ecological sound alternatives as also strengthen domestic recovery.

Note on terminology

The use of the term 'recycle' in the context of steel scrap recovery and reuse is perturbing, mostly because *recycle* in scholarly and practitioner parlance has come to represent a forced degradation in the physical properties and value recovery of a material. The European Union/Australia waste hierarchy, for instance, advocates recycling as the last option before landfill. India's Solid Waste Management Rules too outline recycle as the last mile alternative to landfilling.

Most formal debate and policy prerogatives still refer to steel scrap 'recycling' and this may follow in the forthcoming text too. However, the reuse prospects and current practices of steel scrap reuse suggest the upcycle of steel's material properties; thereby, aligning with the principles of a circular economy. This raises the question: Can metal recycling be referred to as 'upcycling' given the higher value products and material properties created?

The author's intention is to present an accurate account of developments in the field; thus, although 'recycling' may be used in the context of steel scrap, the researcher is inclined to seek opportunities for 'upcycle' as stimulated by the circular economy. Scientific recovery using automation and other technological advances may yield higher value extraction.

[20] Fatima, T. (2017, April 5). Mayapuri Junkyard Is Where Vehicles Go To Die... And Be Reborn, e-article. *Huffington Post*. Retrieved from https://www.huffingtonpost.in/tehreem-fatima/photoblog-mayapuri-junkyard-is-where-vehicles-go-to-die-and_a_22024989/

[21] Iyengar, S. (2019, August 8). India emerges second largest scrap importer, e-article. *The Hindu Business Line*. Retrieved from https://www.thehindubusinessline.com/economy/india-emerges-second-largest-scrap-importer/article28887123.ece#

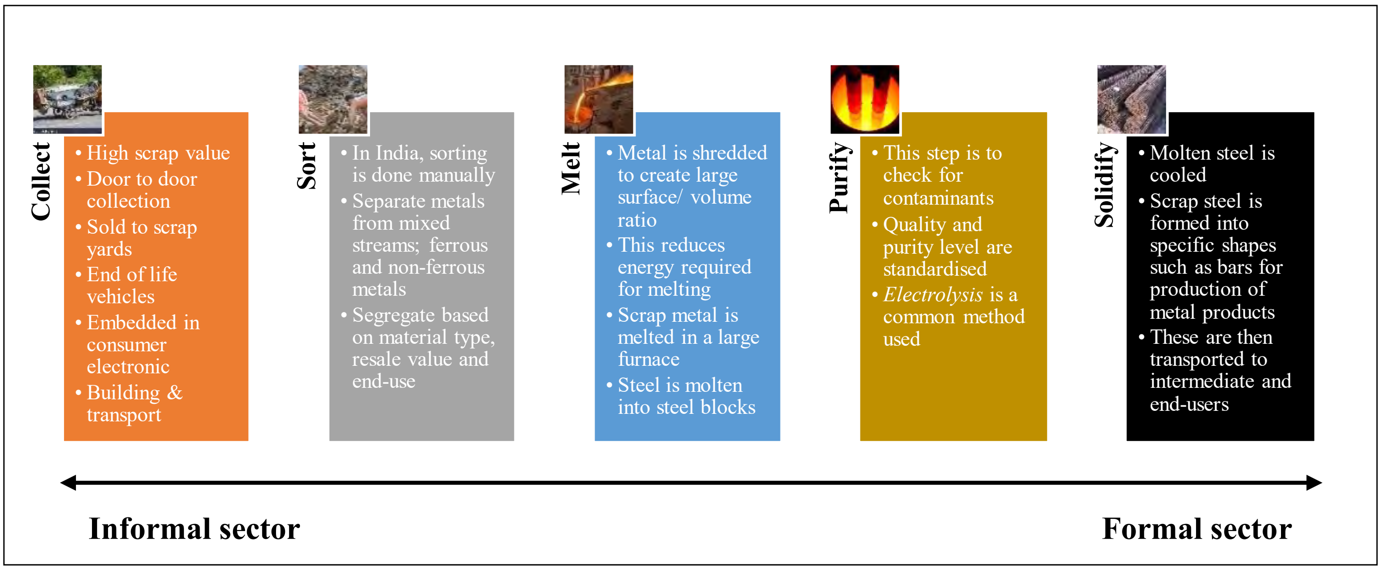

Figure 73: Steel scrap recovery ecosystem and stages in India

Source: Author generated

Informal sector activities span the collection and sorting phases. Owing to the high value of steel scrap (similar to other metals), a vast network of door-to-door scrap collectors and resellers thrives. Usually, households and small businesses receive compensation based on the metal weight. Sometimes, heavy consumer electronics and machinery are compensated based on the metal recovery potential, since intrinsic plastic may not fetch high resale value (Figure 73). End of life vehicles are an important source of scrap metal, and a planned approach to incentivising the recovery of end of life vehicles is currently underway in India. In the USA, scrapped vehicles comprise the biggest source of recovered ferrous metals (Leblanc, 2019). Other sources include demolished building and construction materials, large steel structures, rail tracks, and ships.

Formal sector involvement is minimal in the initial stages of scrap recovery. Mixed waste streams lengthen the metal recovery process, paper must be removed first, followed by plastics and metals. The segregation of ferrous and non-ferrous metals is also conducted during sorting. Sorting and melting are mostly done by small enterprises located in dense marketplaces, their techniques are old-fashioned and involve manual processing. The quality of recovered metal decides its end-use; due to low quality secondary products in India, domestic scrap is hardly used in higher-value manufacturing.

Domestic steel demand is surging due to fuel infrastructure development. The Government of India (GOI) has set targets for steel production capacity to reach 300 million tonnes by 2030[22]. However, reliance on mining ores and imports in order to meet these steep targets will not only put disproportionate pressure on its trade balances, but also expose it to increasingly volatile ecological and political events. As a means of strengthening its domestic recovery potential, India released the Steel Scrap Recycling Policy in 2019, which signals the first inter-ministerial attempt to further a circular economy in manufacturing.

5.4.3 India's Steel Scrap Recycling Policy (2019)

The announcement of India's first formal recycling policy, Steel Scrap Recycling Policy (2019) stated the *promotion of circular economy in the steel sector* as its foremost objective (MoS, 2019). The policy in its full form will realise two significant goals for sustainable steel production. First, it will help organise the activities of currently fragmented scrap collectors and vendors, and be a source of skill development and employment. Second, technological inputs and formal supply chains will advance the use of scrap metal in primary production. Presently, scrap metals are used as raw material by secondary producers; use in primary steel production is only 15% in the charge mix of a Basic Oxygen Furnace (MoS, 2019). High quality scrap input in electric furnaces can assist in the production of high grade steel, so access to pure and standardised steel scrap will incentivise use in primary production.

The immediate target, for the Steel Scrap Recycling Policy (2019), is to replace up to 7 MT of scrap imports with domestic production, with a long-term goal of self-sufficiency by 2030. To achieve immediate goals, 70 new scrap processing centres will be required to service over 300 collection and dismantling centres. A 4+1 hub and spoke model is being implemented, where 4 collection and dismantling centres will feed into 1 processing centre and each composite unit will create up to 400 jobs (MoS, 2019). This will enhance existing operations, and 2800 jobs are anticipated to be created directly from the additional infrastructure. Six circular economy principles are directly involved in this project: *reduce, reuse, recover, redesign, remanufacture, recycle*.

[22] PTI. (2019, November 9). Government announces steel scrap recycling policy, aims to reduce imports; scrap centres planned. *Press Trust of India (PTI). The Economic Times*. Retrieved from https://auto.economictimes.indiatimes.com/news/policy/govt-announces-steel-scrap-recycling-policy-aims-to-reduce-imports-scrap-centres-planned/71979106

Another significant achievement of this policy is the incorporation of Solid Waste Management Rules 2016 for waste management and movement beyond the premises of the generating facility. Since enforcement of the hazardous waste management rules in 2008, which prohibited the transport and reuse of ferrous by-products on account of their high iron content, firms faced challenges with managing scrap. A positive outcome of these stringent measures resulted in plant-level innovation to manage waste onsite, as a means of achieving zero discharge. The case of Essar Steel's Gujarat facility, discussed in the latter part of this section, illustrates pioneering initiatives and quantifiable economic, environmental and social benefits. On the other hand, the hazardous classification for steel waste deterred reuse in primary steel production; the recycling policy addresses some of these inconsistencies.

Prompt action is already visible with large firms capitalising on the policy momentum. Tata Steel, the nation's biggest steel producer and an international leader with manufacturing operations in 26 countries, invested in setting up India's first mega steel scrap shredding unit in Haryana (Metso, 2019). Other notable ventures are by Maruti-Toyota, Mahindra for ELV management and Jaguar Land Rover for closed-loop aluminium recycling. Progress in these ventures is discussed in greater detail in the next section.

Cautionary steps will be essential to prevent Indian recyclers having to deal with unprocessed mixed metal scrap imports to meet additional recycling capacity. In light of China's tightened metal and other waste imports since 2017, India could expose itself to a short-sighted scrap recycling swell where many nations are seeking viable outlets to process their metal waste. These concerns about a surge in low quality metal scrap imports if adequate restrictions are not implemented have already been flagged (S&P, 2019). These apprehensions are especially solid since the import costs per tonne of unprocessed scrap are USD 20-30 lower than processed scrap. Since the physical infrastructure required to furnish additional scrap recycling capacity will take at least 2-3 years to materialise, interim government interventions will be worthwhile. Import restrictions based on material type and a robust domestic metals recovery plan could circumvent the risks.

For India, in addition to decongesting roads and improving air quality, end of life vehicle management benefits will be manifold. It can become the primary means of reducing the scrap deficit, improving domestic metals flows, preventing the influx of unprocessed metal imports and developing a skilled workforce by organising the activities of the currently unorganised and informal scrap recycling sector. This will create substantial local supply, induce scientific separation and technology adoption and formalise employment in the sector. Specialised industrial "eco' parks are being designed for recycling and scrapping activity; recycling-based tax incentives are also planned.

5.4.4 End-of-life vehicles: circular economy through urban mining

An obvious extension of India's steel recycling policy will be the solidification of end-of-life vehicles (ELV) recovery. Between 2006-2016, an average of 150 million vehicles were registered annually (MOSPI, 2018) and 35.4 million should have entered the end-of-use pool (Figure 74). However, the actual number of ELVs is uncertain – a reputed ELV project estimated around 8.7 million ELVs in India and projected an increase up to 22 million by 2025 (CERO, 2018). The discrepancy in hypothetical (average vehicle license is 15 years) and actual data can be attributed to inefficient data collection and longer than intended use due to weak phase out rules. Figure 74 indicates that 75 million ELVs will be generated by 2020. Estimates suggest 210 million ELVs will be added by 2030; the steep 500% rise predicted in the upcoming decade reflects the surge in vehicle registrations (Figure 74).

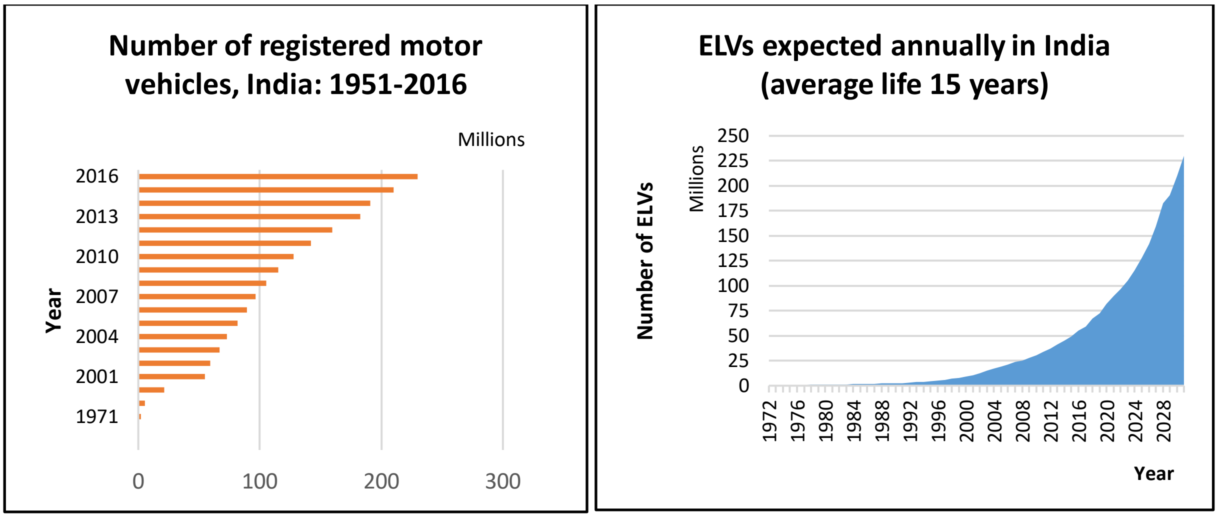

Figure 74: Registered vehicles 1951-2016, actual (left); ELV pool 1972-2030, estimated (right)

Source: Author calculations, based on MoRTH (2016); MOSPI (2018)

Note: The number of ELVs expected to enter the system annually have been calculated based on an average vehicle license for 15 years (Mahindra, 2018). The figures cited reflect the ideal scenario where vehicles will not run on the roads beyond their intended life (this is not the case in reality for India). Data computations are based on the number of vehicles registered over the period 1951-2016; these are not the actual number of ELVs added annually as actual data is currently not being reported in official statistics. Most ELV processing is currently conducted by informal actors, hence reliable estimates on recovery, reuse and recycling are unavailable.

An average car comprises 65 % steel, 10% plastics, 8% aluminium, 5% rubber, 1% copper, 1% glass. Accompanied by 74% energy savings through metal recycling in comparison to virgin mining, ample evidence points to ELVs being storehouses of valuable resources. Scientific ELV management could divert 11 MT of steel and 800,000 tonnes of non-ferrous metals from landfill, annually (CERO, 2018). Controlled recovery of valuable metals from vehicles can be a case of urban mining; scientific evidence points to cost-effectiveness of urban mining in contrast to virgin mining (Zeng, Mathews, & Li, 2018).

Owing to weak regulatory planning for mandatory take-back of ELV in India, vehicles ply on roads for much longer than the intended life. Apart from the value lost due to lack of materials recovery, air emissions by older vehicles increase pollution risks significantly: a 15 year old passenger car is 8 times more polluting than a new one; a 15 year old truck is 10 times more polluting than a new one (Mahindra, 2018). Second, an active informal sector has resulted in fragmented solutions and higher-value material losses in the absence of extended producer responsibility and product stewardship guidelines for ELVs in India. The used vehicle market in India is thriving on account of a vast consumer base with increasing affluence and improvements in road connectivity. Despite this, ELV management is a choke point in the nation's waste infrastructure. Determining the balance is the untapped opportunity for metals, plastic and materials recovery from planned ELV management.

Unorganised scrap markets or junkyards are a massive employer of low-skilled labour; 4000 small-sized firms in Delhi's Mayapuri suburb employ up to 50,000 people, who dismantle 100-150 pieces of machinery and vehicles daily with an annual turnover of USD 900 million (Figure 75). Materials and scrap metals mined with limited automation are reused in army vehicles and industrial products. Despite a thriving secondary economy, manual dismantling in junkyards often leads to breakage in value chains, where only known value-bearing parts are recovered, and those too, are used in lower-value applications. Leaching of hazardous substances like waste oil, lubricants, lead battery-acid , mercury, and plastic discards result from the unscientific and manual processes. Off-street dumping, incineration and run-off into water bodies pose immense environmental and social risks.

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Figure 75: Mayapuri scrap markets, New Delhi
Source: Fatima (2017)

For India, ELV promises not just an opportunity for urban mining but also fast investment returns owing to the scale of the problem. A pioneering joint venture between two automobile manufacturers, Maruti Suzuki and Toyota Tsusho is located in New Delhi. The project has the capacity to process 24000 ELVs annually, to manage end-to-end operations from vehicle collection to end-use in steel manufacturing. Another public-private joint venture, CERO, has an ultramodern automobile shredding and recycling facility to process specialised steel varieties and other non-ferrous metals. Data reporting and measurement is enabled through digital tracking of the scrapping stages. The first plant has capacity for 25,000-30,000 vehicles per annum, expansion plans across the country are underway.

Figure 76 outlines the ELV value chain for India, which has seen rapid investment for automobile manufacturers like Maruti Suzuki, Mahindra and Tata Motors. The implementation of an efficient ELV recovery network, such as the plans laid out by Maruti Suzuki Toyotsu India (MSTI), will enable the recovery of heavy metals like steel and aluminium for input back into the automobile manufacturing value chain. ELVs recovered through the nationwide car dealership network will be transported to a central facility where they will be pre-treated and decontaminated including removal of oils, airbags, batteries and electrical circuits. The vehicles will then be dismantled to recover scrap materials like metals, plastic, fibre, rubber, glass. Considering only the flow of metals through this circular recovery, scrap metals will be transferred for further processing to smelters and metal manufacturers. It is envisaged that a streamlined and automated ELV recovery mechanism can enable high value metal recovery, attracting metal manufacturers to produce high quality secondary metal from scrap metals. These recovered secondary metals can then be used back in new automobile manufacturing, closing the loop for the largest material input in automobiles. This circular loop of metals recovery from ELVs will foster urban mining infrastructure in the country, and also ease demand for primary metals extracted from virgin ores (Figure 76). The illustrated ELV recovery network is a marked transformation from the predominantly linear automobile value chain mapped in Figure 4, and mitigates many of the value loss risks discussed in the introductory chapter.

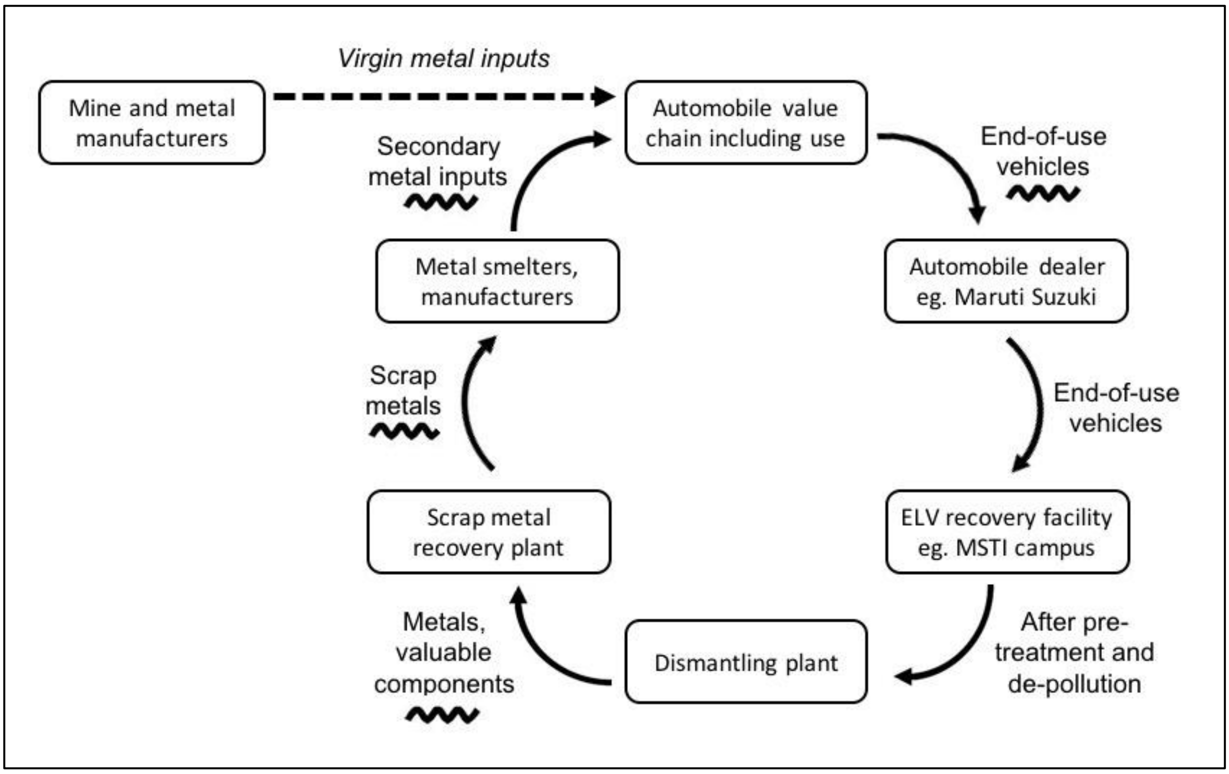

Figure 76: Metal recovery value chain from ELVs in India

Source: Author, based on Vijayraghvan (2019)

denotes by-products

Apart from hard metals and glass, lower value materials like plastics, rubber, textiles, foam, wood comprise 25% of an average vehicle. These materials, also termed as automotive shredded residue, are often disposed of in landfill due to technical difficulties in segregation and impurities from trace metals. To enable efficient recovery, Liu et al. (2017) suggested the recovery of plastics from automotive shredded residue, to transform clay in the manufacture lightweight aggregates. Aggregates are commonly used in the manufacture of concrete blocks, lightweight concrete structures, as insulation material in roads, in water treatment, hydroponic substrates, and aquaponics. Virgin resource inputs in construction are increasingly scarce, with escalating costs and access constraints. Multiple industrial by-products like steel dust and plastic waste from end-of-life vehicles are apposite for the manufacture of lightweight aggregates, and can be a last mile solution for hazardous or irrecoverable materials.

ELV legislative frameworks in major economies are being modelled after the EU, Japan, Korea, China, and Taiwan, which have streamlined vehicle ownership and recovery targets. Directive

2000/53/EC and the Commission Decision 2005/293/EC set out targets for recovery, reuse and recycling of end-of-life vehicles within EU member states. The latest available data for 2015-2016 show that 24 of the 28 EU nations achieved ≥ 85% recycling rate, and 15 states reported recovery rate of 95 % (Eurostat, 2019a, 2019b). In the Indian situation, it will be vital to integrate formal and informal sector activities to accomplish value addition from secondary metals.

Globally, automotive giant Jaguar Land Rover implemented closed-loop aluminium recycling for its premium automobiles, eventually the project became integral to product design resulting in fuel efficiency, lowered emissions and improved performance. An extension of the project is the recovery of post-consumer aluminium waste to 75% circularity in their vehicles[23]. India's forays into ELV management are indicative of an industry-wide trend to realise extended producer responsibility and product stewardship. High capital outlay and large land area (up to 4 hectares) for shredder installation are the main obstacles for private investment. Coupled with the provisions of the latest Steel Recycling policy, participation of large automobile manufacturers in ELV management in India is likely to create an ecosystem for reusing recovered metals in vehicle manufacturing. Formalising a model for metals recovery is a massive opportunity for scaling up India's circular economy pursuits. Effective ELV management can reduce India's dependence on metal scrap imports., which stood at 7 MT in 2018 (MoS, 2019).

The next section delves into circular economy applications within steel manufacturing, analysing the multi-faceted case of a major Indian steel producer, Essar Steel.

5.4.5 Essar Steel's zero waste circular economy

5.4.5.1 Overview of Essar Steel

Essar Steel, the fourth largest single location flat steel producer globally with annualised crude steel production of 6.5 million tonnes, is aiming for zero waste operations in multiple sites. The company's 1500 hectares steel complex in Hazira, Gujarat, is fully-integrated with three main prominent steel-making techniques – blast furnace, electric arc furnace and conarc furnace as well as an onsite power plant and port with 30 million tonnes annual cargo capacity (Figure 77-78).

[23] Mace, M. (2017, September 7). Jaguar Land Rover expands its aluminium circular economy drive, e-article. *Edie Net*. Retrieved from https://www.edie.net/news/16/Jaguar-Land-Rover-expands-its-aluminium-circular-economy-drive/

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Figure 77: Essar Steel Hazira, Gujarat (left); Plate Mill, Essar Steel (right)
Source: EssarSteel (2019)

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Figure 78: Layout of steel complex at Essar Steel Hazira, Gujarat
Source: EssarSteel (2019)

The firm adopted 100% waste recovery targets for industrial, household and municipal wastes in its Hazira township; significant closed loop materials, water and energy exchanges are outlined. Gradual programs for waste reduction and sustainable design at Essar Steel Hazira have resulted in 100% waste recovery of industrial, household and municipal wastes; multiple intra- and inter-firm exchanges facilitate reduction and reuse of primary materials. Since most wastes in steel making are classified as *hazardous* and restricted from leaving generator premises, the zero discharge developments at Essar Steel are especially relevant. Recognition from the Centre for

Science and Environment, Water Digest, World Steel Association, Golden peacock, and Confederation of Indian Industry qualify the following initiatives as a forerunner for industry-wide circular economy adoption.

5.4.6 Industrial symbiosis features uncovered through the study

5.4.6.1 Electricity generation from surplus heat and biogas

Essar Steel is engaged in electricity generation through heat recovery at a centralised 19 MW plant; here surplus steam and gases from different steel production processes are captured and transported to the heat recovery plant. This heat is then transformed into electricity which is used to power common infrastructure, and excess electricity is fed back into the external power grid (Figure 79). Associated air emissions are monitored live and regular internal audits ensure energy efficiency and maximisation of the onsite electricity generation infrastructure. The project has resulted in reduced power costs, lowered GHG emissions, improved energy efficiency, and avoidance of power transmission losses (EssarSteel, 2012). Additionally, a waste to energy network is operational to extract energy in the form of biogas from food waste generated at multiple cafeteria and food outlets within the Steel Complex (EssarSteel, 2015a).

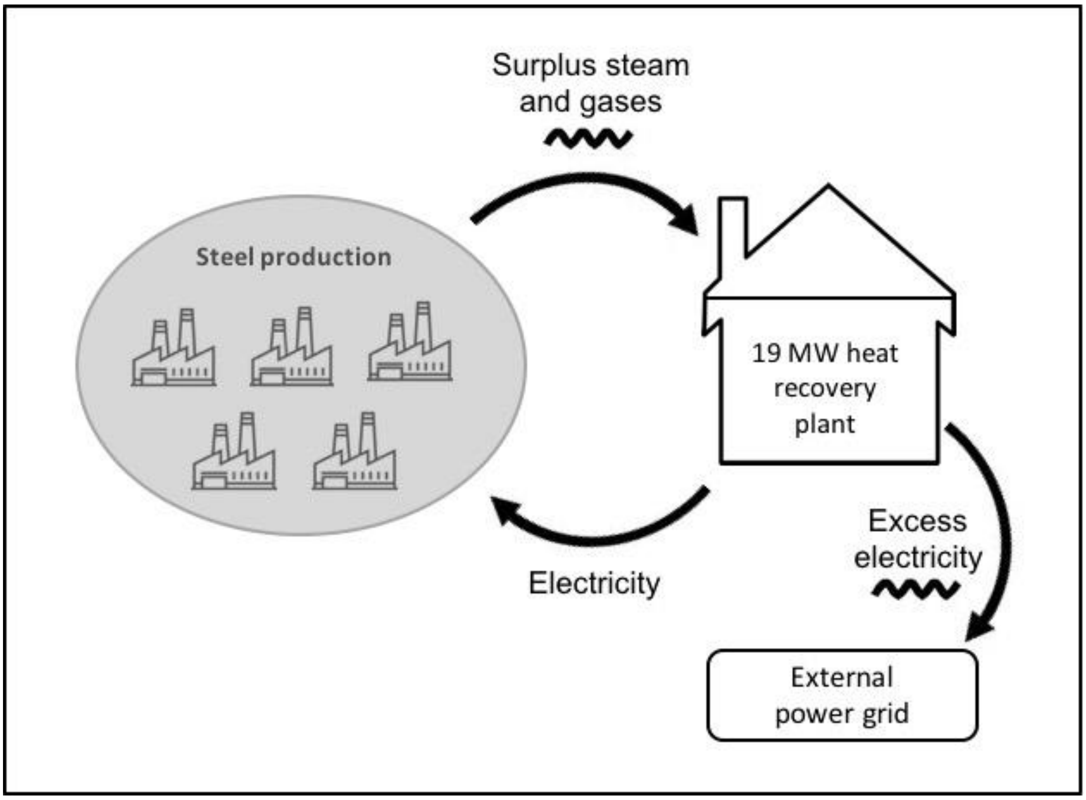

Figure 79: Electricity generation from surplus heat

Source: Author illustration, based on company reports, news and industry data

denotes by-products

5.4.6.2 Industrial by-product recovery and reuse

Significant cost savings, efficiency improvements and supplementary revenue streams accrue to Essar Steel owing to multifarious industrial by-product reduction, recovery and reuse ventures. Two main industrial symbiosis networks (ISNs) are explained here; the first exchange involves the recovery of hazardous iron sludge to manufacture a new production input, micro pellets, which are used internally within the steel making process and are an example of *intra-firm circular exchange*. The second ISN involves an *inter-firm and cross-industry circular exchange* to manufacture material inputs for construction industry by utilising steel by-products. The renewed production inputs, micro pellets, briquettes and construction materials are shown in Figure 80.

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Figure 80: Renewed production inputs from steel industry by-products
Source: Essar Steel company reports, news and industry data

The onsite iron sludge processing unit recovers sludge from the effluent treatment plant at the Cold Rolling Mill. These are combined with iron dust fines from the fume extraction system of the Steel Melt Plant to manufacture micro-pellets, for use in the Sinter Plant. These micro-pellets are upcycled from industrial by-products which would otherwise be disposed of in landfill due to their highly hazardous content, for reuse in Sinter Plant operations (Figure 81). The 100% utilisation of *iron sludge to manufacture micro-pellets* diverted over 2400 tonnes from landfill and led to net profit savings of USD 2 million annually (EssarSteel, 2015c). Thus, the reuse of iron sludge, classified *hazardous*, is yielding profitable ventures at Essar Steel, through waste diversion and upcycling.

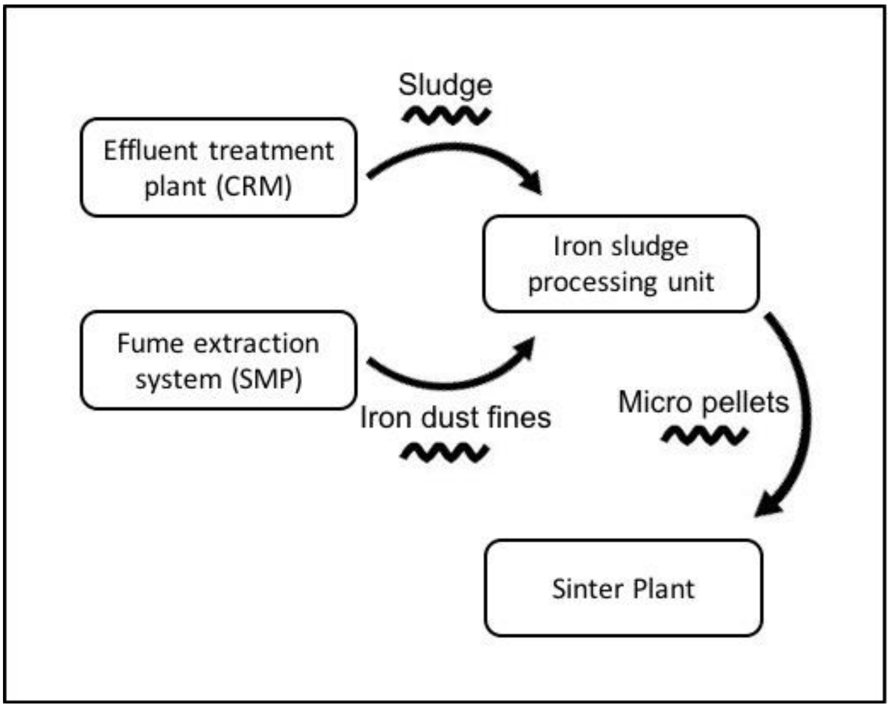

Figure 81: Manufacture of micro pellets from iron sludge at Essar Steel, Hazira

Source: Author generated, based on company reports, news and industry data

denotes by-products

Note: Cold Rolling Mill (CRM), Steel Melt Plant (SMP)

Another application is the *manufacture of briquettes from iron dust*, for coolant in electric arc and conarc furnaces. Dust from the blast furnace, comprising iron and carbon fines, is transformed into briquettes using molasses and lime. Briquettes as cooling liners in electric arc furnace have resulted in efficiency improvements due to lesser erosion and longer life of the furnace lining. The pilot, which successfully produced 200 tonnes of briquettes, has now been expanded to transform a daily output of 150 tonnes of cold direct reduced iron fines into briquettes (Figure 82) (EssarSteel, 2015b). Steel slag from electric arc and conarc furnaces, to the tune of 1 million tonnes annually, was being disposed of due to restricted reuse potential. Limited quantities were recovered for use in furnaces, a large surplus was discarded. By partnering with an international industrial services firm, HARSCO, Essar Steel is now involved in the manufacture of sand, paver blocks, bricks, road laying and cement mix from leftover steel slag. Slag sand is a reliable alternative to sand mining and paver blocks made from steel slag are stronger as well as cheaper than conventional cement blocks. Supplementary annual revenue of over USD 22 million is expected from this partnership (Figure 82) (EssarSteel, 2013b, 2017).

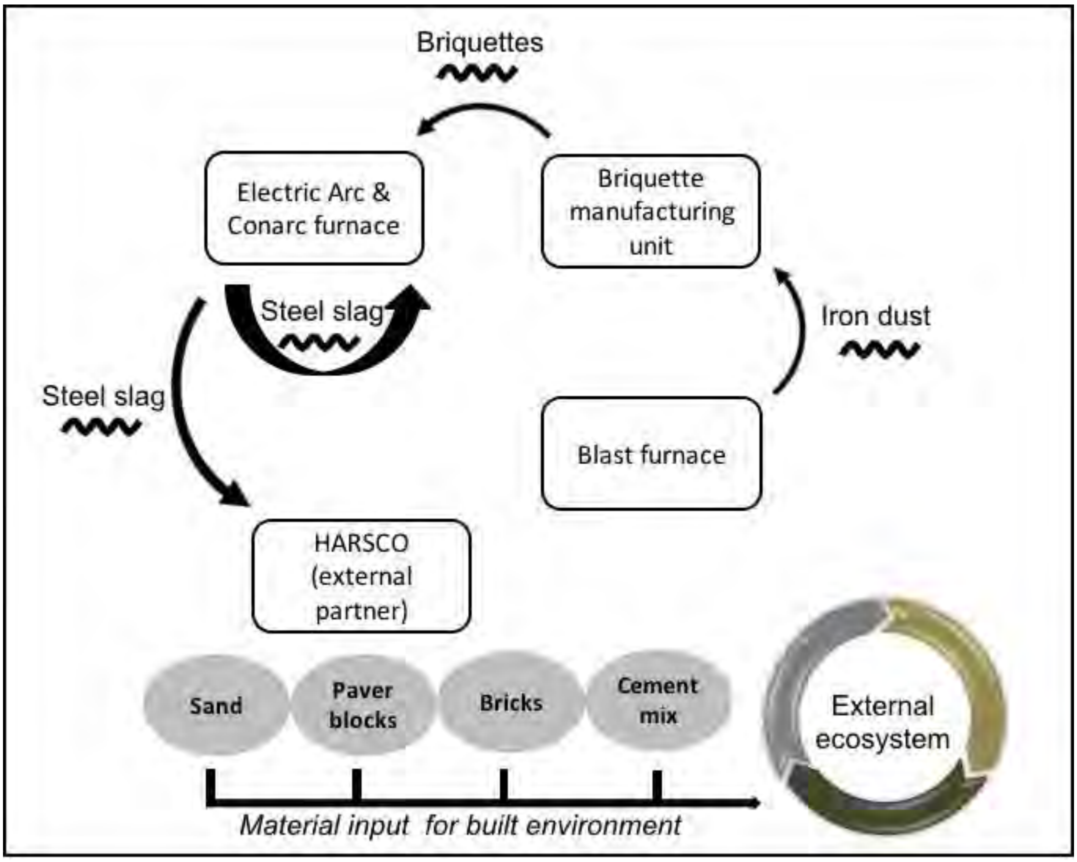

Figure 82: Construction application closed loop material exchange at Essar Steel

Source: Author generated, based on company reports, news and industry data

denotes by-products

5.4.6.3 Circular water flows

Rain water harvesting in eight water reservoirs, active since 2009, resulted in 600,000 cubic metres collected annually for use as freshwater in plant operations. A closed loop water exchange between the power and steel plants has resulted in 95% water recovery and reuse, accruing freshwater savings of 1.48 million cubic metres annually (Essar, 2015; EssarSteel, 2013a). The 515MW power plant used 3.9 million cubic meters of fresh water input annually, drawn from the river Tapti, and discharged into the sea as effluent. Concurrently, the nearby steel plant abstracted freshwater for coolant use. Collaboration between co-located power and steel plants led to a cycle of exchange for treated effluent to be used in steel making, which again was cascaded back into power plant operations (Figure 83).

Alkaline blowdown water from the power plant, which was previously disposed of at sea, is now sent as coolant water into steel-making. This exchange meets 45% of the water demand in the steel plant, and has replaced 644,000 cubic metres of freshwater in steel-making. The balance treated effluent water from the power plant is fed into fire systems, dust control, horticulture and for irrigation in Nand Niketan township. In this loop 86% of the waste water from the power plant is currently recovered and reused in the aforementioned processes (Figure 83). Reverse exchange of effluent water and clarifier sludge from the steel plant, into various applications illustrates the closure of water loops at Hazira. A central water treatment unit extracts water from sludge; the extracted water is fed back into the power plant, while the sludge is used as plant fertiliser on the vast campus. Excess surface runoff water from the steel plant is filtered for reuse in landscaping irrigation. 105,000 cubic metres of freshwater savings have ensued from the clarifier sludge extraction, and the backwash water reuse has diverted 349,000 cubic metres of freshwater (Figure 83) (Essar, 2015).

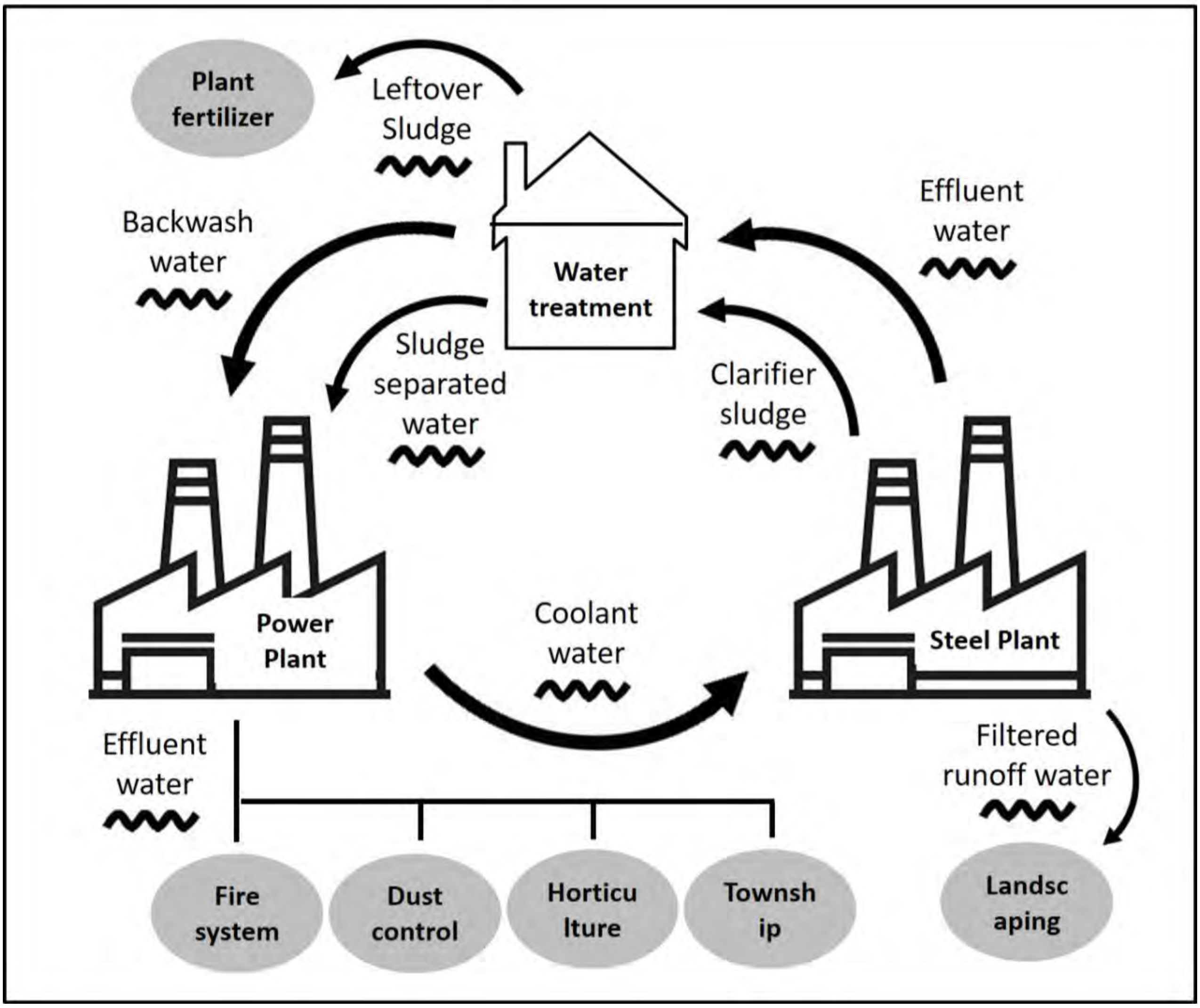

Figure 83: Closed loop water exchange at Essar Steel, Hazira.

Source: Author illustration, based on Essar (2015); EssarSteel (2013a)

denotes by-products

Efficiency improvements included: changes to the powerplant condenser to increase chloride concentration limits in cooling towers; an indigenous system for treated water cascading between power and steel plants; recovery of clarifier sludge water; filtration of surface runoff for landscape irrigation. The closed loop water exchange has reduced annual freshwater demand in the power plant by 835,000 cubic metres. Additionally, alternative uses for treated effluent water have resulted in reduced volumes of marine discharge (Essar, 2015). The water exchange has lowered intensity of freshwater use and resulted in energy savings. It also diverted effluent discharge from freshwater bodies into profitable reuse loops, mitigating ecological damage. The entire system is now self-functioning and has yielded significant monetary savings for all actors, in conjunction with ecology development and reduced dependence on freshwater sources. Daily recovery of 4000 cubic metres of treated effluent for use as coolant in the HBI Plant accrued freshwater savings of 1.48 million cubic metres annually.

5.4.7 Supplementary industrial symbiosis initiatives

5.4.7.1 The ecological impact of the Nand Niketan integrated township

Since 1993, the integrated port city at Essar Steel Hazira has had a mature township spanning 120 hectares and 5000 households. Equipped with an international school, commercial establishments and amenities, the Nand Niketan township received an ISO 14001:2015 environmental management system standard in 2017 (EssarHome, 2017a). The dustbin-free township maintains 70% of the green belt and is home to over 100 bird species (Figure 84) (EssarHome, 2016b).

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Figure 84: Integrated facilities at Essar Steel, Hazira (left); Nand Niketan township (right)
Source: EssarSteel (2019)

Notable municipal and domestic waste reduction initiatives at Nand Niketan township include:

- *Biogas production from food waste*: One of Gujarat state's largest biogas setups with daily capacity to process 1 tonne of food waste is located in Essar Steel Hazira. The energy generated from the biogas plant is used to fuel the central kitchen which services 17 food outlets on campus. This waste-to-energy project eliminated the use of natural gas, utilises entire daily food waste volumes and resulted in significant cost savings for the company.
- *Compost produced from biodegradable waste*: 60 anaerobic compost bins feed into farms and landscaping activities all around the Hazira campus.
- *Hydroponics tomato farm*: nested on the site of a previous garbage yard, the self-managed hydroponics (soil-free) tomato farm employs 12 women from nearby villages, with 400 kilograms daily peak output. The farm yield was 12 tonnes in the first 6 months of operations (Figure 85) (EssarHome, 2017a, 2017b).

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Figure 85: Biodegradable waste compost pit (left); Nand Niketan hydroponics tomato farm (right)
Source: EssarHome (2017b)

5.4.7.2 Plastic and paper recycling

Additional initiatives in the Essar Steel complex include: the eradication of single use plastic in the factory, canteens and households; removal of plastic bags for waste disposal; 100% paper waste recycling in-house to manufacture office stationery. The paper recycling venture led to monetary and environmental savings. Paper demand equivalent to 17 trees was diverted and annual water savings of 26000 litres accrued. To date, 1500 kilograms of paper waste have produced 825 note pads, 2000 envelopes, and 1000 carry bags (Figure 86) (EssarHome, 2016a).

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Figure 86: In-house paper waste recycling at Essar Steel, Hazira
Source: EssarHome (2016a)

Diverse material exchanges at Essar Steel have resulted in complex material loops involving diverse actors, and the integration of *zero waste* goals across industrial, municipal and residential applications. The case examples symbolise firm-level applications of the circular economy; where varied actors engage in strategic dialogue for problem identification, goal-setting, implementation and measurement. Continued learning and incremental capacity development are evident in the vast array of industrial symbiosis links at Essar Steel, Hazira. Owing to the scale of steel making operations in Hazira, Essar Steel was able to find localised solutions for hazardous wastes and water, to extend indigenous solutions beyond mere efficiency improvements. The discussed cases have created triple-bottom line benefits for the firm and neighbouring community.

Electric arc furnace dust, categorised as hazardous waste, has previously been tested to manufacture light weight aggregates, to be used in concrete mixture. Although commercial viability of the recovered materials is to be proven, Cholake et al. (2018) examined the technical characteristics along with the potential to reduce material input costs for construction as well as monetary and energy savings for steel manufacturers. Environmentally safe solutions for recovery and repurpose of steel dust and slag can allay soil contamination risks from landfilling, air emissions and yield significant saving on disposal costs. Alternative applications in construction, like the joint ventures at Essar Steel, will encourage cross-sector collaboration and join problem-solving for improved resource efficiency and waste management in material- and waste-intensive industries like steel and construction.

5.5 Case Study 5: Circular flows for bio products from India's temples

5.5.1 Flower waste disposal: an eco-environmental hazard

India is characterised by a striking cultural and religious diversity, embodied in its 22 official languages in addition to English, and at least six major religious groups (Hinduism, Islam, Christianity, Sikhism, Buddhism, Jainism) (Census, 2011c, 2011d). With the exception of cricket as a sport that binds this diversity together, a ubiquitous cultural custom of offering flowers to deities and to mark auspiciousness with ornate floral decorations is embodied in daily life. Every day before dawn, fresh flower markets spring up in busy commercial centres, merchandising until late at night (Figure 87). To put things in perspective, annually more than 500 million people visit temples and over 8 Million Tonnes of flowers are discarded in the *holy* Ganges river[24] (UNEP, 2019). Nationwide, over 2 Million Tonnes of flower waste is generated daily[25].

Figure 87: Dadar phool (flower) market, Mumbai (left); scene from a temple procession (right)
Source: Author, field visit in December 2018

Adverse environmental effects due to air and water pollution as well as diseases have been reported. The ritualistic consumption of fresh flowers results in off-street litter, clogging in rivers, harmful vapours from decomposing petals and buds released into the atmosphere. The sheer volume of flower waste nullifies the fact that it is, in fact, a biodegradable resource. Furthermore, flowers take a long time to degrade if left in the natural environment, as compared to kitchen waste (Jadhav, Chitanand, & Shete, 2013). Unsurprisingly, noxious pesticides from

[24] CNBC. (2018, September 10). Changing India: HelpUsGreen, video documentary. Retrieved from https://www.youtube.com/watch?v=9zyGaAqaNj0
[25] TOI. (2018, September 14). From flower to compost: How a temple is giving new life, video documentary. *The Times of India*. Retrieved from https://www.youtube.com/watch?v=BTUkoic1GLw

the decomposing flowers trickle into soil, water and air, and contribute to respiratory and water-borne diseases. Populations are exposed to health risks from hepatitis, cholera and diarrhoea[26].

Kanpur city, situated in the northern state of Uttar Pradesh, is home to a flourishing leather and textile trade. As per the latest census, Kanpur ranked as the 12th most populous Indian city and was the 11th most populous urban agglomeration (Census, 2011a, 2011b). Located on the west bank of the Ganges river, Kanpur's eminence as a major trade and commercial centre also led to its classification as one of the most polluted cities in the world by particulate matter concentration[27] (WHO, 2018). The Ganges river provides drinking water to over 420 million people. Conservative estimates suggest that annually over 8 Million Tonnes of flowers are discarded in the *holy* Ganges river[28], and that 16% of garbage in the Ganges constitutes flower waste (UNEP, 2019). Detrimental health and environmental effects are known; yet, the cultural significance of the practice dispelled alternatives to the use of fresh flowers. Composting, which involves the decomposition of organic materials like leaves, grass, food scraps, to produce nutrient-rich compost, is an accepted reuse technique for flower waste. However, in dense temple towns like Kanpur, high daily volumes of flower waste and insignificant disposal costs into nearby water bodies, discouraged composting on temple premises.

5.5.2 Opportunities for effective recovery of temple waste

The environmental and health benefits from temple waste recovery via composting, with extraction of dyes, essential oils, and biogas, are recognised (Yadav, Juneja, & Chauhan, 2015). The embedded value in temple wastes can be recovered by producing organic upcycled products like herbal incense, handmade paper, rose water, herbal colours, and natural dyes. Although numerous applications for these temple wastes are known and accepted, few actual business cases exist.

Coconut shells can be used as secondary material in construction concrete, reducing material costs and diverting waste from landfill and water bodies. Yerramala and Ramachandrudu (2012) compared chemical properties of controlled concrete (standard aggregates added) and concrete produced using coconut shells (where coconut shells replaced 10-20-% coarse aggregates).

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[26] EcoIndia. (2018, December 8). How a Kanpur startup is recycling flowers offered in temples, web series - episode 7. Retrieved from https://scroll.in/video/904921/eco-india-episode-7-how-a-kanpur-startup-is-recycling-flowers-offered-in-temples
[27] CBS. (2019, October 31). The most polluted cities in the world, ranked. *CBS News*. Retrieved from https://www.cbsnews.com/pictures/the-most-polluted-cities-in-the-world-ranked/51/
[28] CNBC. (2018, September 10). Changing India: HelpUsGreen, video documentary. Retrieved from https://www.youtube.com/watch?v=9zyGaAqaNj0

Water:cementitious ratio remained steady at 0.6 for both concrete types, permeable voids, absorption and sorption properties increased for coconut shell replaced concrete. Similarly, Ahlawat and Kalurkar (2014) found that coconut shell concrete was a viable input for reinforced concrete construction, adding to cost-effectiveness and eco-friendly material use.

Vermicompost contains plant hormones like auxin, gibberellins and enzymes; these are known growth stimulants and discourage plant pathogens (Yadav et al., 2015). By mixing biogas digester effluent with temple waste and cattle dung, Gurav and Pathade (2011) produced vermicompost which showed good fertiliser characteristics for flower agriculture. Jadhav et al. (2013) developed a microbial grouping by isolating bacterial cultures from soil near temple premises. The results of using this microbial grouping improved waste digestion to produce bio-manure. When compared with other sources of vermicompost (organic kitchen waste and farm yard waste), flower waste vermicompost showed better physico-chemical parameters, enhancing plant growth.

Owing to increased consumer consciousness to avoid synthetic dyes, natural dyes extracted from used flowers offer immense potential for textile making. Teli, Valia, and Kolambkar (2013) found hibiscus and marigold flower extracts to be successful dyes to colour cotton and cotton/silk blend fabrics. Similarly, Vankar (2009) used dyes extracted from marigold flowers to colour cotton, wool and silk textiles, and confirmed the potential for industrial scale use of natural dyes from flower extracts. Extraction of herbal essential oils, using steam distillation, from rose flower offerings across five temples in Tamil Nadu achieved notable outcomes and demonstrated the commercial viability of such initiatives (Perumal, Moorthy, & Savitha, 2012). Pardeep Singh et al. (2017) extracted natural dyes from temple flowers, vegetable waste, and organic wastes from households and university hostels, using ultra-sonication and spray drying. After successfully using the dye to colour cotton, silk and wool fabrics, the authors found further uses to close the materials loop. Rich in nutrients, these residual wastes were further useful for vermicomposting and biochar production, to be used as organic fertiliser in agriculture.

A renewable and clean energy source, biogas is increasingly being produced to extract value from organic waste. Laboratory tests for biogas, produced using flower waste versus vegetable waste, found that almost double the quantity of biogas was produced per kilogram of flower waste (Ranjitha & Vijayalakshmi, 2014). Puja Singh and Bajpai (2012) reported elimination of pollution effects from flower waste disposal, if it was used to produce methane using anaerobic digestion. This practice is now thriving in Indore city, where two bio-methanation plants process

5 tonnes of wet waste daily to supply 1 tonne bio-CNG to fuel public buses in the city. A third 50 tonne capacity bio-methenation plant is underway, which is expected to sell biofuel cheaper than open market biofuel and CNG (Singh & Khan, 2019)[29].

5.5.3 Circular economy flower upcycling by 'Help Us Green' social enterprise

Help Us Green (HUG), a social enterprise based in Kanpur city (northern India) is addressing the problem of flower waste in crowded temple towns. The grassroots enterprise which conducted a simple pilot project in 2015, today, has operations in four major cities (Kanpur, Mathura, Vrindavan, Varanasi) in the state of Uttar Pradesh with plans to expand nationwide along with initiatives in neighbouring Bangladesh and Nepal. The business employs 73 full-time female staff and has already diverted 11,060 tonnes flower waste and 11 tonnes of chemical pesticides from natural water bodies. One may marvel as to why this is a significant achievement, and the answer lies in appreciating the scale of the problem.

The young social entrepreneur duo, Ankit Agarwal and Karan Rastogi, developed 3 novel products from recovered and treated floral waste. HUG is a prime case of the closure of material loops, in this case with flowers and associated organic materials, which are a daily by-product of temples. The all-women staff are responsible for daily collection of over 4.5 tonnes of discarded flowers from 39 temples; pickup truck routes are optimised for efficiency. Once on HUG premises, manual sorting for organic material, fibre/threads, ceramic idols, glass bottles, plastic, paper and miscellaneous items is done. Organic biocullum sprayed on segregated flowers denatures chemical residues like fertilisers and pesticides.

The next step involves washing the flowers, water from this stage is stored for reuse in vermicomposting. Petals, leaves and branches are separated and sun-dried. Depending on flower species and carotenoid (plant pigments responsible for bright red, yellow and orange hues) levels, the dried flowers are used to manufacture three main products: *natural incense* – aromatic sticks and cones; *vermicompost* – organic fertiliser; and *biothermocol* – biodegradable packaging. A fourth product, *bio leather*, is currently being tested. These fully natural and organic products are thereafter sold commercially and some are directly used in the culture of new fresh flowers (Figure 88-89).

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[29] TNN. (2019, Feb 5 2019). Biomethenation plant success prompts IMC to come up with a bigger one, e-article. *Times News Network (TNN), The Times of India*. Retrieved from https://timesofindia.indiatimes.com/city/indore/imc-biomethenation-plant/articleshow/67841611.cms

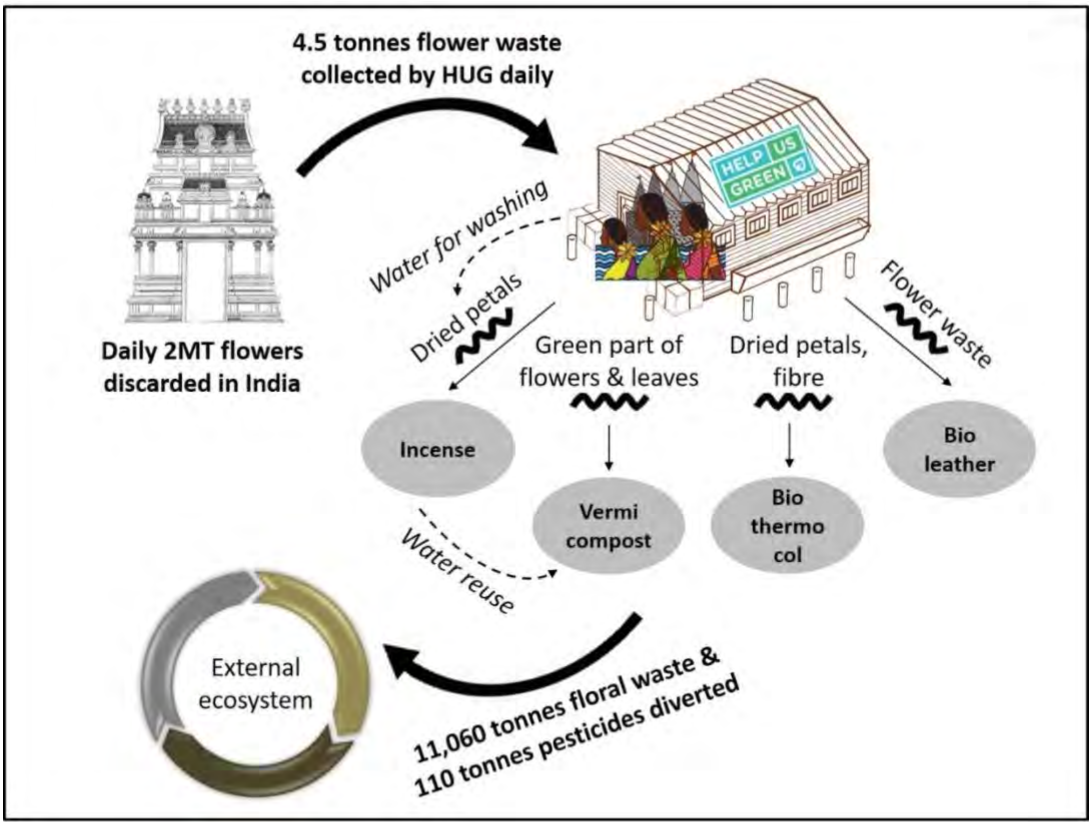

Figure 88: Closed loop process for flower bio products

Source: Author generated, based on EcoIndia (2018); HUG (2019)

denotes by-products

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Figure 89: Phool incense stick and cone (left); Co-founders of Help Us Green (right)

Source: Gulati (2018); HUG (2019)

Phool (incense sticks): Fragrant incense sticks and cones, branded *Phool* (Hindi term for 'flower'), are used in spiritual settings. Available in 13 aromas and priced slightly below 2 USD for a pack, these incense sticks are completely organic and are hand-made; they are a healthier alternative to the predominant Sulphur- and charcoal-based incense. The venture began by exporting *Phool* incense internationally and in 2018 launched sales in India via a vast e-commerce and retail presence.

Vermicompost: Made from the green parts of flowers and leaves, used flowers are crushed and mixed with sawdust and bacteria. Onsite composting of floral waste is not new in Indian temples, the compost acts as a soil conditioner and fertiliser when added to garden landscapes and farms. Although onsite composting does not upcycle the floral waste, it is a localised solution that replaces transportation and disposal costs, if the compost is used within and around the generating site. For example, a large temple in New Delhi composts 30 kilograms of flower waste daily and were able to bring down operation costs lower than disposal costs[30]. However, such localised composting cannot fully resolve the problem in dense temple locales due to excessive volumes. HUG's product extension enables the utilisation of all parts of the collected flowers (Table 10).

Florafoam: A revolutionary new innovation from HUG is Florafoam, a biodegradable alternative to thermocol. Thermocol or Expanded Polystyrene is an extensively used packaging material; although 100% recyclable, its low weight to volume ratio results in it being used largely for single use. High costs for storage and transport make it economically unattractive to recyclers. Today, 91% of thermocol used globally is single-use and its end of life is in rivers, open incineration or landfills[31]. Through intensive research and development, HUG have created a biodegradable alternative using waste flowers at a price that is 27% lower, thereby, making it commercially attractive. Another material, animal-free bio-leather, is currently being trialled and will be marketed soon.

Bio leather: Flower waste to make bio leather is currently being tested as an *upcycled* alternative to animal leather. In addition to producing a higher value material from discarded flowers, the new product will yield significant water and energy savings in comparison to the manufacture of natural leather. Applications for bio leather include high-end fashion clothing, accessories and footwear.

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[30] Desai, K. (2018, September 11). How these temples give a new life to old flowers, e-article. *The Times of India*. Retrieved from https://timesofindia.indiatimes.com/india/how-these-temples-give-a-new-life-to-old-flowers/articleshow/65762167.cms

[31] CNBC. (2018, September 10). Changing India: HelpUsGreen, video documentary. Retrieved from https://www.youtube.com/watch?v=9zyGaAqaNj0

Table 10: Help Us Green products and uses

HELP US GREEN UPCYCLED PRODUCTS	**Incense** 	**Vermi compost** 	**Bio thermocol** 	**Bio leather** 
Natural material inputs	Dried petals, natural plant resin, essential oils; packaging in seed paper	Green part of flowers and leaves, cow dung, earthworms	Dried petals, fibre, natural fungi	Flower waste (exact materials unknown)
Ecological impact in addition to flower upcycle	Replace use of sulphur and charcoal	Reuse water used to wash flowers	100% biodegradable, energy savings, water pollution abatement	Replacement for animal leather, water and energy savings
End use	B2B and B2C overseas exports, e-commerce and retail in India	B2C gardening and farming	B2B – packaging industry	Proposed for use in high fashion clothing and accessories

Source: Author generated

5.5.4 Social-economic-environmental benefits uncovered through the study

5.5.4.1 Circular economy in practice

Globally there are a handful practical examples of the circular economy as a viable business strategy at the firm-level. HUG is a strong case for the adoption of circular economy principles at the level of an individual enterprise, to achieve financial profitability along with strong social and environmental impact (Figure 90). This grassroots venture has received numerous accolades, such as: Momentum for Change presented at UN General Assembly in 2018; nominee for Gates Foundation Goal keepers awards (HUG, 2019; UNFCCC, 2019); and others. These international awards are testimony to the capabilities and contribution of this enterprise.

5.5.4.2 Upcycle of discarded materials

HUG recovered over 11,060 tonnes of floral waste as of late 2019, diverting 11 tonnes of chemical pesticides from fresh water streams into profitable and ecologically sustainable uses. This approach builds on cradle-to-cradle principles. The venture helped declog polluted rivers (eg. Ganges which flows through the holy city of Varanasi), recover, reuse and upcycle the hitherto unutilised resource of flower waste. Having begun by transforming only 12 kilograms of floral waste daily; today, HUG creates higher value products from 4.5 tonnes waste daily. This elucidates the economic opportunity of HUG's closed loop operations.

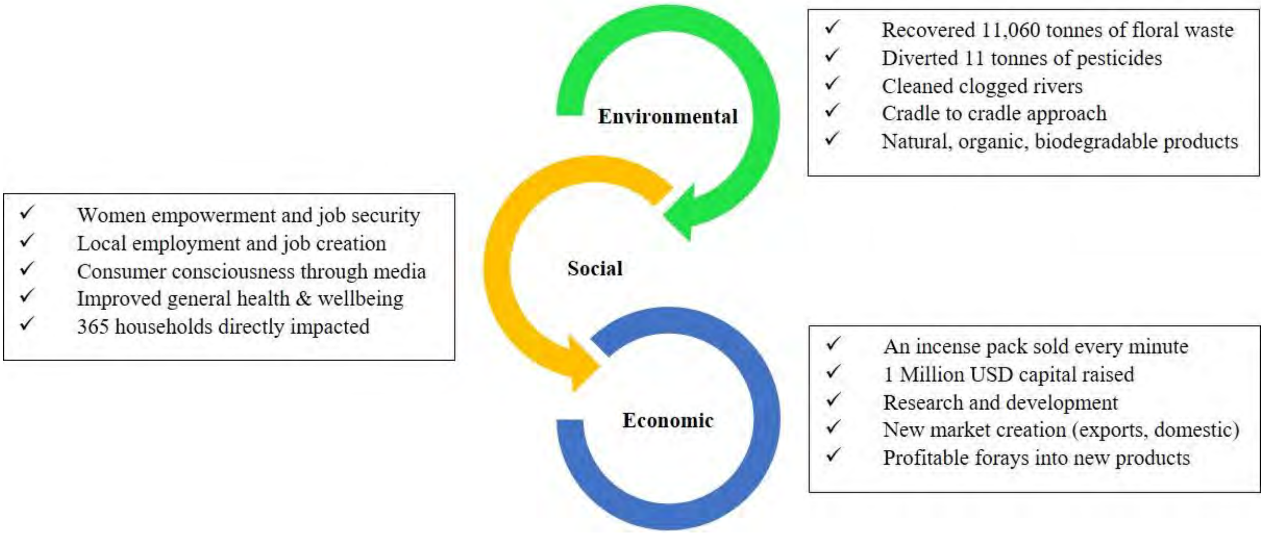

Figure 90: Results of circular economy practices at Help Us Green
Source: Author generated

5.5.4.3 Employment of women and their empowerment

73 women are employed full-time as a respectable and steady substitute for their earlier jobs in informal garbage collection and cleaning. These women manage end to end operations, starting from collection of waste flowers in temple premises to the sorting, drying and crushing for use in different products. 365 households directly benefit from regular incomes, workers' insurance, medical funding, education incentives; thereby, improving overall living standards. In addition to its environmental contribution and financial feasibility, the activities of Help Us Green have created positive social impacts in a short span since commencement.

5.5.4.4 Behavioural shifts

The awards and media coverage of HUG's ingenuity have contributed to their commercial success, also building consumer consciousness and transcending religious practices (of discarding flowers after visiting a temple). Incense sticks, which are a staple in Indian households (burning incense is a daily ritual in many cultures as a symbol of purity and mindfulness) are a low value but high utility product. Phool has witnessed high market acceptance, benefitted by the repeatability of product purchases.

5.5.4.5 Health and wellbeing

Contemporary incense sticks are chemical-based, sulphur and charcoal are key ingredients. Phool's natural origins not only contribute to the waste flower upcycling but also alleviate respiratory risks from the burning of incense. Medical facilities and insurance for HUG employees ensures the creation of a safe work environment, and the uplifting of local communities through job creation and education.

5.5.5 Creation of a circular economy for bio-products

HUG is a strong example of *upcycle*, where the value of discarded products is improved to create alternate uses, in order to increase the life span and thus utility of embodied materials (EMF, 2013; Stahel, 2016). Upcycling of waste is a distinct characteristic of circular economic applications, it diverges from recycling as a downstream, end-of-pipe solution. The upcycling of floral waste from India's temples into manufactured products is a prime example of the circular economy in practice and represents a commodity reuse that has scale and engages citizens. The enterprise implemented a simple and scalable solution to the problem of flower waste in India. It began with an environmental purpose and a modest USD 900 start-up fund, through multi-stakeholder collaboration it quickly transformed into a research-driven and commercially-viable operation. The business model is being replicated internationally, HUG aims to employ 5000 women and recover 51 tonnes of temple waste (daily) by 2022[32].

The transition wasn't without obstacles. For temple authorities, associating with HUG meant discontinuing current arrangements with waste collectors – a massive risk in favour of an untested venture. *Continuity* surfaced as the foremost concern for suppliers (temples) and the moral imperative guided decision-making. Economic outcomes soon surpassed expectations, facilitating fast expansion and media attention. The all-round impact of HUG's activities magnifies the strategic capabilities of circular economic business processes.

One criticism of HUG's current operations is the reliance on a single material stream (flower waste). The literature echoes two concerns: i) the primary goal of a circular economy is to reduce materials use and foster the usage of renewable materials and energy with minimal environmental impact. In the case of flowers, these are naturally biodegradable materials and a product of the natural environment. However, chemically intensive flower culture and unsustainable land use are supply-side negatives. A second, more likely risk, is that of circular economy rebound; where efficiency improvements can lead to increased consumption (Figge & Thorpe, 2019; Figge, Young, & Barkemeyer, 2014).

[32] Gulati, V. (2018, December 12). Indian 'Help Us Green' wins UN award for recycling temple waste, empowering women, e-article. *Firstpost*. Retrieved from https://www.firstpost.com/tech/science/indian-help-us-green-wins-un-award-for-recycling-temple-waste-empowering-women-5716391.html

The problems of invidious floral consumption and ill-effects of waste are not new. In order to reduce ritualistic use, a major behavioural shift is desirable, but not straightforward. The effect of a circular economy rebound could have dire consequences for the environment and the entire supply chain for fresh flowers. Citizen awareness campaigns can sow the seeds for a shift in consumer behaviour towards frugality, the results for which will take time to manifest. Thus, although an end-of-pipe solution, Help Us Green's activities directly increase value for discarded materials, lessen water and air pollution, and is an exemplar for circular economy in practice.

5.6 Case Study 6: Co-processing in cement through alternative fuels and raw materials

5.6.1 Co-processing as a circular economy solution

Co-processing refers to the recovery, treatment and reuse of hitherto *waste* as a source of secondary material or energy in industrial processes, in order to replace virgin raw materials and fossil fuels. By-products of industrial manufacturing like slag from steel making, fly ash from thermal power plants, sludge from effluent treatment, used tyres, plastic, municipal solid waste are well known alternative fuels and raw materials (AFRs) suitable for co-processing in cement making. India's Central Pollution Control Board (CPCB) introduced co-processing guidelines for cement, power and steel sectors in 2010 (CPCB, 2010). Furthermore, programs for energy efficiency like Perform, Achieve and Trade (PAT) are driving investments for co-processing technology and infrastructure advancement among Indian cement manufacturers.

This case evaluates the landscape for co-processing in India. Indian cement plants are considered to be technologically advanced and energy efficient, compared to global counterparts. The country also is the second largest cement producer and consumer, supplying 7% of global demand in 2018. While nationwide co-processing data and models are emergent, the use of AFR in cement plants in the western state of Gujarat is noteworthy. Based on field-study data, inextricable links for circular by-product use between cement and chemical industries surfaced, promising regional resource exchange opportunities for circular economy in India.

5.6.2 Overview of cement industry in India

A core sector for the Indian economy, the cement industry constitutes a few large-sized firms and 98% of these belong to the private sector. India is the second largest cement market, both in production and consumption, after China; it manufactured 285 million tonnes (MT) in 2018, supplying 7% of global demand (IBEF, 2018b, 2018c). In contrast to the ageing cement plants in the USA, Indian cement industry employs state-of-the-art techniques, has relatively new plants and is very energy and emissions efficient. Modernisation and technology adoption have made Indian cement manufacturing firms leaders in production efficiency and environmental performance.

Direct applications for cement in India include residential and commercial building construction, and as binder input in concrete, mortar, and many non-specialty grouts. Cement manufacturing has a nationwide footprint with regional hubs; southern India holds 35% share of capacity, followed by northern India (23%). Western, central and eastern regions have an average share of 14% of India’s installed cement capacity (Figure 91). Production capacity was 425 million tonnes per annum (MTPA) in 2017, this is expected to increase to 735 MTPA in the next decade, in order to meet surging demand for cement domestically (IBEF, 2018c; ICR, 2013).

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Figure 91. Cement installed capacity and key regions in India
Source: IBEF (2018c)

In terms of number of cement plants, Rajasthan state in western India leads manufacturing with 15 plants, followed by Andhra Pradesh with 10 plants. Madhya Pradesh, Tamil Nadu and Gujarat are other important states where the cement industry is agglomerated. The top 20 firms contribute 70% to total production (IBEF, 2018b, 2018c). Domestic demand is significant and is expected to reach 600 MT by 2025 (CMA, 2019); exports constitute less than 2%. Although, India’s per capita consumption of cement, at 195 kg, lags behind the global average of 500 kg (China’s per capita consumption is 1000 kg) (BEE, 2020), a swell in domestic demand is imminent in the next decade to support infrastructure development, urban housing and industrial growth. Projects like the Smart Cities Mission to upgrade 100 satellite cities at par with main urban centers will be the main drivers.

5.6.3 *Resource and energy challenges for the cement industry*

Owing to the inevitable increase in demand for cement, which is expected to triple to almost 800 MT by 2030 (BEE, 2020), access to virgin material (sand), energy use and waste output are dominant challenges facing the industry. The use of AFR in cement manufacture can alleviate some of the resource availability and environmental impact challenges for the industry. The next section will illustrate the opportunity for *chemical gypsum*, a by-product of chemical manufacturing processes. Evaluation of by-product exchanges and their economic models has found that chemical gypsum can be a viable alternative to natural gypsum, easing dependence on virgin mining and imports of raw material for India. Before evaluating the case for Gujarat, a few national initiatives for energy efficiency are reviewed.

Perform, Achieve and Trade (PAT) initiated in 2012 by the Government of India Bureau of Energy Efficiency (BEE), is a regulatory tool to reduce specific energy consumption and increase energy efficiency of heavy industrial plants. Among nine industrial sectors identified as *designated consumers* in phase 1 (2012-2015), due to its high energy dependence, the cement industry was nominated. The market-based mechanism allowed trading of energy certificates based on energy savings. In this phase, total energy savings of 8.67 million tonne of oil equivalent (Mtoe) were achieved, diverting 31 million tonne of CO_2 emissions (BEE, 2020). The 75 cement plants in phase 1 contributed 17% to the total energy savings (MoP, 2018). Subsequently, three-year PAT cycles have continued with new industrial sectors added in each phase. The cement sector continues to participate in PAT energy reduction targets and this has spurred investments in: energy efficient technologies, waste heat recovery and co-generation, AFR for co-processing and the use of renewable energies.

From an environmental standpoint, cement making is one of the most pollution- and energy-intensive sectors globally; process-related emissions constitute the vast majority of environmental impacts. By itself, cement making is responsible for more than 5% of global anthropogenic carbon dioxide emissions (UNFCCC, 2017). In a recent benchmarking study, India had the lowest electricity (kWh/t cement) and fuel intensity (GJ/t clinker) in comparison to fourteen other cement producing regions (GEI, 2019); however, efforts are underway to lower the emissions intensity (kgCO2/t cement) of Indian industry even further. Adoption of AFR through co-processing is a step in this direction.

5.6.4 Alternative fuels in India's cement industry

The 2016 Solid Waste Management Rules lay down guidelines for co-processing of high-calorific hazardous wastes to fuel in cement kilns. There is no clear direction for the use of alternative raw materials; thus, industry actors need to seek state pollution control board support for such practices. In Europe, alternative fuels contribute 40% of heat generation in cement kilns; in India this share is a meagre 4% (GEI, 2019). Although nascent in India, the use of alternative fuels has led to significant cost savings and emissions mitigation for Indian cement producers (Table 11).

Table 11: Summary of the use of alternative fuels in the Indian cement sector

Firm, state	AFR application	Results
Madras Cement, Tamil Nadu	Coffee husk, cashew nutshell incineration to generate bioenergy	Cost saving of USD 1.7 million annually
India Cements Ltd, Tamil Nadu	Sludge containing low sulphur heavy stock (LSHS) used as alternate fuel	Cost saving of USD 6500 annually
UltraTech Cement, Gujarat	Tyre chips and rubber dust used as alternate fuel	Carbon emission reduction of 30,000 tonnes annually
Lafarge, Chattisgarh	Rice husk as a substitute for coal in cement kilns	10% reduction in coal use, energy saving and carbon emission reduction

Source: Author, based on IBEF (2018c)

Gujarat leads India's pursuit for co-processing. Among large manufacturers, Ambuja Cements and Ultratech Cement have witnessed spectacular increases in co-processing. Ultratech Gujarat were leaders in AFR for manufacturing; their three plants in Gujarat cumulatively processed 13,859 MT in 2009. By 2017, Ultratech was using 752,270 MT of waste in their cement kilns. Ambuja Gujarat had a modest start with 1834 MT in 2009, but the company recorded the highest increase with 811,577 MT of waste processed by 2017 (GPCB, 2019a). Key sources of alternative fuel include: plastic waste, mixed waste including municipal solid waste, TDI Tar (by-product of petrochemical industry) and pet coke (by-product of oil refining).

The Gujarat Pollution Control Board along with industrial waste and by-product generators, recyclers and municipal corporations are assisting speedy development of co-processing networks across the state. Figure 92 illustrates different waste categories in Gujarat's alternative fuels mix, and variations in use over almost a decade. Owing to its disproportionate aggregate quantities, pet coke was excluded; yet, some interesting movements are noted. The use of pet coke in cement increased drastically between 2009-2011 and 2013-2015, aggregate quantities increased 900% from 63,310 MT in 2011 to 6,36,898 MT in 2015. Pet coke had 86% share of alternative fuel in 2015-16 (GPCB, 2019b).

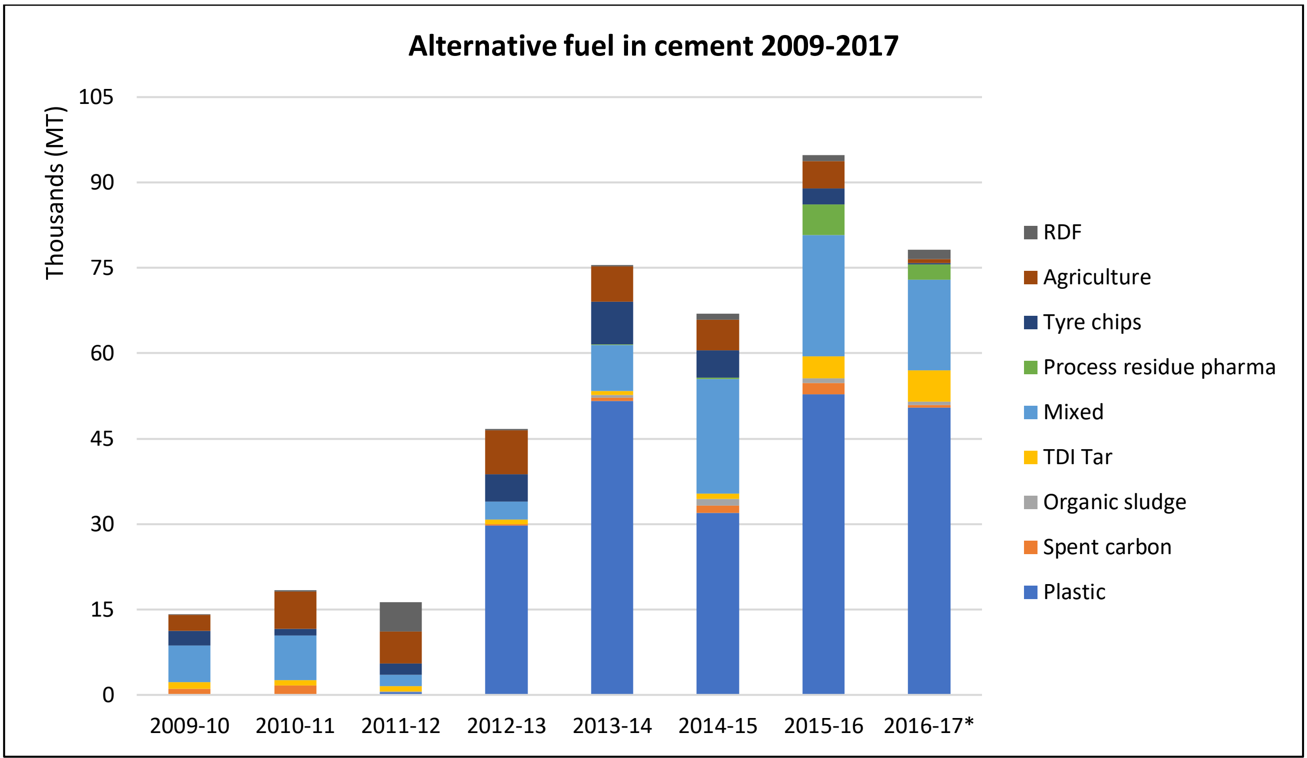

Figure 92. Gujarat state: Alternative fuels in cement 2009-2017

Source: Author calculations, based on GPCB (2019b)

Gujarat was one of the first states to implement CPCB guidelines for co-processing. There was a significant increase in waste to fuel between 2011 and 2013, especially for plastic, mixed waste and tyre chips (Figure 92). India's thrust towards standalone waste-to-energy plants resulted in shifting Refuse-derived fuel (RDF) use from cement kilns. The use of agricultural waste has remained more or less consistent over the period; the decline in rubber from waste tyres is indicative of use in alternative industries like furniture, roads, and construction materials. The volume of spent carbon, organic sludge, TDI tar, and pharmaceutical residue sent to cement kilns is steadily rising (Figure 92); a concerted effort at the industrial estate level has contributed to this increase. A more detailed discussion, including cases of implementation at Nandesari estate, will be discussed later in this section.

The next figure (Figure 93) presents categories of alternative fuels in the cement industry in Gujarat for 2015/16. Plastic had a 52% share, followed by mixed waste (15%); other categories included agricultural by-products (5%), waste tyre chips (3%) and RDF (1%). Miscellaneous fuels comprised resins, expired pharmaceutical drugs, wooden dust, sugarcane bagasse, paint sludge, treated effluent sludge, rags and cotton waste (GPCB, 2019b). An in-depth assessment into the material flows from source to kiln of main categories offers insight into the best applications for these by-products, as fuel use in cement kilns is considered to be the last measure, at the end of useful life. Second, there is no study outlining differences in carbon emissions of cement kilns using coal versus alternative fuels. Such a comparison will help substantiate economic, environmental and social benefits from co-processing. Lastly, in future, if data become available for nationwide use of alternative fuels and categories, it will be useful to plot for India and compare with key industrial nations.

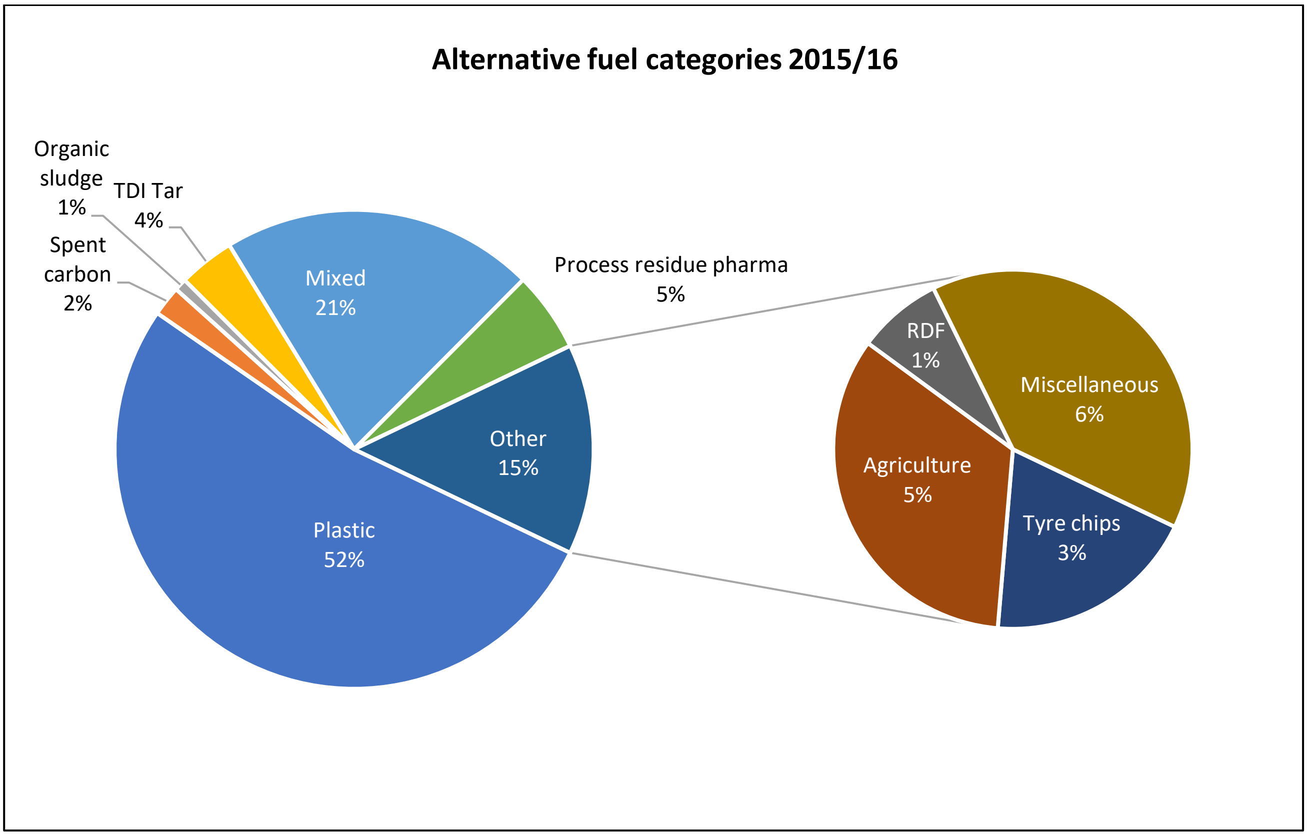

Figure 93. Gujarat state: Alternative fuel categories used in cement kilns 2015/16

Source: Author calculations, based on GPCB (2019b)

5.6.5 *Alternative raw materials in India's cement industry*

Fly ash, the by-product of coal-based thermal power plants and secondary slag from steel blast furnaces are widely used in India as alternative fuel sources. Annually, 50 MT of fly ash and 15 MT of blast furnace slag are recovered for reuse in the production of blended cement[33] . In addition to the diversion from landfill and cost economies, recovery of alternative fuels has resulted in productive land use. For example, diverted fly ash would otherwise occupy 18,720 hectare of land for disposal. Figure 94 illustrates changes in alternative raw material inputs for cement industry in Gujarat from 2012-16. There were noticeable changes in material categories as a response to the CPCB co-processing guidelines issued in 2010. The use of fly ash in cement has been steadily increasing with an average 65% share; the rise indicates better recovery techniques at thermal power plants and proven cases of the scale of economies (GPCB, 2019b).

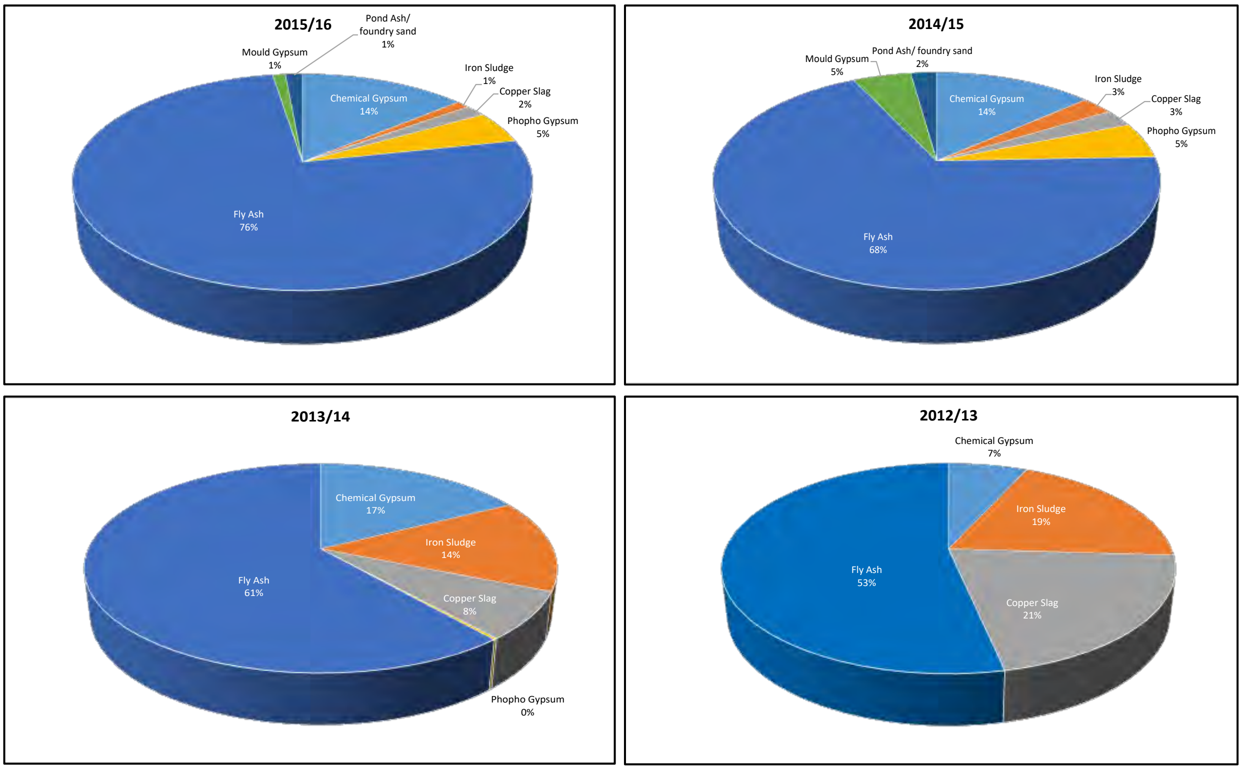

Figure 94. Gujarat state: Alternative raw material categories in cement 2012-16
Source: Author calculations, based on GPCB (2019b)

[33] Singhi, M. K., & Mehra, P. (2017, November 7). Trying to cement a sustainable future, e-article. *The Hindu Business Line*. Retrieved from https://www.thehindubusinessline.com/specials/clean-tech/trying-to-cement-a-sustainable-future/article9947520.ece

Until 2013, copper slag was the second highest by-product sent for co-processing with a 21% share. This has drastically declined and was only 2% in 2016 (Figure 94). Copper slag, a by-product of copper mining, is best suited as a (partial) replacement for sand and fine aggregates in concrete. However, recent studies have found that more than 40% copper slag reduces durability and strength of concrete, as it also increases water absorption capacity (Selvi, Narayani, & Ramya, 2014). This is detrimental for use in construction; hence, copper slag has limited reuse potential in concrete. Iron sludge which contributed 19% in 2013, declined to merely 3% from 2015 onwards (Figure 94). Although 5% phopho gypsum was sent for co-processing from 2014-16, there were negligible quantities earlier. Mould gypsum and pond ash/ foundry sand, too, had an insignificant share prior to 2014 (Figure 94) (GPCB, 2019b).

Despite the pure gypsum content in POP moulds from the ceramic industry, their use in cement is not as widely practiced as chemical gypsum due to its light density; thus, higher transportation costs vis-à-vis volume. Ceramic-cement exchange was tested in Naroda but was not found to be feasible and scale economies are still unknown. The following shortcomings have constrained the exchange of mould gypsum:

- Volume generated at individual ceramic units was very low so neither ceramic producers nor cement makers were interested in pursuing the exchange, as it was neither cost nor time efficient. Cement makers spend USD 2.5 per tonne for transportation of chemical gypsum, however, due to the low density of POP gypsum, the cost of transportation was USD 4 per tonne – and cement producers were unwilling to bear the entire cost. They offered to implement if enough volume became available from the ceramic producer and if that producer agreed to bear the USD 1.5 difference. This didn’t work well for ceramic producers, as their dumping cost in landfill was around 75 cents per tonne.

- Gypsum in POP moulds is not hazardous, therefore disposal is not as big an issue as chemical gypsum. POP moulds can be disposed of at multiple sites with rather inexpensive dumping costs. In contrast, gypsum from chemical industry is hazardous, hence, options for its reuse and/or disposal are limited and costly.

The most significant increase was for chemical gypsum, which surged 2.5 times in 2013/14 with a 17% contribution. This was the second highest share for chemical gypsum in subsequent years (Figure 94). Developments at Naroda and Nandesari estates are exemplars of the emerging model for manufacture of chemical gypsum from chemical industry by-products and wastes.

Specifically, for Gujarat, which supplies 35% of India's chemical output, and is home to large cement plants, the potential for increased use of chemical gypsum is substantial. As cost and scale economies are achieved this exchange will soon become the norm.

<u>Note for data analysis</u>

GPCB (2019b) has not explicitly stated the geographic location of by-product generation and its eventual reuse for co-processing. Thereby, the author has analysed data on the assumption that all stated quantities were generated and reused within the state of Gujarat.

5.6.6 Opportunity for circular economy through utilisation of chemical gypsum

Gypsum, a hydrated calcium sulphate, is a critical input in cement production, used to control the rate of hardening of cement. Other applications for gypsum include fertiliser and plaster of paris (POP) industries. Around 5% of cement consists of gypsum, added to clinker before final grinding; no suitable substitute for gypsum has been found yet. Naturally occurring gypsum, called mineral gypsum, is the purest form and is most suitable for use in fertilisers. Apart from mineral gypsum, phospho-gypsum and marine gypsum are important sources. Marine gypsum from salt pans, is recovered in limited quantities, mainly from the states of Gujarat and Tamil Nadu (IndianMineralsYearbook, 2018). Phospho-gypsum, a by-product of phosphoric acid and fertiliser industries, is proven to have detrimental health and environmental effects from radioactive uranium, radium and fluoride uptake, ground and surface water pollution.

China, USA, Iran and Thailand produce almost 50% of the world's gypsum (Table 12). Thailand was a preferred source for gypsum; however, recent export restrictions by the Thai government coupled with escalating local demand have concerned key importers including India. India's total stock of gypsum as of April 2015 was estimated at 1330 MT, of which 37 MT was designated as 'Reserve'. About 80% of the total stock is for fertiliser and the pottery grade and only 13% is cement or paint grade. The western state of Rajasthan holds 81% of the stock, followed by Jammu and Kashmir (14%), and Tamil Nadu (2%) (IndianMineralsYearbook, 2018). India imported 4.4 million tonnes gypsum in 2015 of its gypsum requirement; key exporters were Oman (68%), Pakistan (20%), and Iran (8%) (IndianMineralsYearbook, 2015).

Table 12. Global gypsum production in 2014 (MT, million tonnes)

Country	Gypsum production (MT)	Share	Country	Gypsum production (MT)	Share
China	39	22%	Spain	7	4%
USA	18	10%	Russia	7	4%
Iran	14	8%	Australia	3.5	2%
Thailand	14	8%	Brazil	3.5	2%
Iraq	11	6%	Canada	3.5	2%
Turkey	9	5%	India	3.5	2%
Mexico	9	5%	**Total**	**28**	**16%**
Total	**114**	**64%**	**World**	**176.7**	**100%**

Source: Author calculations, based on IndianMineralsYearbook (2015)

Note: Quantities are approximate and have been rounded off

In 2014-15, the organised sector in India consumed approximately 9 MT of gypsum; of this, natural gypsum is reported to have maximum share at 58%, by-product gypsum (37%), and marine gypsum (5%). Natural gypsum, the purest when mined, was almost fully used in cement manufacture; whereas, only 60% purity is needed to produce cement (IndianMineralsYearbook, 2015). In recent years, the high cost of gypsum has been a key concern for cement makers. Particularly for India, where increasing logistics costs and export restrictions have elevated resource security concerns for a critical material in a highly important sector of the economy.

Domestic demand for gypsum is projected to rise at a CAGR of 6.5% between 2017 to 2022 (BW, 2018). In order to utilise increase in production capacity, 428 MT gypsum will be needed by 2030. Of this, around 115 MT can be fulfilled from domestic reserves and extraction, the balance (75%) of demand will be reliant on imports (ICR, 2013), unless substitutes are identified. A potential alternative to mineral gypsum is chemical gypsum, a secondary material manufactured from chemical industry waste. Known cases of recovery and reuse of chemical gypsum are sparse in India due to poor awareness of the local situation, the lack of incentives for waste generators and insufficient quantities generated at firm or estate level.

5.6.7 Akash Dyes: gypsum transfer directly to cement industry

In 1999-2000, a Resource Efficient and Cleaner Production (RECP) survey was conducted within Naroda GIDC, where 500 participant firms shared data on materials, waste and by-product flows. GCPC played a crucial role in partnering with the Naroda Industries Association and providing appropriate methodology for data collection, analysis and recommendations

(GCPC, 2019). RECP methodology has since, been formalised by the United Nations Industrial Development Organisation (UNIDO) under Enterprise-level indicators for resource productivity and pollution intensity (UNIDO, 2010). The RECP assessment at Naroda was, in part, a result of the Gujarat government's increased focus on waste reduction and management. GPCB environmental standards are among the most streamlined, with strict monitoring and control of emissions, effluents and waste; punishments are severe and include firm closure for severe violations.

Akash Dyes, a firm which manufactures 3 intermediates for the pigment industry, was one of the earliest adopters of RECP in Naroda GIDC. In 2000, the cost to convert raw material into finished goods for Akash Dyes was 50 cents per kilogram (kg); this included for cost of waste treatment (cost of production excluding treatment was 30 cents). Producers outside Gujarat, however, were not obligated to meet similar waste treatment norms; and so, their costs for treatment were much cheaper (3 cents). This disparity resulted in competitor products being available in the market at a lower cost of production of 33 cents, in comparison to 50 cents for Akash Dyes.

As a result of RECP findings and recommendations, Akash Dyes employed cleaner production technologies which brought down the cost of production to 40 cents. But despite these efficiency and cost improvements, their product was still cost-inefficient to external suppliers. An additional burden was the high volume of gypsum by-product being generated from core operations. In order to manufacture 1 tonne of finished product, 6 tonnes of gypsum by-product were generated. At the time, the cost of disposing of gypsum was USD 8 per tonne, an additional cost for Akash Dyes. It would have been impossible to internalise this disposal cost; which directly resulted in the firm's search for alternative uses for gypsum.

Concomitantly, Ambuja Cements, one of the India's largest cement manufacturers, was buying natural and marine gypsum @ USD 16 per tonne in the year 2000. Their Gujarat unit consumed around 10,000 tonnes of gypsum daily. After exhaustive lab experiments and pilot testing, an exchange began; where, at no cost, Akash Dyes transferred gypsum by-product to cement producers like Ambuja Cements (Figure 95). Cost of transportation (USD 2.5 per tonne) was borne by the cement partner, yielding direct savings of USD 13.5 per tonne for Ambuja Cements.

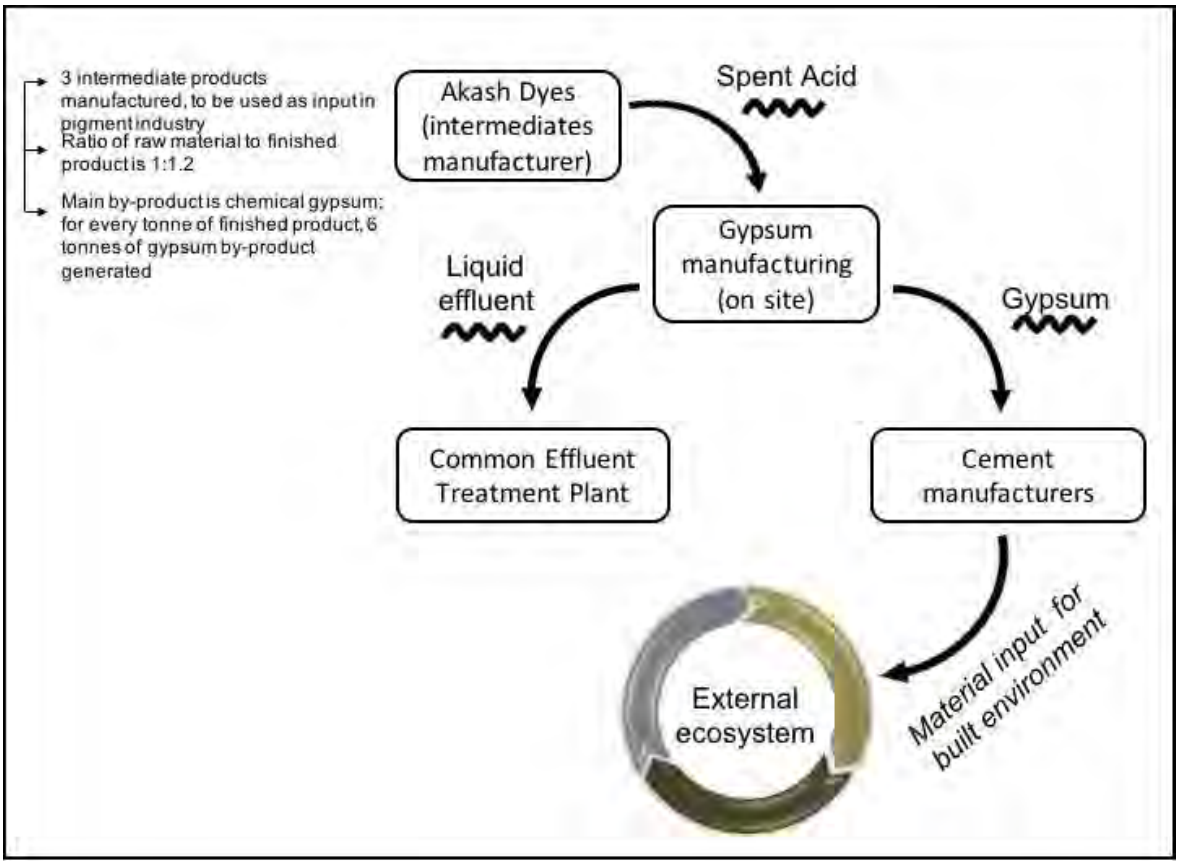

Figure 95. Chemical gypsum manufacture from dye by-products

Source: Author generated, based on field visits, interviews and secondary data

denotes by-products

The gypsum exchange in Figure 95 is active to this day, and Akash Dyes currently transfers almost 4000 tonnes each month. Key partners include Geocycle, Ambuja Cements, and Sauratra Cement. As of 2019, the cost of production for Akash Dyes has risen to USD 1 per kg (including treatment cost). Managing liquid effluent from gypsum production is an additional cost burden. Similar market dynamics persist, whereby external products cost 80 cents. After the gypsum exchange started, Akash Dyes was able to sustain their existence. Thus, rather than an environmental imperative, the drive for Akash Dyes to seek alternative uses for their by-product was in fact one of survival. In this instance economic drivers superseded environmental and social goals.

5.7 Chapter conclusion

5.7.1 Evolution experiences of ISN in India

Table 13 summarises the evolution of ISN in each of the six case study sites, by reviewing the *initiation, implementation, and accomplishments* of the nineteen ISN uncovered through this research. The *initiation* facets identify the key historical, policy and institutional developments that led to inviting action for industrial symbiosis opportunity evaluations by different stakeholders. *Implementation* reflects on the nature of the industrial symbiosis actions in terms of the circular economy principles and the main actors involved in ISNs. Kirchherr, Reike, and Hekkert (2017) developed a typology of ten circular economy strategies, also referred to as the 10R. The strategies are *recover, recycle, repurpose, remanufacture, refurbish, repair, reuse, reduce, rethink, refuse*. The 10R strategies span actions more closely associated with the linear economy such as recovery and recycling, to more circular actions such as reduction, rethinking, refusing (Appendix 15). The 10R circular economy categorisation by Kirchherr et al. (2017), along with industrial symbiosis principles such as resource sharing, inter-firm resource exchange, co-generation, common infrastructure, will be used to evaluate the implementation actions in the case study sites (Table 13). Lastly, *accomplishments* are reported in terms of the benefits resulting from the ecosystem development, as also noteworthy recognition and achievements of the ISNs. The quantifiable results and resource synergy impacts from each of the ISNs are assessed in Chapter 6.

Table 13: Summary of evolution of industrial symbiosis network (ISN) in the six case sites

<table>
<tr><th rowspan="2">Industrial Symbiosis Network</th><th colspan="2">Evolution of ISN</th><th rowspan="2">Accomplishments from ecosystem development</th></tr>
<tr><th>Initiation</th><th>Implementation</th></tr>
<tr><td>1. Chemical gypsum to replace mineral gypsum in cement mix</td><td rowspan="4">• Case site: Naroda chemical manufacturing industrial park
• RECP assessment by UNIDO in the year 2000 identified 8 waste categories for recovery and reuse.
• The findings invited action from the Naroda Industries Association and individual firms, supported by local pollution control boards and external partners for the ISNs.</td><td rowspan="4">• CE principles addressed through ISNs: Recover, reduce, reuse, remanufacture, repurpose (alternative materials).
• Main actors involved in ISNs: Chemical, dye and textile manufacturers; food manufacturers; Naroda industries association; Naroda CETP; NOVEL spent acid management; farmers; external cement manufacturers.</td><td rowspan="4">• Knowledge and community development through delegate exchanges, educational workshops, environmental training for members.
• Social networks through formal & informal links between actors, use of shared services and common infrastructure, centralised planning and upkeep by industry association.</td></tr>
<tr><td>2. Acid reuse in dye, chemical and textile manufacture</td></tr>
<tr><td>3. Condensate and sludge reused as alternative fuel</td></tr>
<tr><td>4. Water, biomethane and biofertiliser reused</td></tr>
<tr><td>5. Steam co-generation & inter-firm steam exchange</td><td rowspan="3">• Case site: Nandesari chemical manufacturing industrial park
• One of five Indian industrial parks in UNIDO's resource efficiency & cleaner production mission (2016).
• RECP assessments showed potential to reduce 19,427 tonnes GHG emissions; 45,006 cubic meters water; 4270 metric tonnes material recovery; 1800 KWh electricity.</td><td rowspan="3">• CE principles addressed through ISNs: co-generation, inter-firm exchange, repurpose (alternative fuels), reuse, refuse (groundwater).
• Main actors involved in ISNs: Pharmaceutical, dye, chemical manufacturers; external firms; boiler plant; Industries association; CETP; Nandesari Environment Control Limited; cement pre-processors; cement manufacturers.</td><td rowspan="3">• Shared access to knowledge, capital and technology for resource recovery and waste management.
• Regional linkages between Nandesari Environment Control Limited, Nandesari CETP, cement pre-processors such as Geocycle, have strengthened alternative fuels and raw material (AFR) use.</td></tr>
<tr><td>6. Alternative fuels used in cement manufacture</td></tr>
<tr><td>7. Water exchange between firms to replace freshwater use</td></tr>
</table>

<table>
<tr><th rowspan="2">Industrial Symbiosis Network</th><th colspan="2">Evolution of ISN</th><th rowspan="2">Accomplishments from ecosystem development</th></tr>
<tr><th>Initiation</th><th>Implementation</th></tr>
<tr><td>8. Integrated services & shared infrastructure</td><td rowspan="5">• Case site: Jawaharlal Nehru Pharma City (JNPC) pharmaceutical manufacturing park

• Public-private-partnership, positioned as India’s first planned ‘eco’ industrial park through shared services, common infrastructure and advantageous initiation procedures.

• Zero waste goals to manage toxic and hazardous pharmaceutical by-products; scientific processes for recovery, treatment, disposal.</td><td rowspan="5">• CE principles addressed through ISNs: common infrastructure, sharing, recover, inter-firm exchange, reuse, repurpose (alternative fuels), refuse (coal in boilers).

• Main actors involved in ISNs: Pharmaceutical & chemical manufacturers; Park management; State Pollution Control Board; external recyclers; CETP; Coastal Waste Management Plant; external aggregators; cement manufacturers.</td><td rowspan="5">• Locational benefits to firms in terms of physical infrastructure, shared services, cost and time savings, skilled labour, knowledge development.

• Internal and external supply chain links, ability to centrally collect & utilise data on material flows, scientific waste treatment and disposal, higher control of park management and pollution control authorities on illegal dumping and wastes leaving park premises.</td></tr>
<tr><td>9. Zero waste operations; live air emissions monitoring</td></tr>
<tr><td>10. Heat to steam exchange to replace coal use in boilers</td></tr>
<tr><td>11. Intra-firm steam & solvent reuse</td></tr>
<tr><td>12. Co-processing of alternative fuels for cement</td></tr>
<tr><td>13. Urban mining of heavy metals from ELV recovery</td><td>• Case site: Maruti Suzuki Toyotsu India (MSTI) end-of-life vehicle recovery

• India’s Steel Scrap Recycling Policy (2019) conceived 4+1 hub & spoke model for collection & processing of ELV across India.</td><td>• CE principles addressed through ISNs: recover, reduce, repurpose, remanufacture, recycle, shared infrastructure, new business models.

• Main actors involved in ISNs: Automobile users, dealers & manufacturers; specialised ELV recovery facilities like MSTI; metal smelters, metal manufacturers.</td><td>• Scale-up in ELV investments from large manufacturers such as Tata Steel, Mahindra Automotive.

• Diversion of unscientific ELV management from unorganised sector; improvements in hygiene, safety, quality of material recovery; reduced environmental burden from leachate of hazardous substances, seepage in soil, air, water.</td></tr>
</table>

Industrial Symbiosis Network	Evolution of ISN		Accomplishments from ecosystem development
	Initiation	Implementation	
14. Electricity from surplus heat, circulated in internal facilities & external grid 15. Micro pellets manufactured from iron sludge 16. Briquettes & construction materials manufactured from iron dust & steel slag 17. Closed loop water exchange with co-located firms	• **Case site**: Essar Steel • **Hazardous waste management rules (2008)** prohibited the transport and reuse of ferrous by-products. This **resulted in onsite innovations.** • **Solid Waste Management Rules (2016)** impacted hazardous waste movement beyond the premises of the generating facility, pushing manufacturers to seek local solutions.	• **CE principles addressed through ISNs:** remanufacture, reuse, recover, recycle, repurpose, refuse, reduce. • **Main actors involved in ISNs:** Essar Steel Hazira; external power suppliers; construction partner; power plant; residential township.	• **Zero waste successes** through localised solutions for industrial, municipal & residential by-products; firm-level circular economy. • **Continued learning and capacity development** resulting in triple-bottom line benefits for the firm & neighbouring communities. • **Awards** from the Centre for Science and Environment, Water Digest, World Steel Association, Confederation of Indian Industry.
18. Innovative products from upcycle of biowaste in temples	• **Case site**: Help Us Green (HUG) social enterprise • **Alarmingly high rates of freshwater clogging** from mounting volumes of fresh flowers and temple discards. • **Successful pilot in 2015;** today, has operations in four Indian cities with plans for international expansion.	• **CE principles addressed through ISNs:** recover, recycle, repurpose. • **Main actors involved in ISNs:** Temples; firm including female staff & families, extended communities.	• **Creation of a circular economy for bio-products**; financial profitability along with strong social and environmental impact • **Awards** such as Momentum for Change presented at UN General Assembly in 2018; nominee for Gates Foundation Goal keepers.

Industrial Symbiosis Network	Evolution of ISN		Accomplishments from ecosystem development
	Initiation	Implementation	
19. Chemical gypsum manufactured from spent acid, for use as alternative raw material in cement industry	• **Case site**: Akash Dyes – chemical manufacturer • India's Central Pollution Control Board introduced **co-processing guidelines for cement, power and steel sectors in 2010.** Gujarat was one of the first states to implement these guidelines. • **Solid Waste Management Rules (2016)** laid down guidelines for co-processing of high calorific hazardous wastes to fuel in cement kilns.	• **CE principles addressed through ISNs:** recover, recycle, repurpose, reuse, reduce. • **Main actors involved in ISNs:** Akash Dyes; cement manufacturers; State Pollution Control Board.	• **Lasting symbiotic exchange** yielding partnership with various cement manufacturers. • **Reduced demand for virgin mineral gypsum** in cement manufacture, along with cost and efficiency improvements for chemical and cement producers.

Source: Author, based on case study analysis and Kirchherr et al. (2017)

5.7.2 Drivers of industrial symbiosis networks in India

Empirical data for industrial symbioses initiatives at three manufacturing parks, Naroda, Nandesari (chemical industrial parks) and Jawaharlal Nehru Pharma City (JNPC, pharmaceutical industrial park), showed early signs of eco-industrial transformation. The industrial symbiosis features, exchange network characteristics and shared services uncovered through the case studies of industrial parks reveal numerous possibilities for incorporating circular economy in existing estates. Given the focus on industrial waste in this study, especially categories of hazardous waste which have minimal potential for reuse, alternative fuels and raw materials in cement production represent telling examples of potential solutions. All three case studies magnify inter-sectoral linkages and present symbiosis implementation beyond estate boundaries. Greenfield circular economy solutions for existing industrial parks are a pipedream for the foreseeable future; financial and technological constraints, along with physical space limitations, already exist. Instead, organic implementation of industrial ecology solutions is shown to have lasting success and potential to involve multiple stakeholders.

The case analyses demonstrated not just successful examples of industrial symbiosis through resource exchange between co-located firms within the industrial park, but also the evolution of institutional structures and support networks; these suggest early signs of embeddedness and a concerted effort to initiate resource efficient and cleaner production in Indian manufacturing. While the existence of infrastructure like roads, canteens, hospital and fire services, and shared utilities like water and power supply, waste recovery, treatment and reuse were a common paradigm, an unforeseen driver for industrial symbiosis was found in the ‘industry associations’ (Chertow & Ashton, 2009). Industry associations as internal actors, with the ancillary role of local and regional governance institutions could establish the industrial dynamics of a circular economy in India. Positive and negative feedback loops keep the network iterative and self-improvising, growing network dependence between active and passive actors.

While information on materials, energy and water exchange is fragmented and a focused pursuit of eco-industrial projects is warranted, positive progress is evident. Specifically for SMEs, which constitute a vast majority in these two sites, the lack of technical knowledge, finance and technology hinder circular economy progress; industrial symbiosis networks, thus, propose avenues for higher combined economic, social and ecological benefit. Reporting and access to data on material flows is the first and most important step to identifying the circular economy potential within an industrial park. Confidentiality and proprietary information exposure by sharing market-sensitive data are justifiable concerns for private firms, especially in highly advanced and competitive industries (Chertow et al., 2008). A central data repository managed by a reliable party will accelerate the pace of knowledge creation and capacity mobilisation.

Previously unreported exchanges were discovered through the field study. The case studies pointed to strong cross-sectoral links emergent between dye, chemical, pharmaceutical and cement industries, especially for the recovery and reuse of alternative fuels and raw materials. Key findings point to *localised* by-product and waste solutions. Important shared utilities and infrastructure like research and development incubation centres, centralised liquid effluent treatment, hazardous waste management unit, and fire/hospital services signify *formative* features of an industrial symbiosis network. JNPC exemplified an emergent model for industrial park development, where government industrial infrastructure and environmental agencies played a supplementary role and private partners are leading the park setup, operations and management. Such a model has proven successful in China, but is only recently emerging in India.

Together, the six case studies were produced to ascertain cross-actor interactions, collaboration drivers and the emergence of circular economy networks for information and resource sharing. Nineteen ISNs were uncovered through the research. All of the reported cases involved active participation of more than one actor, suggestive of ecosystem emergence for circular business models. The roles and activities of various actors are mapped throughout the case study analysis. Circular economy practices were mapped to examine industrial symbiosis features of industrial parks, intra- and inter-firm resource exchanges. Resource efficiency advances in steel, bio-products and cement industries were reported – with intra- and inter-firm resource exchanges, product and process innovations with multifarious economic, environmental and social benefits for all actors.

Small and medium enterprises (SMEs) constitute the vast majority in Indian manufacturing; but they face technological and financial limitations for the adoption of resource efficiency. Improving business performance and firm competitiveness are known drivers for environmental initiatives within SMEs (Ashton, Russell, & Futch, 2017). Cost advantages from waste reduction and resource efficiency were known to drive previous ecological pursuits among firms (Bansal & Roth, 2000). Cost-saving, along with the expectation for "high return on sustainability investments" (Ashton et al., 2017, p. 2146), and the potential for increased profitability, are important considerations for green practices in SMEs, who are often constrained with financial resources (Lewis & Cassells, 2010; Singh, Jain, & Sharma, 2015).

This research found successful examples of circular economy practices in Indian SMEs, in addition to identifying relevant mechanisms for fostering stronger knowledge and resource exchange networks amongst SMEs. The case of Akash Dyes, a small pigment intermediates manufacturer, who is engaged in the exchange of excess gypsum by-product for reuse as raw material input in cement making with Geocycle, demonstrated favourable prospects for co-processing in India. Co-processing in cement production through the input of by-products like plastic, mixed waste and tyre chips as fuel, and chemical gypsum (a by-product of dye chemical manufacturing) as an alternative raw material, are all promising opportunities.

The case study analyses revealed multiple ongoing inter-firm material, water and energy exchanges. Intricate cross-sectional linkages between formal and informal actors were uncovered; their participation in the network evolved as circular exchanges intensified. In contrast to other Asian countries, industry action was found to be the main driver for circular economy in India. Cost economies appeared to bear significant consequences on the inclusion of small and medium enterprises in ISNs. A revelation from the field study was the openness of industry to seek eco-environmental solutions, despite being constrained by technology and informational capabilities. Apart from individual firms, other important stakeholders emerged in the form of industrial development bodies, environmental and cleaner production agencies, and park management. In addition, several state and federal government departments run financial assistance programs for individual factory units and park developers. The success of resource efficient and cleaner production in India will depend on implementation at varying scales of industrially concentrated regions like industrial parks.

5.7.3 Future prospects for co-processing in India

Alternative materials like chemical gypsum and alternative fuels to replace coal use in cement kilns are circular economy solutions that will need to be undertaken on a large scale to be effective from economic and environmental standpoints. The reported cases demonstrate collaboration between diverse industry actors: chemical manufacturing firms (Akash Dyes) and cement manufacturers (Geocycle-Ambuja Cements). In order to accumulate collective gains, a stronger push towards research of alternative uses and shared platforms for cross-industry networking is needed. Accompanied by emissions reduction and efficiency improvements by the cement sector to meet India’s PAT targets, co-processing is a meaningful opportunity in India. Given the pace of construction boom in the country, alternatives to finite virgin materials will further the greening of India’s industrialisation. Ample evidence in favour of co-processing is reported globally. A concerted effort to expand knowledge and technological assets from various industries, coupled with the Indian cement industry’s global competitiveness, will be instrumental in accelerating resource efficiency in the industrial sector.

CHAPTER 6. DATA SYNTHESIS AND FINDINGS

6.1 Introduction

India was ranked as the seventh largest economy with 7% growth rate in 2018 (WB, 2018a, 2018b), with future national growth considered intrinsically linked to its manufacturing sector (IBEF, 2019b). In light of India's growing dependence on material and energy sources to fuel economic development, complex interlinkages have emerged between rising affluence, industrial growth and consumption patterns on one hand, and its pathways to attain long term sustainability and resource efficiency on the other. Critical sectors of the economy like manufacturing, construction and energy are showing progress towards lowered virgin resource use and improved resource utilisation for longer material, energy, water and economic flows. While a singular strategic direction for the circular economy necessitates accelerating its green growth, concrete headway by India's industrial sector suggests ground-up action.

Industrial symbioses through by-product exchange, sharing of utilities and common infrastructure among co-located firms in an industrial park, or between industrial actors in regional economies, have demonstrated the gains from economic, social and environmental synergies in many globally advanced industrial regions. Examples of such synergies, indicative of circular economy implementation at the meso-level, appear to be limited in India. Recent research has been constrained by poorly documented regional material flows and theoretical applications, with scant empirical evidence. Although the retrofitting of older industrial parks into eco-industrial design is well-understood, pragmatic achievements in India were unknown. Specifically in terms of implications of resource efficient and cleaner production practices for small and medium enterprises, this thesis investigated ongoing exchanges and emergent models of cross-actor collaboration.

The strategy to retrofit existing industrial parks with eco-industrial design and closed loop resource flows not only reduces firm exposure to external market conditions, but also nurtures innovation and entrepreneurship in new industry sectors. For India, where industrial activity in parks and clusters is predominant, a collective approach to quantifying regional material flows will enable rapid transition to a green industrial future, owing to a well-structured public-private sector nexus. ISNs rely on the ability, capacity and interest of multiple stakeholders in congregating to improve their material and energy footprint, reduce waste and accrue higher individual and joint benefit, whether monetary or otherwise. Thus, the economic, ecological and social impact of circular economy practices are directly proportional to the ability of the network's members to share, access and build-upon information and connections, utilising network benefits for embedded resources and information exchange.

The next section will elaborate on the main findings of the study from macro, meso and micro perspectives, by linking observations to specific theoretical and conceptual insights.

6.2 India's material and energy shifts

Domestic material consumption (DMC), the aggregate of a nation's material use, showed India's rise to the second highest material consumption, after China. In 2017, India's DMC was 7.42 billion tonnes, a sharp 92% increase over the year 2000. The acceleration in India's material use is linked directly to surges in industrial, infrastructure and housing development. Consequently, the nation's demand for fossil fuels and non-metallic minerals increased by 74% and 66%, respectively, between 2007-17 (IRP, 2018), driven by construction, industry and agriculture sectors. In contrast to aggregate consumption, India's per capita material consumption is lower than major industrial nations, indicating possibilities to leapfrog traditionally material intensive growth patterns. As of 2015, India's DMC per capita was 5.34 tonnes, significantly lower in comparison to Australia (38.38 tonnes), China (23.65 tonnes), USA (21.14 tonnes), Europe (13.84 tonnes), and Japan (9.38 tonnes) (Dittrich, 2014; IRP, 2018; OECD, 2016).

India's IPAT identity recorded rising affluence since 1990, when the process of economic liberalisation began in India. Population showed linear growth and GDP rose at a CAGR of 6.5%. Aggregate DMC doubled in less than two decades, but lowered material intensity on account of rising GDP suggests relative decoupling. Caution is necessary when assessing decoupling of fast-growth economies like India, where GDP surges drive down material intensity levels, and may not denote an improvement in overall material performance of the economy. Overall India's material productivity (the ratio of GDP and DMC), showed consistent improvements owing to lowered material intensity (IRP, 2018; UNEP, 2016).

To complement the material performance indicators for India, National Resource Efficiency Policy (NREP) is being prepared; the plan is to specify targets for resource efficiency in core economic sectors like heavy metals, construction, transport, plastic/ packaging, and agriculture. Ongoing consultations on the draft NREP suggest circular economy business models as the chief driver for India's resource efficiency. Presently, India does not measure and report its material flow accounts, unlike Europe or China or the USA where such indicators are quantified at different scales. By formalising the NREP India plans to report indicators like resource productivity, disaggregated material consumption indices, environmental value chains for primary and secondary raw materials, recovery rates and recycling (MoEFCC, 2019). This will be a monumental step in mainstreaming India's transition to a more resource efficient and self-dependent sustainable future.

India's electricity needs are expected to triple from 4926 TWh (in 2012) to 15,280 TWh in 2040 (IBEF, 2019c). In March 2019, India's total energy capacity stood at 356 Giga Watt (GW), to which coal and thermal sources had a large but declining share at 64% (226.3 GW), followed by renewable energy sources (RES) at 22% (77.6 GW) and large hydro at 13% (45.4 GW). Together, Wind, Water, Solar (WWS) sources comprised a 35% share of India's energy capacity in 2019 (CEA, 2019a).

Since 2007, there has been a striking rise in India's RES outputs, owing to the singular direction by the National Action Plan for Climate Change (NAPCC). Time-series analyses showed massive shifts towards India's uptake of solar and wind energy capacity and generation, to reduce dependence on coal. RES had a negligible (<1%) contribution to India's energy mix in 2000, but had witnessed a 1000-fold increase in capacity by 2017. Similarly, electricity generation from RES stood at 8% in 2017. In fact, since 2017, more solar and wind capacity was commissioned, than coal[34] [35]. Between 2007-2018, solar capacity witnessed the highest increase among RES at 121% CAGR. In terms of absolute RES capacity, wind energy led at 35.6 GW in 2019, followed closely by solar photovoltaic (28.2 GW) (CEA, 2019b).

India witnessed early success towards a 175 GW target for renewables capacity by 2022, under the Nationally Determined Commitments (NDC) for the Paris Agreement. Although, still only about halfway to its 175 GW mark (excluding large hydro), significant progress for WWS in India (123 GW) was visible, when compared to Germany (123 GW) and USA (227 GW). India's goal of 40% of non-fossil fuel installed power capacity was close to realisation: non-fossil fuel installed electricity capacity which includes large hydro, nuclear, and renewable energy, was 38% in 2019 (Joshi & Jaiswal, 2019). The cost-efficiency of India's renewables is praiseworthy.

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[34] Ramanathan, S. (2019, October 16). Renewable capacity additions exceed new coal in India. Blog. Retrieved from https://www.downtoearth.org.in/blog/energy/renewable-capacity-additions-exceed-new-coal-in-india-67269
[35] Sarkar, S. (2020, March 27). Coal power wanes in India despite new additions, e-article. *India Climate Dialogue*. Retrieved from https://indiaclimatedialogue.net/2020/03/27/coals-power-wanes-in-india-despite-new-additions/

RES tariffs were 31% cheaper than coal-powered utilities (Buckley & Shah, 2020) and India's levelised cost of electricity (LCOE) was the lowest in all of the Asia Pacific[36].

Renewable energy scale-up through wind, water, solar infrastructure, generation and storage demonstrated prime success in India's clean energy goals. Acceleration in solar and wind infrastructure in the country coupled with increased generation from WWS sources are driving the nation's green energy shift. India's electric power generation of 1532.2 TWh (as of March 2018) more than doubled since 2005, placing the nation in the 'super-power' league. Concomitantly, the lowering of dependence on coal sources, especially in terms of new capacity addition, and the increasing share of private sector investment in renewable energy projects, are promising for India's green energy transformation.

6.3 Circular economy in Indian industry

6.3.1 Organisational and social perspectives of ISN

The findings of organisational perspectives in IS, including social factors, suggested interesting patters of scholarly inquiry. Colocation, diverse firms and actor roles, common vision between organisations and individuals were found to be **antecedents** for IS relationships. Important **lubricants** for IS connectivity were the existence of "intermediaries, trust, knowledge creation, embeddedness, culture, social and network ties, and communication" (Walls & Paquin, 2015, p. 34). Power asymmetry among actors, unreliable material flows and restrictive environmental guidelines appeared to be **limiters** for ISN. Some interesting **consequences** of ISN related to innovation, economic and environmental benefits, and organisational learning (Walls & Paquin, 2015). These findings provide desirable insights into the non-technical facets of IS which span individuals and organisations, and have been found to have lasting impact on the resilience and self-sufficiency of ISN. While a deliberative effort to introspect the organisational dimensions of ISN in India is required, to embody the unique institutional and social systems, some of the aforementioned social factors were also evident in the chosen case sites.

The case studies documented here uncovered 19 cases of industrial symbiosis networks (ISNs). Numerous material, water and energy savings resulted from multifarious resource synergies

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[36] Samanta, K. (2019, July 29). India's renewable energy cost lowest in Asia Pacific: WoodMac, e-article. *Reuters*. Retrieved from https://www.reuters.com/article/us-india-renewables-woodmac/indias-renewable-energy-cost-lowest-in-asia-pacific-woodmac-idUSKCN1UO0L8

revealed in the six main case studies. The key features of the ISNs reported are summarised in Table 14. Some of the main resource synergies are examined below.

6.3.2 Product innovation for bio products

Diverse evidence of industrial applications for the circular economy emerged in India. Data from chemical, pharmaceuticals, steel, automobiles, cement and construction, as well as bioproduct industries signalled steady advances towards the scaling up of resource efficiency and closed loop resource exchange. Firm-level upcycling of waste products, as in the case of the Help US Green (HUG) social enterprise, resulted in *product innovation* to manufacture four new products using recovered temple waste: i) **Phool** fragrant incense sticks and cones; ii) **Vermicompost** organic fertiliser; iii) **Florafoam** biothermocol for biodegradable packaging; and iv) **Bio** leather, an alternative to animal leather for fashion clothing and accessories. The grassroots enterprise recovered 11,060 tonnes of floral waste as of late 2019, diverting 11 tonnes of chemical pesticides from fresh water streams to create higher value products. In addition to upcycling 4.5 tonnes waste daily, the venture employs women and locals to support over 365 households directly. The economic opportunity of HUG's closed loop operations is demonstrated by the USD 1 million capital already raised.

6.3.3 Circular economy for metals: prospects for urban mining

India had the second highest steel production, globally, of 111.2 million tonnes (MT) in 2019 (IBEF, 2020). A consequence of the booming construction, transport and infrastructure, and automobile industries is an increased domestic demand for steel; India's per capita consumption of steel rose sharply from 57.6 kilograms in 2014 to 74.1 kilograms in 2019 (IBEF, 2020). The National Steel Policy (2017), geared towards production capacity expansion to 300 million tonnes by 2030, offers an estimate of the projected rises in domestic consumption and linked energy and emissions from steel manufacturing. On the other end of the spectrum, metal recycling is an inadequate, informal trade sector, with hazardous dismantling and weak formal supply chains. This combination of factors renders current metal scrap output to low value reuse. Due to these shortcomings, India is highly dependent on imports of good quality metal scrap to support primary steel manufacturing.

In 2018, 25 million tonnes of scrap were supplied through the unorganised domestic sector, and another 7 million tonnes were imported to meet India's demand. India, succeeded Turkey as the second largest scrap importer[37] (MoS, 2019). Presently, scrap metals are used as raw material by secondary producers; use in primary steel production is only 15% in the charge mix of a Basic Oxygen Furnace. High quality scrap input in electric furnaces can assist in the production of high grade steel; access to pure and more standardised steel scrap will encourage use in primary production.

High prospects for urban mining of metals became apparent through the analysis of India's end-of-life vehicles (ELV). Between 2006-2016, an average of 150 million new vehicles entered the economy annually, and India will end up with an estimated 75 million ELVs by the end of 2020. Estimates suggest 210 million ELVs will be added by 2030, and reflects the surge in vehicle registrations (MoRTH, 2016; MOSPI, 2018). An average car comprises 65 % steel, 10% plastics, 8% aluminium, 5% rubber, 1% copper, 1% glass. Efficient recovery of steel scrap from ELVs is a strong economic opportunity. Accompanied by 74% energy savings through metal recycling, scientific ELV management can divert 11 MT of steel and 800,000 tonnes of non-ferrous metals from landfill (CERO, 2018). Each tonne of scrap can replace 1.1 tonne of iron ore, 630 kg of coking coal and 55 kg of limestone inputs in steel manufacturing, reducing energy consumption by 40% and air emissions by 86% (Wübbeke & Heroth, 2014). Despite the opportunities presented from reduced dependence on virgin ores, only 30% of steel used in Australia, Brazil, China and India is recycled (Yellishetty & Mudd, 2014).

India's Steel Scrap Recycling Policy (2019), which pivots the expansion of circular economy for metals, will be a major step towards reducing India's import dependence on scrap metal and for strengthening local metal recycling value chains. The immediate target will be to replace up to 7 MT of scrap imports with domestic production, with the long-term goal of self-sufficiency by 2030 (MoS, 2019). For India, ELV promises not just an opportunity for urban mining but also fast investment returns due to the scale of the problem. Industry-wide trends are visible to actualise circular economy through extended producer responsibility and product stewardship. Maruti Suzuki's joint venture with Toyota Tsusho to process 24000 ELVs annually, including creating an ecosystem for used vehicle collection, sorting, scientific dismantling, processing and transporting to primary steel manufacturers, is a first. Another public-private joint venture, CERO, has adopted digital tracking for automobile shredding and recycling to mine 30,000

[37] Iyengar, S. (2019, August 8). India emerges second largest scrap importer, e-article. *The Hindu Business Line*. Retrieved from https://www.thehindubusinessline.com/economy/india-emerges-second-largest-scrap-importer/article28887123.ece#

vehicles annually, for specialised steel varieties and other non-ferrous metals, will be a crucial participant in India's ELV recovery plans.

6.3.4 Closed loop industrial and societal ecosystems at Essar Steel

Essar Steel has industrial, commercial and residential operations over 1500 hectares in Hazira, Gujarat. The steel complex was able to achieve 100% waste recovery of industrial, household and municipal wastes. The research revealed multiple intra- and inter-firm resource exchanges, with profitable economic returns for the firm. The main circular economy advances included: iron sludge converted into micro-pellets; iron dust fines combined to make briquettes for use as coolant in steel furnaces; steel slag remanufactured into construction materials like sand, paver blocks, bricks, cement mix; multiple waste reduction, reuse and organic farming initiatives spanning 5000 households at Nand Niketan township; closed loop water exchange within power and steel plants, an illustration of industrial symbioses between co-located actors.

The circular economy ventures across Essar Steel's industrial and residential communities have yielded numerous supplementary revenue streams for the firm, in addition to invaluable environmental savings and biodiversity revival. Freshwater savings of 1.48 million cubic metres were made annually by achieving 95% water recovery and reuse within plant operations. Treated effluent from the power plant is cascaded into the steel plant to replace 45% fresh water demand in steel making. Some 86% of waste water from the power plant is being reused in steel making, fire systems, dust control, horticulture and irrigation. In addition, 150 tonnes of iron fines are converted daily into briquettes used as cooling liners; supplementary annual revenue of over USD 22 million was expected from remanufactured materials used in construction.

Internal efficiency improvements and external partnerships to cultivate valuable reuses for industrial by-products at Essar Steel demonstrate various applications of the circular economy at a large manufacturer. The closed loop exchanges span hazardous by-product materials, excess water and energy where surplus steam is transformed to heat for electricity generation. These initiatives have benefitted the manufacturer through lowered power costs, GHG emissions reduction, improved energy efficiency, indigenous innovations, intra-firm collaboration and multiple economic revenue streams from hitherto waste streams. The scalability of such closed loop practices necessitates continual investment in research and development, measurement and analytics, as well as close participation of multiple stakeholder categories.

Table 14: Industrial symbiosis networks (ISNs) uncovered through the study

Industrial symbiosis network		Case site	Resource synergies	Network actors	Results
1.	NOVEL – chemical gypsum as alternative material in cement (Figure 41)	Naroda	*Chemical gypsum* recovered from excess spent acid, used to replace mineral gypsum in cement mix	Chemical manufacturers; Naroda industries association; Naroda CETP; NOVEL; cement manufacturers	300 tonnes of chemical gypsum sent for cement manufacture
2.	NOVEL – acid reused in dye, chemical and textile manufacture (Figure 42)	Naroda	*High strength acid, colourless acid, alum and ferrous sulphate* remanufactured from excess spent acid	Chemical manufacturers; Naroda industries association; Naroda CETP; NOVEL; cement manufacturers	0.5-0.8 million litres of spent acid processed daily
3.	Condensate and sludge recovery from liquid effluents (Figure 43)	Naroda	*Condensate* from liquid effluent reused; *sludge* from dried effluent reused as alternative fuel in cement manufacture	Chemical, dye and textile manufacturers; Naroda CETP; cement manufacturers	3 MLD liquid effluents processed; hazardous and inorganic liquid effluents recovered into valuable materials
4.	Water, biomethane and biofertiliser from food industry wastes (Figure 44)	Naroda	*Water* from liquid effluent reused; *biomethane* and *biofertiliser* from organic wastes	Food manufacturers; Naroda CETP; farmers	0.5 MLD of organic wastes processed; 80% recovered methane used to power the CETP; 20% diesel recirculated in biogas plant; energy efficiency improvements in water supply
5.	Inter-firm steam exchange via common boiler (Figure 56)	Nandesari	*Steam* co-generation for heating	Firms within industrial park; Boiler plant operated by third party; Nandesari industries association	Reduced primary coal use; inter-firm steam sharing and heat-steam exchange
6.	Alternative fuels in cement manufacture (Figure 58)	Nandesari	*Alternative fuel inputs* from treated inorganic and organic wastes	Pharmaceutical, pesticide, dye, food, chemical manufacturers; Nandesari CETP; Nandesari Environment Control Limited; cement pre-processors; cement manufacturers	1 million litres liquid effluent processed at CETP daily; USD 0.7 million CETP revenue annually; reverse logistics for cement packaging and plastic laminates
7.	Water circularity to replace freshwater use (Figure 59)	Nandesari	*Co-located water exchange* to reuse wastewater and replace groundwater	Reliance Industries; Nandesari Environment Control Limited; firms within industrial park; Nandesari CETP	12 MLD freshwater demand fully replaced by treated effluent water; monetary savings of 13 cents per kilolitre are likely for industrial-users
8.	Integrated services and shared infrastructure (Figure 65)	JNPC	*Common infrastructure and utilities*; *incremental services* like solid and liquid effluent management; *knowledge*	Ramky Pharma City; firms located in JNPC; Ramky Enviro Engineering; Andhra Pradesh Pollution Control	Start-up cost and time savings for firms; scientific effluent treatment, recovery and onsite disposal; entrepreneurship

			and capacity development through incubator, R&D	Board	and innovation
9.	Zero waste operations (Figure 67)	JNPC	*Internal and external by-product reuse* for spent solvents, salts, organic and inorganic chemicals; *alternative fuels inputs* from non-hazardous solid and liquid effluents; *live air emissions* monitoring and reporting	Pharmaceutical manufacturers; Ramky Pharma City; external recyclers and remanufacturers; JNPC CETP; Coastal Waste Management Plant; cement manufacturers	Recovery and reuse of solid by-products like spent solvents, salts, organic and inorganic chemicals; hazardous industrial wastes diverted from landfill; opportunity for park-wide resources circularity
10.	Heat to steam exchange between co-located firms (Figure 69)	JNPC	*Excess heat transferred as steam* to replace coal use in industrial boilers	Kanoria Chemicals; Laurus Labs	40% reduction in carbon footprint; retirement of 3 coal-fired boilers; lowered air emissions; supplementary revenue stream for donor firm; knowledge and information sharing
11.	Intra-firm steam and solvent reuse (Figure 70)	JNPC	*Steam condensate* reused as coolant water; *excess solvent* recovered for internal reuse	Laurus Labs – different internal manufacturing processes	Freshwater use replaced; production efficiency improvements; material value recovery; cost savings from diversion of virgin resource use and landfilling
12.	Co-processing of alternative fuels from pharmaceutical wastes (Figure 71)	JNPC	*Alternative fuels* from organic and non-hazardous solid wastes	Pharmaceutical manufacturers; Coastal Waste Management Plant; Andhra Pradesh Pollution Control Board; external aggregators; cement manufacturers	80% of organic waste from Coastal Waste Management Plant sent to cement manufacturers; 100% of organic waste from large pharmaceutical manufacturers like Laurus Labs diverted from incineration for fuel use in cement; reduced air emissions and energy use
13.	Circular economy in end-of-life vehicles through urban mining (Figure 76)	MSTI	*Recovery of heavy metals* like steel and aluminium back into the automobile manufacturing value chain	End users; Automobile manufacturers and dealers; specialised ELV recovery facilities like MSTI; metal smelters and manufacturers	Foster urban mining infrastructure; other materials recovery like, plastic, fibre, rubber, glass; reduced metal scrap import dependence for India
14.	Electricity generation from surplus heat (Figure 79)	Essar Steel	*Electricity* through heat recovery supplied to internal facilities and external grid	Essar Steel – different internal manufacturing processes; 19 MW heat recovery plant; external power suppliers	Reduced power costs for Essar Steel; energy efficiency through by-product recovery; onsite electricity generation; reduced air emissions; avoidance of power transmission losses

15.	Intra-firm industrial by-product reuse (Figure 81)	Essar Steel	*Micro pellets* manufactured from iron sludge	Essar Steel – different steel manufacturing plants	2400 tonnes iron sludge diverted from landfill; 100% utilisation of iron sludge; USD 2 million annual net profit savings; hazardous waste diversion and upcycling
16.	Inter-firm industrial by-product reuse (Figure 82)	Essar Steel	*Briquettes* from iron dust and *construction materials* like sand, paver blocks, bricks, road laying, cement mix manufactured from excess steel slag	Essar Steel – different steel manufacturing plants; HARSCO external construction partner	150 tonnes of cold direct reduced iron fines converted into briquettes daily; efficiency improvements due to lesser erosion and longer life of furnace lining; USD 22 million supplemental annual revenue from construction materials
17.	Closed loop water exchange between co-located power and steel plants (Figure 83)	Essar Steel	*Coolant water in steel-making* from recovered alkaline blowdown water from co-located the power plant; *reverse exchange of effluent water and clarifier sludge* from steel plant	Essar Steel plants; co-located power plant; Nand Niketan township	95% water recovery and reuse; 1.48 million cubic metres annual freshwater savings; 45% water demand in steel plant supplied through this exchange; 644,000 cubic metres of freshwater use in steel-making replaced; 105,000 cubic metres of freshwater savings from clarifier sludge extraction; 349,000 cubic metres of freshwater diverted due to backwash water reuse; 835,000 cubic metres reduction in freshwater demand at power plant due to closed loop water exchange; 4000 cubic metres of treated effluent recovered daily
18.	Upcycle of biowaste (Figure 88)	Help Us Green	*Aromatic natural incense sticks and cones*; *vermicompost* organic fertiliser; *biothermocol* biodegradable packaging; *bio leather* upcycled from flowers and organic by-products from temples	Temples; Help Us Green	11,060 tonnes flower waste upcycled; 11 tonnes of chemical pesticides diverted from water bodies; numerous environmental and social benefits
19.	Co-processing of chemical gypsum as alternative raw material in cement (Figure 95)	Akash Dyes	*Chemical gypsum* manufactured from excess spent acid within firm's operations	Akash Dyes; cement manufacturers	4000 tonnes chemical gypsum by-product sold by Akash Dyes monthly; USD 13.5 per tonne cost savings to cement manufacturers; virgin raw

					materials, natural and marine gypsum, replaced in cement manufacture

Source: Author, based on case study data and analysis

Case site abbreviations
Naroda: Naroda chemical industrial park; Nandesari: Nandesari chemical industrial park; JNPC: Jawaharlal Nehru Pharma City; MSTI: Maruti Suzuki Toyotsu India; Essar Steel: Essar Steel Complex, Hazira; Akash Dyes: Akash dye and dye intermediates.

6.3.5 Co-processing in cement and chemical industries

Co-processing through the recovery of alternative fuels and raw materials (AFRs) from chemical and pharmaceutical manufacturers illustrated many cases of inter-firm resource exchanges. Cement manufacturing being a mainstay for India, firms are successfully improving resources efficiency by utilising high-calorific hazardous waste to fuel cement kilns. The State of Gujarat led India's co-processing efforts. Ultratech Gujarat were the leaders in AFR for manufacturing; their three plants cumulatively processed 752,270 MT of waste to fuel. Ambuja Cements recorded the highest jump among Gujarat cement manufacturers to process 811,577 MT of AFR in 2017 (GPCB, 2019a). Key sources of alternative fuel were found to include plastic waste, mixed waste including municipal solid waste, TDI Tar (by-product of petrochemical industry) and pet coke (by-product of oil refining) (GPCB, 2019b).

For alternative materials in cement, fly ash, the by-product of coal based thermal power plants and secondary slag from steel blast furnaces are widely used in the production of blended cement in India[38]. Chemical gypsum, as an alternative to mineral gypsum which is a critical input for hardening of cement, revealed promising opportunities for symbiotic exchange between chemical, pharmaceutical and cement manufacturing firms. Chemical gypsum is a secondary material which is generated as a by-product of dye and pharmaceutical industries. Effective recovery and reuse of chemical gypsum had been limited. However, during the field study of manufacturing parks, the investigator uncovered interesting ongoing closed loop exchanges for chemical gypsum. Akash Dyes, a pigment intermediates manufacturer, identified the opportunity to reuse excess gypsum by-product in cement making in the year 2000. After laboratory testing, the firm was able to partner with Ambuja Cements, a large cement manufacturer. Ambuja Cements' resource recovery division, Geocycle, has been leading similar AFR recovery from manufacturers across India.

For small firms like Akash Dyes, AFR exchanges have meant financial stability in core operations, as they were able to build a recurring revenue stream from an otherwise valueless by-product. Similar exchanges were discovered at Nandesari industrial park where various organic and inorganic wastes are recovered by Nandesari Environment Control Limited (NECL), to be treated and sent as AFR in cement operations. Economies of scale through NECL operations resulted in plummeting costs of AFR procurement for cement makers; previous costs of USD

[38] Singhi, M. K., & Mehra, P. (2017, November 7). Trying to cement a sustainable future, ibid. Retrieved from https://www.thehindubusinessline.com/specials/clean-tech/trying-to-cement-a-sustainable-future/article9947520.ece

195 have been brought down to USD 59 per tonne. These developments are anticipated to encourage further co-processing by chemical and pharmaceutical manufacturers. In addition to the diversion from landfill and cost economies, recovery of AFRs result in productive land use for alternative applications.

6.3.6 Industrial symbiosis for spent acid and chemical gypsum

Spent acid, a by-product of dye and dye intermediate manufacturing, is recovered from three independent industrial parks in Gujarat for transfer to a central facility for treatment and reuse. NOVEL is the central facility where secondary material inputs are manufactured using spent acid, for applications in alum, ferrous sulphate, cement (chemical gypsum), dye intermediates (H-Acid, FC Acid, DASA), and textiles . Having 1.5 million litres capacity, NOVEL currently reuses 0.5-0.8 million litres of spent acid daily. Of the renewed materials, almost 300 tonnes of chemical gypsum are sent daily to cement manufacturers in the state. Multiple actors are involved in this industrial symbiosis exchange: *individual donor firms* (where spent acid by-product is created), *industrial park management*, *NOVEL*, *state and local government agencies*, *recipient firms* (who use the secondary material inputs). The non-localised nature of this exchange is striking, as it reveals multi-actor complex *regional* symbioses.

6.4 Eco-industrial facets in India's industrial parks

Industrial parks in India agglomerate a large proportion of organised industrial manufacturing, especially the activities of small and medium enterprises who benefit from co-locating within an industrial park premises. SMEs gain from sector specialisation, supply chain connectivity, labour availability, knowledge and technology transfer effects, as well as fiscal and monetary benefits like tax incentives, subsidised land, energy and capital costs, access to shared services like common roads, transportation and commercial services, lighting and infrastructure, health and housing. Once a function of government enterprises, India's industrial park landscape is witnessing increased investment from private developers, which has increased the quality of services and infrastructure accessible by occupant firms. The involvement of reputed agencies like GIZ and UNIDO in the design of new parks as well as the eco-industrial transformation of existing parks, is beneficial to apply international best practices in Indian industrial estates.

Two of the five pilot sites nominated by UNIDO (2017b) for the global resource efficiency and cleaner production mission, were chosen for the field study in this thesis. Both the sites, Naroda and Nandesari, represented established industrial parks in India with mature operations, meaning their transition to eco-industrial parks was extremely complex due to land, capital and technology constraints faced by the parks' occupants. Typical of other industrial estates in Gujarat, Naroda and Nandesari were set up by the Gujarat Industrial Development Corporation (GIDC) in the 1960s as part of the state's early industrial development. The majority of enterprises in these parks comprise small and medium firms in the dye and dye intermediate, pharmaceutical, textile, and food industries.

A third park, Jawaharlal Nehru Pharma City (JNPC) was chosen to investigate eco-industrial features at a relatively new and planned eco-industrial park. In contrast to Naroda and Nandesari which are owned and management by the state development agency – GIDC, JNPC had a novel public-private-partnership for initialisation and subsequent operations. JNPC specialises in pharmaceutical bulk-drug and contract manufacturing, and is home to firms like PharmaZell of Germany, Eisai Pharma of Japan, Biocon and Laurus Labs of India, and US multinational Hospira Healthcare. Thus, the mixture of firms at JNPC is medium-large scale multinationals with few local SMEs. JNPC is an example of an integrated eco-industrial park with end-to-end facilities for research, development and production of Active Pharmaceutical Ingredients (API), a host of shared services, and a100% export-oriented Special Economic Zone.

Eco-industrial facets like the common boiler at Nandesari for circular heat-steam exchange between firms and the installation of solar panels on factory rooftops at Naroda are indicative of the ongoing transformation to eco-industrial parks for mature estates. Circular heat-steam exchange is a central feature of advanced eco-industrial symbioses like Kalundborg in Denmark, and so is an important step in Nandesari park's transition to an eco-industrial park. A big revelation of the field study was the enduring heat-steam exchange between Kanoria Chemicals and Laurus Labs, two co-located firms in JNPC. The exchange, which was initiated to resolve practical material challenges, has yielded financial and environmental benefits to both actors and strengthened collaboration on other projects.

Kanoria earns supplementary revenues from heat that was otherwise being wasted through air emissions. Risk and impact assessment at Laurus Labs showed reduction in carbon footprint by meeting 40% of steam demand through this exchange, retirement of 3 coal-fired boilers, and 30% cost savings. Heat-steam circular loops are an intrinsic feature of advanced symbioses networks at Kalundborg and TEDA. Yet, in India, a planned infrastructure to enable such exchange is yet to be realised. Owing to the localised and bi-lateral nature of this heat by-product exchange, which was uncovered as a result of the study, future exchanges at JNPC may be modelled on the Kanoria-Laurus partnership.

Accomplishments for effective treatment of liquid and solid effluents at a centralised facility have encouraged streamlined waste management in the parks and common infrastructure for the transfer of effluent from individual sites to a Common Effluent Treatment Plant (CETP). This has led to different resource recovery, treatment and reuse applications being discovered at the CETP in respective industrial parks. While efficient CETP operations are known to be the norm in many countries, this is not always the case in Indian industrial parks due to various bureaucratic and capital impediments. Hence, the reported exchanges facilitated by the CETP at Naroda and Nandesari are noteworthy examples for other sites. At JNPC, separate facilities for liquid and solid waste have realised significant gains for individual pharmaceutical manufacturers who were unable to find profitable ways of handling effluents. Linkages with cement manufacturers for the reuse of organic wastes and segregated treatments for low and high Total Dissolved Solid (TDS) effluents were noted.

Hazardous wastes and by-products constitute a major share in all three industrial parks owing to their chemically active industry types. The toxicity of wastes generated limits the possibilities for reuse and repurpose. Thus, the synergies uncovered indicate significant strides in resource efficiency and circular economy in India's manufacturing sector. The case studies of Naroda and Nandesari highlight inter-sectoral linkages and symbiosis exchanges beyond the physical boundaries of an industrial park. In contrast, many of the resource synergies at JNPC were found be localised, conceivably a reflection of the diversity of firms within the park. JNPC is also an example of an emergent model for industrial park development in India, where government industrial infrastructure and environmental agencies play a supplementary role and private partners are taking the lead in park setup and operations. This model has proven successful in China, but is only recently emerging in India.

A revelation from the field study was the openness of industry to seek eco-environmental solutions, although constrained by financing, cost, technology and informational capabilities. The analysed case studies demonstrated not just successful examples of industrial symbioses through resource exchange and shared services, but also distinctive institutional structures and support networks to facilitate a circular economy amongst industrial actors. Industry associations as internal actors at Naroda and Nandesari, with the ancillary role of local and regional government, was an interesting finding. A contrast at JNPC was the weak representation of industry associations in ecological projects, and the prominence of the private developer in decision making relating to firm appointment, park operations and environmental management. The next section will view the operations at the three industrial parks through the lens of *institutional capacity building* for industrial symbiosis networks.

6.5 Institutional capacity building of industrial symbiosis networks

The literature offers evidence that institutional capacity building kindles collaboration within and between governance actors to create impact, building upon extant networks to intensify dialogue and linkages (Healey, 1998). In a bid to theorise the evolution of industrial ecosystems through the creation of resource sharing networks, Chertow and Ehrenfeld (2012) posit an evolving non-linear three-phase model: *formative, intentional pursuit*, *formalisation.* The most sophisticated 'formalised' phase has limited examples, Kalundborg in Denmark being the most prominent.

Industrial ecosystems as self-organising networks influenced by dynamic market conditions were found to have lasting success, in contrast to centrally managed or planned industrial symbiosis. Barring a few cases of Chinese success with demonstration projects by the National Development and Reform Commission (NDRC), the pervasive failure of planned symbiosis is ascribed to the emphasis on by-product exchange over economic benefit, the latter being the most fundamental consideration for business. Eco-industrial parks which have invited companies based on their industrial symbiosis potential have met with limited success in the USA, EU and China. In addition to irregular demand or supply patterns for by-products, volumes and quality variations hinder the development of elaborate ISNs.

Boons et al. (2011) first examined the applicability of institutional capacity building in explaining industrial symbiosis network development, and found dynamic linkages amid the three main elements of institutional capacity building; namely, knowledge resources, relational resources, and mobilisation capacity. UNIDO's evaluation of eco-industrial progress in eight countries identified opportunities to strengthen "knowledge dissemination, sharing experiences, and peer-to-peer learning between industrial parks and the regulating authorities" (van Beers et al., 2020, p. 20) in high performance industrial parks. Furthermore, public-private-partnership and private management models recorded better results for EIP initiatives, in comparison to parks solely managed by government enterprises or supported primarily by public-entity initiatives (UNIDO et al., 2017; van Beers et al., 2020).

The current study investigated signs of institutional capacity building in the three industrial parks of Naroda, Nandesari and Jawaharlal Nehru Pharma City (JNPC). Communication links, often spontaneous through informal or social connections, have been found to prompt formal networks for industrial symbiotic exchange. The practical resource management problems and informal dialogue among peers initiated previous symbioses at Kalundborg and Nanjangud (Bain et al., 2010). Collaboration which started with shared goals, problem solving and informal dialogue between actors, resulted in positive and negative feedback loops to further formal symbiotic links.

Past research in the Netherlands, Colombia and China found that institutional capacity of industrial symbiosis networks increased over time by mobilising capacity, relational links and knowledge resources between member and non-member actors of the network (Boons & Spekkink, 2012; Spekkink, 2013; van Hoof & Thiell, 2015; Wang, Deutz, & Chen, 2017). Drawing on theoretical roots of industrial symbiosis, *knowledge resour*ces include data repositories for by-products and waste, technical information on recovery and reuse potential, best practice guides, skill enhancement programs. *Relational resources* refer to the communication and information links between actors and the resultant ‘trusting relationships’, which encourage data sharing (thus, strengthening knowledge resources), improve overall benefit and reduce costs of participating in the symbiosis. *Mobilisation capacity* is the ability of network actors to capitalise on extant resources, engage in industrial symbiosis, stimulate the depth and range of resource sharing and exchange; thereby, resulting in self-sustaining ‘formal’ networks (Boons et al., 2011; Wang et al., 2017).

Based on the results of the current study and evidence from literature, the central role of industry associations in advancing symbiosis emerged clearly (Chertow & Ashton, 2009). Ashton (2008) echoed the importance of industry associations in creating an enabling environment for inter-firm collaboration, whereby managers may have the opportunity to interact, share and navigate joint challenges. In the case of Barceloneta, Puerto Rico, the Wastewater Advisory Council and Puerto Rico Manufacturers' Association were instrumental in initiating dialogue among pharmaceutical firms, which later embarked on industrial symbiosis exchanges. The author found a positive correlation between membership of industry associations and cross-sectoral manager networks. Interestingly, the Wastewater Advisory Council, which had an initial mandate of setting up the wastewater plant, later became an active “institutionalisation mechanism for IS”. Some of the Council’s contributions were identified as “creating familiarity, increasing trust…, establishing by-product reuse, cooperative resource management…" (Ashton, 2008, p. 48).

In order to contextualise the findings for India, prominent symbiotic activities and their links to known sources of institutional capacity building are categorised (Tables 15-17). Findings from the case study sites demonstrated varying degrees of institutional capacity building. Peer-to-peer information channels, through the activities of industry associations, at Naroda and Nandesari laid the foundation for ISNs. In addition to holding education and community development workshops and seminars, these industries associations represented member firms interests' to government agencies, participated in policy dialogue, organised funding for efficiency improvement projects, like the installation of solar panels at Naroda and reverse osmosis (RO) water treatment at Nandesari. As stated earlier, a platform for member engagement and joint action was absent at JNPC, where the developer, Ramky, was the key to inter-firm linkages.

The findings of a new industrial symbiosis study at Naroda industrial estate identified weak trust-building and the absence of co-operative actions to be particularly challenging for competitor firms to network. In such contexts, environmental management issues usually are the starting points for inter-firm networking among managers, which can gradually foster an enabling environment for IS (Gokulram, 2021). While this finding is not new from international experience, the results from Gokulram (2021) and the case studies reported in this thesis confirm the similarities in the emergence characteristics for ISN in India.

Table 15: Evidence of *knowledge resources* creation and enrichment

Symbiotic behaviour	Main actors	Enablers for closed loop thinking	Evidence in case sites
Informal networks – travel together, public transport, local housing, people changing jobs within same region.	Plant staff to mid-management levels.	Knowledge spill over, best practice sharing, problem sharing, practical solutions.	Jawaharlal Nehru Pharma City (JNPC).
Shared research and development.	Industries Association, park management.	Data banks of waste/by-product streams, knowledge sharing, innovation, partner matching (if proactive in industrial symbiosis pursuits).	Naroda waste action centre; Nandesari CETP R&D Centre; JNPC incubation laboratory.
Skill enhancement programs, training, firefighting.	Often initiated by industry associations and supported by municipal corporation, GIDC. Participants of these programs include low-mid level staff, new recruits and fresh graduates.	Knowledge transfer through informal networks, skilled manpower development, proactive action to create future-ready workforce and reduce worker migration outside industrial park.	Naroda Industries Association tie-up with local Skill Development Centre and government institutes to meet skill shortages and development; TERI, WRI seminars and workshops in GIDC estates.
Common Effluent Treatment Plant.	Industries Association, state pollution control boards, park management.	Traditionally CETP was a passive ‘recipient’ of waste, an intermediary between waste generators and final disposal. Proactive estates view CETP as the centre of research and development – data depository on waste and effluent patterns, scientific waste treatment methods, water and energy recovery and reuse.	Nandesari CETP sludge recovery and reuse in cement manufacture; Naroda CETP and biogas plant; JNPC solid and liquid waste management facilities; Monitor, control and report on firm environmental compliance to state pollution control boards.

Source: Author, based on literature, field study, participant interviews and secondary data

Table 16: Evidence of *relational resources* creation and enrichment

Symbiotic behaviour	**Main actors**	**Enablers for closed loop thinking**	**Evidence in case sites**
Shared goals, problem solving – environmental targets, local ecology improvement, inefficiency of public governance, infrastructure development.	Resident companies within industrial park are often the initiators, member representatives from company – human resources manager, senior management, owners.	Success in implementing efficient environment management and closed-loop practices only when resident companies actively participate.	Formation of industries association at Naroda, Nandesari industrial estates; member training and seminars which aid learning, technical advice and expert advocacy.
Community events.	Industries Association, member companies, local community/residents.	Training and workshops, cultural exchange, community development among resident companies, local employment.	World environment day; fire safety and health programs; tree plantation drives; sports events; COVID response clinics – Naroda, Nandesari, JNPC.
Specialised fora, professional associations, specific action groups – environment, supply chain linkages.	Respective specialists, senior management, plant managers.	Best practice sharing, policy dialogue, supply chain partnerships/ efficiencies.	JNPC – Bulk Drug Manufacturers Association; Pharm Excel; WRI and TERI knowledge seminars.
Shared utilities (transport, food canteens, hospitals, fire/post/police services).	Industries association, park management, local council.	Informal exchange of knowledge resources, problem sharing, joint sense of community, local ecosystem development.	Evident in most established industrial parks and estates; especially those having planned development and support of state industrial corporation.

Source: Author, based on literature, field study, participant interviews and secondary data

Table 17: Evidence of *mobilisation capacity* development

Symbiotic behaviour	**Main actors**	**Enablers for closed loop thinking**	**Evidence in case sites**
Intentional pursuit of symbiotic partners.	Evidence of individual firms seeking profitable use for by-products. In the case of hazardous by-products, rules and mandatory permission from government can be detrimental to symbiosis.	At the firm level, reduced disposal costs, complementary revenue streams and overall improvement of local ecology.	Most uncovered cases of symbioses involved intentional pursuit by the individual firm, supported by institutional actors like industry associations and government. This was in stark contrast to the experience of Chinese eco-industrial parks.
Participation in industry association.	Member companies, independent agencies like GCPC.	RECP assessment, comparative performance metrics and suggestions for by-product exchange.	Comprehensive RECP assessment at Naroda industrial estate led to identification of five key product categories with recovery and reuse potential; some of these are currently active in industrial symbiosis.

Source: Author, based on literature, field study, participant interviews and secondary data

6.6 Agglomeration economies and ISN

Chertow et al. (2008) conceptualised linkages between agglomeration economies and industrial symbiosis networks, by applying the conceptual framework to industrial regions in Puerto Rico. Three types of industry concentrations were considered:

i) **Localisation economies**: These might refer to industrial settings where a bulk of firm activity belongs to specific industry, whereby the nature of resource inputs, outputs, by-products and waste is similar. JNPC holds many features of localisation economies. Krugman (1991) identified three key sources for localisation economies as “the presence of a large and concentrated pool of firms and skilled workers (labour pooling); the availability of industry-specific inputs at lower costs resulting from supplier economies of scale (input sharing); and the opportunities for information exchange essential to the innovation process (knowledge spill overs)" (as cited in Chertow et al., 2008, p. 1302).

ii) **Urbanisation economies**: This type of industrial setting comprises economic activities resulting from a diverse set of industries, not directly connected to one another or having supply chain relationships. Mega-scale industrial regions such as TEDA in China might be considered as a recent example of urbanisation economies. In terms of our case study parks, Naroda and Nandesari may lie at the spectrum between localisation and urbanisation economies.

iii) **Static and dynamic economies**: Agglomeration economies may be *static* where benefits such as lower costs of production, labour and infrastructure accrue to participants within the industrial setting, when compared to similar firms which operate outside (Harrison, Kelley, & Gant, 1996; Henderson, Kuncoro, & Turner, 1995). JNPC's developmental model closely follows this type of agglomeration economies and the co-locational benefits to pharmaceutical firms within JNPC were underscored in the field interviews. In addition to the benefits of static agglomeration economies, *dynamic* economies build on knowledge creation and shared learning among participants; these usually develop over longer periods of interaction and intensify with experience and time (Henderson et al., 1995).

Against the three types of industry concentrations, three mechanisms of *sharing*, *matching* and *learning*, as proposed by Duranton and Puga (2004), were examined. This 3x3 matrix by Chertow et al. (2008) is depicted in Table 18. Following the analytical approach by Chertow et al. (2008) and the categorisation in Table 18, agglomeration economies in three case study industrial parks of Naroda, Nandesari and JNPC are assessed in Table 19. The analysis is based on the types of industrial concentration agglomeration economies and industrial symbiosis mechanisms uncovered through the thesis.

Table 18: Environmentally related agglomeration economies and industrial symbiosis

		Types of industrial concentrations in agglomeration economies		
		Localisation economies	**Urbanisation economies**	**Static/dynamic economies**
Industrial symbiosis mechanisms, adapted from Duranton and Puga (2004)	**Sharing**	Industry-specific services	Utility sharing and non-industry-specific services	Static agglomeration gains from increased efficiency through shared resource management
	Matching	By-product exchanges from core industry firms with other regional actors	By-product exchanges among firms in multiple industries	Static agglomeration gains from increased efficiency through cycling of resources
	Learning	Continuous pursuit of industry-specific collaboration to improve resource efficiency and the sustainability of operations	Continuous pursuit of broad-based partnerships to improve the resource efficiency and sustainability of operations	Dynamic agglomeration gains from increased learning and collaboration around sustainability issues

Source: Chertow et al. (2008)

Table 19: Agglomeration economies in Indian industrial parks

Case study industrial park	**Industrial concentration**	**Industrial symbiosis mechanisms**
Naroda chemical manufacturing park	Localisation to urbanisation economies	Matching, learning
Nandesari chemical manufacturing park	Localisation to urbanisation economies	Sharing, matching
Jawaharlal Nehru Pharma City (JNPC)	Localisation economies, static agglomeration economies	Sharing, matching

Source: Author, based on Chertow et al. (2008)

Interestingly, the three industrial parks relate to more than one type of industrial concentration, possibly representing the evolution of industrial activity and the physical boundaries of an industrial park adopted in this research. Over time and evolution of industrial activity as well as extraneous factors such as urban residential development, land use changes, support industry and infrastructure development in the region, once localised agglomeration economies may transition closer to becoming urbanisation economies. This is evident in Naroda and Nandesari chemical manufacturing parks. JNPC stood out as bringing extraordinary benefits to firms located within the park, and its specialisation as a pharmaceutical manufacturing hub, make JNPC a prime example of localisation and static agglomeration economies (Table 19).

6.7 Industrial symbiosis ecosystem emergence

Domenech et al. (2019) distinguished patterns of self-organised symbiosis networks; where, localised interactions predominated information, knowledge and physical resource exchanges. Manufacturing centred around specific industries or clusters and in these industrial actors employed industrial symbioses as a core strategy for waste minimisation and organisational efficiency. Generally, in the European Union, private enterprises and industry actors have self-organised with ancillary support from government and policy. The idea of self-organised symbiosis is uncommon in Chinese industrial parks where numerous complex symbiotic links emerged, but almost all cases involved government direction. In the reviewed cases of Naroda, Nandesari and JNPC, the symbiotic linkages are still nascent and hence, the modes of organisation are not fully understood.

Based on the qualitative study, five foremost factors were found to influence the establishment of industrial symbioses: i) availability and transmission of data on resource flows of firms, parks and entire regions; ii) systems and expertise to test synergistic possibilities and innovative secondary materials/products; iii) identification of commercial opportunities and payback periods; iv) ability to secure consistent inflows of recovered resources, in order to justify investment and transition from ongoing supply chains; and v) skill development and knowledge resources to equip operators and managers to recognise synergistic opportunities. Reliable metrics, data measurement and reporting is a current gap in India; targeted systems and standardisation could eliminate significant barriers to circular economy systems.

The findings offer scope for future research into evaluating the social dimensions of the industrial symbiosis networks at Naroda, Nandesari and JNPC. Although not the focus of this research, field interactions with various actors pointed to the informal links established between participants, through the wider pursuit of resource efficiency, cleaner production and green energy. Especially in settings like Naroda and Nandesari, where core operational activities of an individual firm are complemented by park-wide initiatives knowledge sharing, networking and capacity development, aspects of social embeddedness and social capital, as synthesised by Ashton and Bain (2012), will have useful implications.

It has been observed that symbiotic networks expand from local to regional or inter-regional; principal firms/actors involve nearby firms by demonstrating use cases and logging quantifiable results (Domenech et al., 2019). Once significant synergies are established locally, the scope for widening the network emerges, inviting external participants and intensifying network capabilities. In the process, information dissemination and knowledge is strengthened, regional capacity and institutional arrangements mature. Intriguingly, the industrial symbiosis exchanges that unfolded in India did not follow this pattern; localised networks were still not entirely explored while regional exchanges grew. A possible explanation could be the connectedness of different waste/by-product streams with industries located outside the industrial park – this occurred strongly for the chemical-cement industry nexus at Naroda and Nandesari. Other factors that can influence inter-firm exchanges are transportation distance and associated costs. For spent acid and gypsum exchanges in Naroda, these tipped the scales in favour of donor enterprises. Lastly and most importantly, marketable value for secondary materials dictates interest for pursuing symbioses.

The final chapter synthesises the key discussion points and draws conclusions from the entire study. Identified limitations of the research are briefly summarised and possible priority areas for future investigations of the Indian situation suggested.

CHAPTER 7. DISCUSSION AND CONCLUSIONS

7.1 Progress of circular economic systems and underlying theory

Circularity of resources in order to create closed-loop systems for technical and biological nutrients, entails a marked transformation from predominantly virgin material and energy dependent linear economic systems, to circular economies where higher value extraction from existing resources supplants virgin resource use. Industrial symbiosis, which points to business-to-business exchanges for materials, energy, water, waste and by-products, information and technology, is a concrete pathway for the transformation of linear value chains into closed-loop circular economic systems, in manufacturing. Delinking resource consumption (quantity and intensity) from economic growth and ecological impact, also referred to as decoupling, promises more sustainable development. The critical examination of decoupling progress at various scales in India's growth trajectory, formed the basis for this study.

Owing to the cross-disciplinary nature of the study, a combination of established methods was used to seek holistic understanding of the circular economy landscape in India. The adopted methodology followed contributions by: Ghisellini, Cialani, and Ulgiati (2016); Mathews and Tan (2011, 2016); Pinjing, Fan, Hua, and Liming (2013); Su, Heshmati, Geng, and Yu (2013). These authors critically appraised key policies, national frameworks, and inter-disciplinary roots of circular economy concepts (Ghisellini et al., 2016; Pinjing et al., 2013; Su et al., 2013), and illustrated circular economy business models using specific case sites and measurement metrics (Mathews & Tan, 2011, 2016). Primary and secondary data on macro (nation) level, meso (industrial region/park) level and micro (firm) level were investigated for links to circular economy practice. The manufacturing sector was chosen as the object of analysis, owing to its resources and emissions intensity in parallel with the sector's dominance in India's economic growth outlook.

Theoretical underpinnings of a circular economy, while nascent and evolving, have significantly focused on diverse industrial regions, for example, North America, Europe, Japan and China. Among developing regions, China's leadership in mainstreaming a circular economy action plan, through a nationwide set up of eco-industrial parks with robust measurement and guidance through policy and financial incentives, has yielded some success. However, India's distinctive socio-political climate is showing divergent signs of ground up action. Previous examination in

India revealed the potential for industry-driven eco-industrial park development, and this research confirms concrete progress pioneered by industry actors, in the absence of an overarching national circular economy or eco-industrial framework.

7.2 Contributions and gaps

The research contributions lie in uncovering ecosystem facets, stakeholder roles, institutional structures and institutional capacity building mechanisms in India. While industrial ecology implementation has shown the prevalence of physical exchanges and material flows in industrial symbiosis networks, recent scholarly inquiry is seeking deeper understanding of the co-ordination mechanisms and support structures that facilitate bottom-up action, especially in different geographical contexts. Experience from diverse geographies and economic competencies reiterated spontaneous symbioses to yield high levels of sustainable development, and for such spontaneity, inter-firm collaboration is key. Channels of communication that nurture joint problem identification, definition, solution and implementation are vital to elicit bottom-up action. Support institutions in the form of local governments, advocacy groups, industry associations, social and environmental organisations, research and think tanks are beneficial, and their active involvement has proven to be paramount in the success of enduring inter-firm collaborations (Chertow & Ashton, 2009; Shi, Chertow, & Song, 2010).

Gaps exist in the understanding of India's eco-industrial development approaches. Planned industrial park development with eco-industrial facets is just one opportunity for the design of closed-loop circular economic systems. A physical design-focused strategy might be useful for forthcoming industrial park projects, where infrastructure and information is accessible for the recovery and reuse of industrial by-products, recirculation of water and renewable energy sources. However, a vast majority of industrial parks in India are dated with a limited physical capacity for infrastructure refurbishment or expansion. For such mature industrial parks, local and regional symbiosis networks through brownfield eco-industrial park development, will facilitate circular economies. Unlike a few pioneering developing countries like Ethiopia, where the Industrial Park Development Corporation has implemented (since 2014) a national mandate for eco-industrial parks under institutional aegis from UNIDO, India does not yet have a federal directive for planned eco-industrial park development.

A deliberative plan for eco-industrial park transformation in India is necessitated with the ongoing impetus to circular economy forays in policy and industry. Given the sizeable share of mature industrial parks cohabited by small and medium enterprises across India, the recommendations of the International Framework for Eco-Industrial Parks by UNIDO et al. (2017) will offer useful direction for transformation of industrial parks into eco-industrial parks. van Beers et al. (2020, p. 5) outlined three areas where the framework can facilitate practical guidance for stakeholders such as park management authorities, tenant firms, government agencies and community: "(a) to assist relevant stakeholders in developing and transitioning to EIPs; (b) to consistently approach, encourage, and recognise EIPs; and (c) to improve the performance, sustainability, and inclusiveness of the industrial sector and to move toward an international standard on eco-industrial parks".

Korea's National Eco-Industrial Park Development Program (2005-2016) was successful in fostering nationwide change through a large number of diverse and complex industrial symbiosis networks. Korean EIP expansion followed a participative, goal-oriented model, enabled by active stakeholder engagement and collective learning (Park et al., 2019). Korea's Regional EIP centres led project conceptualisation, feasibility analyses, stakeholder communication and information sharing, equipping EIP transition for industry in a short span of twelve years. This model represents valuable learnings for India, yet to adopt a formal Industrial Symbiosis development strategy.

The aforementioned gaps notwithstanding, India is showing optimistic headway in the greening of its industrial practices, as evidenced through the quantitative assessment and case studies in this research. The research questions identified gaps in the prospects for circular economy within India's developmental plans, and the comparative performance of India's industrial sector with international industrial hubs. The comparative assessment of India's materials and energy performance vis-à-vis global counterparts underscored low per capita consumption, declining material intensity and the likelihood of relative decoupling. Concurrently, acceleration of India's renewable energy capacity and generation is facilitating a clean energy shift to fulfil the nation's expected rise in energy demand. Qualitative assessment through the cases of eco-industrial parks, steel, bio-products and cement industry circular economy advances, demonstrated early signs of eco-industrialisation in India. The formalisation of a National Resource Efficiency Policy, along with Solid Waste Management Rules (2016), as well as the Steel and End-of-life vehicles recycling frameworks, are all suggestive of imminent shifts from *brown* (pollution and resource intensive) to *green* (clean energy, resource recovery and efficiency) shifts in India's growth trajectory.

A centralised data repository for disaggregated material use will be instrumental to scale up India’s green industrial transition. Such an initiative will build transparency and accountability in the industrial sector. Secondly, approaches to upskill and involve the informal waste sector actors will be important to capitalise on inherent grassroots knowledge and experience. The dominance of India’s informal sector in waste and resource management cannot be overlooked. While informal sector actors play an essential role in plugging gaps in India’s waste collection and sorting infrastructure, these informal recycling activities are mainly end-of-pipe and lack scientific or technological know-how. These shortfalls pose serious health and environmental risks and inhibit prospects for higher value recycling or upcycling of resources. In terms of cross-actor collaboration in industrial parks, a complicated web of roles, responsibilities and accountability was demonstrated in the case studies. Previous research has not delved into these composite relationships, and the ecosystem perspectives are a key contribution of the current study.

The research was the first exhaustive and up-to-date in-depth assessment of India’s industrial symbiosis and circular economy accomplishments. Scholarly contributions of this thesis lie in the originality of data and the combination of data sources to arrive at a rounded understanding of circular economy in India. Field level empirical insights on emergence of eco-industrial parks, industrial symbiosis networks and circular economy facets offered novel evidence from India. There are gaps in implementation evidence, especially from fast industrialising nations like India. Calls have been made for greater representation of developing economy idiosyncrasies, to arrive at strategies for wider circular economy adoption. The agglomeration of industrial activities in industrial parks is not unfamiliar; however, circular economy principles applied within these settings can nurture lengthier and higher value resource loops, promoting the use of secondary materials and easing the burden on finite virgin resources. While the focus of the thesis was on materials and energy circularity, some progress in the recirculation of water resources was clear. Water is a vital yet threatened resource in India, a deeper investigation of water circularity deserves singular attention.

Some of the methodological challenges in the current research included incongruencies between national and international statistics, for data collection and reporting techniques, measurement and reporting. To address these gaps, complex databanks were used collectively in line with methodological assumptions and recommendations by Dittrich, Giljum, Lutter, and Polzin (2012); Eurostat (2001); Martinico-Perez, Fishman, Okuoka, and Tanikawa (2017); UN (2016a, 2016b). News and reports by the World Economic Forum (WEF), OECD, World Bank, International Monetary Fund, were used to address discrepancies between data collection methodologies and reported results. For India, Ministry of Statistics and Programme Implementation (MOSPI), Central Statistics Office (CSO), Ministry of Finance, Central Electricity Authority (CEA), Central Pollution Control Board (CPCB), The Energy and Resources Institute (TERI), publish rigorously tested and updated statistics for national and state-level indicators; these were valuable in computing longitudinal indicators.

7.3 Limitations and the future

The author recognises the limited character of cases and the usefulness of seeking firm-level data in future to trace patterns of material use, by-products, waste and in order to identify potential for initiating symbiotic exchange. Quantifiable data on material flows will enable deeper analysis of savings and benefits of closed loop operations. At this stage, only mandatory disclosures to government departments like the Central and State Pollution Control Boards or voluntary information shared by participants are available for analysis. In future, if a structured program like the National Industrial Symbiosis Program in the United Kingdom is put forth, numerous possibilities will arise for in-depth evaluation of stakeholder motivations, barriers, and benefits from industrial symbiosis. Such information will be invaluable to analyse the transition of industrial symbiosis networks, international comparison and theoretical development.

While the thesis has focused on the middle of the spectrum, to evaluate circular economy initiatives in *production* activities, the extreme ends of the spectrum need due attention too. In theory, a circular economy model adopts resource efficiency practices right from the conceptualised and design stages of a product, service or business; extending circular economy approaches through supply-chain wide implementation, including production, packaging, transportation and distribution. The other end of the spectrum relies on consumption efficiency to achieve *reduction* as one of the fundamental goals in a circular economic system. While theoretical and practical knowledge of these facets from circular economy perspectives is still nascent, a deeper inquiry into the imperatives for India is merited.

In summary, it is to be hoped that the recommendations from this research will accelerate India’s development of circular economic projects, for more sustainable outcomes at larger scales.

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APPENDICES

Appendix 1 – Top 10 manufacturing countries: 2007-17

Table 20: Top 10 manufacturing countries: 2007-17

Rank	2017	2016	2015	2014	2013	2012
1	China	China	China	China	China	China
2	USA	USA	USA	USA	USA	USA
3	Japan	Japan	Japan	Japan	Japan	Japan
4	Germany	Germany	Germany	Germany	Germany	Germany
5	India	India	India	South Korea	South Korea	South Korea
6	South Korea	South Korea	South Korea	India	India	India
7	Italy	Italy	Italy	Italy	Italy	Italy
8	France	France	France	France	Brazil	France
9	Indonesia	Brazil	Brazil	Brazil	France	Brazil
10	United Kingdom	United Kingdom	United Kingdom	Russian Federation	Russian Federation	Russian Federation

Rank	2011	2010	2009	2008	2007
1	China	China	USA	USA	USA
2	USA	USA	China	China	China
3	Japan	Japan	Japan	Japan	Japan
4	Germany	Germany	Germany	Germany	Germany
5	South Korea	South Korea	Italy	Italy	Italy
6	Italy	Italy	South Korea	Brazil	France
7	India	India	France	France	Brazil
8	Brazil	Brazil	India	South Korea	South Korea
9	France	France	Brazil	India	United Kingdom
10	United Kingdom	United Kingdom	United Kingdom	United Kingdom	India

Key
Red text - developing economy
Yellow highlight - major change
Russia - economy in transition (blue text)

Source: UNCTAD (2020), Gross Domestic Product by kind of economic activity, ranked based on GDP from manufacturing (USD at constant 2010 prices, in millions)

Appendix 2 – Interview protocol

Key terms

Industrial Park (IP): An industrial park is an area zoned and planned for industrial development. For the purpose of this study, only industrial parks designated for manufacturing are considered.

Eco-industrial Park (EIP): EIPs differ from regular industrial parks in the sense that they are specifically designed to create *closed-loop* manufacturing systems. Industries and operations in such parks are set up in a manner that material and energy wastes from one firm become inputs for another firm, leaving very little total waste from manufacturing. One of the best-known examples of successful EIPs is at Kalundborg, Denmark (Ehrenfeld & Gertler, 1997; Lowe & Evans, 1995); other recent successful examples include Kawasaki (Japan), TEDA (China), Ulsan (Korea), Kwinana and Gladstone (Australia) (Mathews & Tan, 2011).

Industrial Symbiosis (IS): Industrial Ecology literature suggests that businesses can reduce their environmental and social impacts by the creation of closed-loop processes where different businesses exchange materials and by-products to reduce total waste into the biosphere (Frosch & Gallopoulos, 1989; Lowe & Evans, 1995). The ensuing material and energy exchange between co-located firms is termed as *industrial symbiosis* (Chertow, 2000).

Anchor Firm: If a firm's existence is integral to the IP's functioning, and if it was one of the main factors that attracted other firms to locate operations here, the literature has termed such a firm as an 'Anchor Firm'.

Criteria for shortlist

Industrial Park: Is operational (i.e., is not still in planning stages) and majority of the firms undertake manufacturing activity onsite.

Firms in Industrial Park: Manufacturing is the core operation within the IP; it is beneficial if there have been some prior reported cases of IS, or the intention to undertake IS.

Government/ administrative departments: Are responsible for the setup of IPs and EIPs; they are involved in both national and regional industrial development.

Appendix 3 – Interview guide for semi-structured interviews – industrial park authorities/ management

Participant background

Name

Role

Since when have you been associated with this IP?

Prior experience (similar role/ area?)

Experience of setting up the Industrial Park

When did this IP commence operations?

Were you involved with the IP setup since inception? If yes,

How did it come about (government incentives, anchor firm, part of an industrial cluster, agglomeration for existing firms or a way to attract new firms/ operations to develop specialised cluster in the region?)

How many years did it take since approval to operations commencement?

Could you enlist key challenges that were faced during the set-up stage?

Have all phases of the project been completed? If not, what are the next phases?

How many firms are presently located within the IP; how much area is under the IP? Future capacity extension

Is this a public-private partnership? How involved is the local/ state government in operations? Monitoring, environmental compliance?

What are the main industries operational here? Do they have supply chain support in the vicinity? What factors drive firms to locate their manufacturing here? (availability of skilled labour; ease of access to material inputs; incentives – subsidised electricity, tax benefits; finance/ loan?)

Surrounding area – other IPs; are there any supply chain wide firms supporting key industries?

Evidence of Industrial Symbiosis

Shared facilities/ utilities (transport/ logistics, common effluent treatment plant, waste heat recovery, power plant, water treatment)

Environmental monitoring and compliance – are there are mandatory reporting/ tests conducted on firms in the IP for air/ water/ soil quality, emissions, energy use? Is this the responsibility of individual firms/ IP authorities/ local or state government?

Are there any other mandatory disclosures wrt environmental performance that firms are required to make to local/ state governments? How often is this information collected?

Are you aware of any extant material exchange networks within firms or between different firms (for example ….). Could you introduce me to the ___ manager in ___ firm (if firm is involved in IS)?

Is there a waste heat recovery and power generation system within the IP? Do firms share power or physical premises between themselves?

I will explain concept of an EIP, and ask if there are any plans to transform present IP into an EIP.

Anything else you would like to add that would be helpful for the research project?

Appendix 4 – Interview guide for semi-structured interviews – government and administrative agencies

Participant background

Name

Role

Since when have you been associated with this department?

Prior experience (similar role/ area?)

Experience of setting up the Industrial Park

When did this IP commence operations?

Were you involved with the IP setup since inception? If yes,

How did it come about (government incentives, anchor firm, part of an industrial cluster, agglomeration for existing firms or a way to attract new firms/ operations to develop specialised cluster in the region?)

How many years did it take since approval to operations commencement?

Could you enlist key challenges that were faced during the set-up stage?

Have all phases of the project been completed? If not, what are the next phases?

How many firms are presently located within the IP; how much area is under the IP? Future capacity extension

Is this a public-private partnership? How involved is the local/ state government in operations? Monitoring, environmental compliance?

What are the main industries operational here? Do they have supply chain support in the vicinity? What factors drive firms to locate their manufacturing here? (availability of skilled labour; ease of access to material inputs; incentives – subsidised electricity, tax benefits; finance/ loan?)

Surrounding area – other IPs; are there any supply chain wide firms supporting key industries?

Evidence of Industrial Symbiosis

Shared facilities/ utilities (transport/ logistics, common effluent treatment plant, waste heat recovery, power plant, water treatment)

Environmental monitoring and compliance – are there are mandatory reporting/ tests conducted on firms in the IP for air/ water/ soil quality, emissions, energy use? Is this the responsibility of individual firms/ IP authorities/ local or state government?

Are there any other mandatory disclosures wrt environmental performance that firms are required to make to local/ state governments? How often is this information collected?

Are you aware of any extant material exchange networks within firms or between different firms (for example …). Could you introduce me to the ___ manager in ___ firm (if firm is involved in IS)?

Is there a waste heat recovery and power generation system within the IP? Do firms share power or physical premises between themselves?

I will explain concept of an EIP, and ask if there are any plans to transform present IP into an EIP.

Anything else you would like to add that would be helpful for the research project?

Appendix 5 – Interview guide for semi-structured interviews – firms in industrial park

Participant background

Name

Role

Since when have you been associated with this firm?

Prior experience (similar role/ area?)

Experience of operating within the Industrial Park

When did your firm commence operations in this IP/ location?

There is a possibility that this is an 'Anchor Firm' or the presence of an Anchor Firm was critical in their decision to locate operations here.

Were you involved with the firm since inception (of this facility)?

What factors drove the firm to locate manufacturing here? (availability of skilled labour; ease of access to material inputs; incentives – subsidised electricity, tax benefits; finance/ loan?)

What benefits has your firm witnessed by locating manufacturing here? (government incentives, anchor firm, part of an industrial cluster, develop specialised cluster in the region?)

Could you list key challenges that your business faces (continuing manufacturing operation at this site)?

Have any supply chain partnerships/ integrations (within or around the IP) resulted from the firm's operations here?

Evidence of Industrial Symbiosis

Shared facilities/ utilities (transport/ logistics, common effluent treatment plant, waste heat recovery, power plant, water treatment)

What systems are in place to monitor material flows and waste? How often does the firm conduct LCA (Life Cycle Assessment) and MFA (Material Flow Analysis?)

What recent changes have been implemented as a result of LCA/ MFA? Any reductions (material use) or benefits recorded?

Is the firm currently involved in any material exchanges with co-located firms in the IP? If yes,

What benefits have you witnessed/ foresee from such symbiotic networks? (cost reduction, improved profitability, waste reduction, R&D collaboration)

How did the exchange get initiated? (IP authorities, practical solution to reduce purchase of materials from market, transportation/ logistics benefit, informal networks between managers at different firms – eg. Nanjangud study)

Was the IP Management involved in facilitating the exchange?

Are there future plans to implement IS networks?

Are there any other mandatory disclosures wrt environmental performance that firms are required to make to local/ state governments? How often is this information collected?

What role does the local government play in implementing/ monitoring environmental standards? Is there any mandatory compliance you need to meet?

Which Central/ State/ Local legal and policy frameworks are applicable to the firm's emissions, electricity use, hazardous waste disposal, by-product recovery and reuse, recycled material use (in manufacturing)?

Would you be willing to share details of material flows throughout your operations? (This will be used to verify data collected from IP Authorities and other firms to check for data validity and reliability, and identify any discrepancies in measurement techniques and monitored indices)

Are you aware of any extant material exchange networks within firms or between different firms (for example, waste ___ released from ___ process is further treated and used as an input of ___ within ___ process). Could you introduce me to the ___ manager in ___ firm (if firm is involved in IS)?

Anything else you would like to add that would be helpful for the research project?

Appendix 6 – Sample email to prospective participants

Hi ____,

Further to our discussions, I plan to visit India in Dec 2017 (**tentative date of visit to Vizag is 11th Dec 2017**). My intention is to plan a field trip to Jawaharlal Nehru Pharmacity with the following research objectives:

To learn about experience of setting up the Pharmacity, incentives for firms to locate their operations there and challenges faced in setting up of a Pharma SEZ.

To meet and interview operations/ environmental management team members from Ramky as well as partner firms; Ramky-APIIC partnership.

To gain in-depth knowledge of waste management targets, reporting and processes.

To identify cases of inter-firm materials and energy exchange, with the overall goal of reducing waste.

To know more about the energy infrastructure to satisfy power requirements of firms and any renewable energy initiatives.

To visit partner firm sites and interview relevant managers (as found appropriate by your team). I would be specifically interested in visiting manufacturing facilities and waste management/ infrastructure sites located in and around the Pharmacity.

I truly appreciate Ramky team's support, and would be happy to invite your comments/ feedback on my research plan. The upcoming visit is one of the key field visits for my PhD research, a brief bio about my research background is appended to this email. I would like to assure you that complete confidentiality will be maintained for any data collected, and prior consent will be taken before interviewing participants.

It will be great if you could confirm the visit via return email, as well as suggest how many days I should plan the visit for. If your team could also recommend accommodation options close to the Pharmacity, it would be a great help.

Do let me know if you require any further information.

Bio

Simran is a doctoral candidate at Macquarie University and her research interests lie in the Circular Economy (CE), with a focus on fast industrialising nations/economies. She has also recently submitted her Master of Research thesis entitled "A macro investigation into the evidence for circular economy initiatives in India: National policy, key indicators and future implications", at Macquarie University Sydney.

Simran's doctoral research is dedicated to exploring progress of CE initiatives in Indian industry; specifically, cases of industrial symbiosis, 3R (Reduce, Reuse, Recycle) in India's manufacturing sector, industrial parks and accomplishments in electronic-waste recovery and management. She is also developing a line of inquiry into the role of renewables in contributing to India's energy security, and as a strategic means of decoupling the impact of intensive industrialisation from dependence on virgin energy sources.

Through comparative analyses of global CE progress, Simran's research aims to develop a framework for CE implementation distinct to fast industrialising nations, acknowledging their need for rapid uptake of materials and energy in the midst of geopolitical limits to resources availability.

Read more about her research at http://www.mq.edu.au/research-impact/2017/01/04/a-circular-economy-the-case-for-india/#.WUoR5TN7Gu6.

Best Regards,

Simran Talwar

Appendix 7 (pages 269-271) removed from Open Access version as it may contain sensitive/confidential content.

Appendix 8 – Participant Information and Consent Form (sample)

Chief Investigator/ Supervisor: Professor John Mathews
Co-investigator: Ms. Simran Talwar, Doctoral Candidate

Participant Information and Consent Form

Name of Project: *An empirical investigation into the evidence for circular economy initiatives in Indian industry*

You are invited to participate in a study of circular economy implementation in industry. The purpose of the study is to investigate the direction of decoupling in India. The idea that resource consumption (both quantity and intensity), economic advancement and environmental degradation should be de-linked is referred to as *decoupling.*

A field study of manufacturing industrial parks in India is being conducted in order to evaluate cases of Industrial Symbiosis, i.e., evidence of symbiotic material and energy networks. The key participant groups include Industrial Park Authorities, Firms located within industrial parks, and Council/ State/ Federal governments.

The study is being conducted by Ms. Simran Talwar to meet the requirements of the Doctor of Philosophy (PhD) degree under the supervision of Professor John Mathews () of the Macquarie Graduate School of Management.

If you decide to participate, you will be asked to share your firm/ department's experience of working in an industrial park. Information on ongoing inter- and intra- firm material/ energy exchange networks will be sought, along with data on material flows. The investigators will be grateful for your help in introductions/ contacts with other firms or government departments.

The interview will be semi-structured, the co-investigator will ask you open-ended questions to seek detailed understanding of the set-up of industrial parks in India, and likely challenges faced by firms. The interviews will be conducted face-to-face or via Skype, maximum duration will be 1 hour. Interviews will be audio-recorded for later transcription. Photographs of field sites may be taken for documentation and use in thesis/publication. Proper arrangements have been made for the security and storage of confidential data.

Any information or personal details gathered in the course of the study are confidential, except as required by law. No individual will be identified in publication of the results. The above listed investigator and her supervisor will be the only people with access to the data. The data may be used in future Human Research Ethics Committee-approved projects. A summary of the results of the study can be made available to you on request.

The results of the study will be published in the PhD Thesis and in academic article(s), and will be presented at academic conferences. At the end of this form, please tick the box if you do not have any objection to the use of organisation/ department name in publication. The use of name will help familiarise readers with case sites, and enable future partnerships and research. None of publications will include any information identifying individual participants.

Participation in this study is entirely voluntary: you are not obliged to participate and if you decide to participate, you are free to withdraw at any time without having to give a reason and without consequence.

We thank you for your time. Please fill and sign the next page.

[ ] I <u>do not</u> object to the use of organisation/ department name in publication of results.

I, ___________________________ *(participant's name*) have read *(or, where appropriate, have had read to me)* and understand the information above and any questions I asked have been answered to my satisfaction. I agree to participate in this research, knowing that I can withdraw from further participation in the research at any time without consequence. I have been given a copy of this form to keep.

Participant's Name:____
(Block letters)

Participant's Signature: ________________________ Date:__________________

Investigator's Name:____
(Block letters)

Investigator's Signature: ____________________ __ Date:__________________

The ethical aspects of this study have been approved by the Macquarie University Human Research Ethics Committee. If you have any complaints or reservations about any ethical aspect of your participation in this research, you may contact the Committee through the Director, Research Ethics & Integrity (telephone (02) 9850 7854; email ethics@mq.edu.au). Any complaint you make will be treated in confidence and investigated, and you will be informed of the outcome.

[ ] INVESTIGATOR'S COPY [ ] PARTICIPANT'S COPY

Appendix 9 – IPAT percentage growth rates, India, 1970-2015

Table 22: Detailed IPAT calculations for percentage growth rates, India, 1970-2015

Plan period	Year	I			P			A			T					
		DMC, kg	% change yoy, DMC	% change over the plan period, DMC	Population persons	% change yoy, Population	% change over the plan period, Population	GDP/capita	% change yoy, Affluence	% change over the plan period, Affluence	Material intensity, DMC/GDP	% change yoy, MI	% change over the plan period, MI	GDP USD 2005	% change yoy, GDP	% change over the plan period, GDP
4th plan	1970	1.4E+12			5.54E+08			259.95			9.71			1.44E+11		
	1971	1.4E+12	0.46%		5.67E+08	2.29%		257.67	-0.88%		9.62	-0.91%		1.46E+11	1.39%	
	1972	1.39E+12	-1.33%		5.8E+08	2.33%		250.09	-2.95%		9.56	-0.65%		1.45E+11	-0.68%	
	1973	1.46E+12	5.27%	4.35%	5.93E+08	2.35%	7.13%	252.76	1.07%	-2.77%	9.72	1.76%	0.18%	1.5E+11	3.45%	4.17%
5th plan	1974	1.46E+12	0.27%		6.07E+08	2.36%		248.58	-1.65%		9.69	-0.40%		1.51E+11	0.67%	
	1975	1.56E+12	6.58%		6.22E+08	2.35%		265.40	6.77%		9.45	-2.46%		1.65E+11	9.27%	
	1976	1.58E+12	1.30%		6.36E+08	2.33%		264.08	-0.50%		9.40	-0.51%		1.68E+11	1.82%	
	1977	1.66E+12	4.97%		6.51E+08	2.31%		276.54	4.72%		9.21	-2.02%		1.8E+11	7.14%	
	1978	1.73E+12	4.62%		6.66E+08	2.31%		285.31	3.17%		9.13	-0.88%		1.9E+11	5.56%	
includes 5t	1979	1.68E+12	-3.04%	14.97%	6.81E+08	2.32%	12.17%	265.65	-6.89%	6.86%	9.29	1.78%	-4.09%	1.81E+11	-4.74%	19.87%
6th plan	1980	1.7E+12	1.30%		6.97E+08	2.33%		276.81	4.20%		8.83	-5.00%		1.93E+11	6.63%	
	1981	1.83E+12	7.66%		7.14E+08	2.34%		287.29	3.79%		8.95	1.36%		2.05E+11	6.22%	
	1982	1.91E+12	3.92%		7.3E+08	2.35%		291.66	1.52%		8.95	0.02%		2.13E+11	3.90%	
	1983	2.02E+12	6.01%		7.47E+08	2.34%		306.41	5.06%		8.82	-1.39%		2.29E+11	7.51%	
	1984	2.05E+12	1.42%	20.29%	7.65E+08	2.31%	9.67%	309.94	1.15%	11.97%	8.65	-2.01%	-2.05%	2.37E+11	3.49%	22.80%
7th plan	1985	2.1E+12	2.45%		7.82E+08	2.28%		319.66	3.14%		8.40	-2.88%		2.5E+11	5.49%	
	1986	2.16E+12	3.10%		8E+08	2.24%		327.66	2.50%		8.26	-1.62%		2.62E+11	4.80%	
	1987	2.21E+12	2.34%		8.17E+08	2.20%		336.50	2.70%		8.05	-2.50%		2.75E+11	4.96%	
	1988	2.39E+12	7.92%		8.35E+08	2.17%		361.70	7.49%		7.92	-1.72%		3.02E+11	9.82%	
	1989	2.52E+12	5.24%	19.84%	8.53E+08	2.13%	9.03%	377.61	4.40%	18.13%	7.81	-1.29%	-6.95%	3.22E+11	6.62%	28.80%
Annual pla	1990	2.59E+12	3.12%	3.12%	8.71E+08	2.10%	2.10%	390.53	3.42%	3.42%	7.63	-2.34%	-2.34%	3.4E+11	5.59%	5.59%
Annual pla	1991	2.67E+12	2.84%	2.84%	8.89E+08	2.06%	2.06%	384.91	-1.44%	-1.44%	7.80	2.24%	2.24%	3.42E+11	0.59%	0.59%
8th plan	1992	2.79E+12	4.39%		9.06E+08	2.02%		397.15	3.18%		7.74	-0.83%		3.6E+11	5.26%	
	1993	2.79E+12	0.27%		9.24E+08	1.99%		408.88	2.95%		7.39	-4.50%		3.78E+11	5.00%	
	1994	2.88E+12	2.95%		9.43E+08	1.96%		430.72	5.34%		7.08	-4.15%		4.06E+11	7.41%	
	1995	3.03E+12	5.27%		9.61E+08	1.94%		455.83	5.83%		6.91	-2.42%		4.38E+11	7.88%	
	1996	3.19E+12	5.53%	14.69%	9.79E+08	1.92%	8.03%	479.94	5.29%	20.85%	6.80	-1.65%	-12.15%	4.7E+11	7.31%	30.56%
9th plan	1997	3.25E+12	1.78%		9.98E+08	1.89%		492.07	2.53%		6.62	-2.57%		4.91E+11	4.47%	
	1998	3.34E+12	2.70%		1.02E+09	1.86%		511.61	3.97%		6.42	-3.03%		5.2E+11	5.91%	
	1999	3.5E+12	4.73%		1.03E+09	1.83%		538.18	5.19%		6.28	-2.22%		5.57E+11	7.12%	
	2000	3.51E+12	0.36%		1.05E+09	1.79%		550.56	2.30%		6.05	-3.62%		5.8E+11	4.13%	
	2001	3.61E+12	2.92%	11.10%	1.07E+09	1.75%	7.42%	569.09	3.37%	15.65%	5.92	-2.14%	-10.57%	6.1E+11	5.17%	24.24%
10th plan	2002	3.61E+12	0.08%		1.09E+09	1.71%		580.63	2.03%		5.71	-3.56%		6.33E+11	3.77%	
	2003	3.82E+12	5.78%		1.11E+09	1.67%		618.93	6.60%		5.57	-2.40%		6.86E+11	8.37%	
	2004	3.85E+12	0.73%		1.13E+09	1.63%		659.61	6.57%		5.18	-7.00%		7.43E+11	8.31%	
	2005	4.04E+12	4.91%		1.14E+09	1.59%		709.59	7.58%		4.98	-4.00%		8.12E+11	9.29%	
	2006	4.36E+12	7.93%	20.64%	1.16E+09	1.55%	6.60%	763.28	7.57%	31.46%	4.92	-1.20%	-13.91%	8.87E+11	9.24%	40.13%
11th plan	2007	4.75E+12	9.02%		1.18E+09	1.51%		825.64	8.17%		4.88	-0.72%		9.74E+11	9.81%	
	2008	4.95E+12	4.19%		1.2E+09	1.47%		843.73	2.19%		4.90	0.48%		1.01E+12	3.70%	
	2009	5.06E+12	2.12%		1.21E+09	1.43%		905.96	7.38%		4.60	-6.23%		1.1E+12	8.91%	
	2010	5.26E+12	3.90%		1.23E+09	1.38%		982.95	8.50%		4.34	-5.55%		1.21E+12	10.00%	
	2011	5.78E+12	9.97%	21.57%	1.25E+09	1.34%	5.74%	1034.11	5.20%	25.25%	4.48	3.15%	-8.21%	1.29E+12	6.61%	32.44%
12th plan	2012	5.87E+12	1.59%		1.26E+09	1.29%		1076.30	4.08%		4.32	-3.64%		1.36E+12	5.43%	
	2013	5.99E+12	1.96%		1.28E+09	1.26%		1133.26	5.29%		4.13	-4.37%		1.45E+12	6.62%	
	2014	6.19E+12	3.31%		1.3E+09	1.23%		1204.36	6.27%		3.96	-3.97%		1.56E+12	7.59%	
	2015	6.35E+12	2.64%	8.11%	1.31E+09	1.22%	3.76%	1281.42	6.40%	19.06%	3.78	-4.69%	-12.48%	1.68E+12	7.69%	23.53%

Source: Author, based on Global Material Flows database (IRP, 2018); NITI (2020)

Notes

1. Fourth plan onwards - important economic and political reforms in India
2. 1969 excluded as data unavailable
3. Based on data availability, the calculations were made assuming the period of Jan-Dec, start year of plan inclusive and end year excluded to avoid duplication. Typically, India's plans follow the financial year of Apr-Mar.
4. 1974–1979 includes 5th plan and rolling plan; 1978 and 1979 plan period overlap due to changes in ruling political party
5. 1990 and 1991 annual plans enforced
6. Complete data reported until 2015

Appendix 10 – Comparison for energy capacity and generation shares, India, 1990-2017

Table 23: Comparison for energy capacity and generation shares, India, 1990-2017

Energy mix: installed capacity						
Year	**Total capacity (GW)**	**Coal**	**Thermal miscellaneous**	**Nuclear**	**Hydro**	**RES**
1990	**66.1**	65%	4%	2%	29%	
1995	**83.3**	63%	8%	3%	25%	
2000	**101.6**	59%	12%	3%	24%	1%
2005	**124.3**	54%	11%	2%	26%	3%
2010	**173.6**	56%	10%	3%	23%	10%
2017	**344.0**	58%	8%	2%	14%	18%

Electricity mix: generation						
Year	**Total generation (TWh)**	**Coal**	**Thermal miscellaneous**	**Nuclear**	**Hydro**	**RES**
1990	**292.7**	65%	8%	2%	24%	0.01%
1995	**423.7**	70%	11%	2%	17%	0.13%
2000	**569.7**	68%	15%	3%	13%	0.52%
2005	**715.9**	67%	14%	2%	15%	1.55%
2010	**981.5**	67%	14%	3%	13%	3.54%
2017	**1532.2**	74%	6%	3%	9%	8%

Source: Author, based on CEA (2018; 2019a); IEA (2020)

Notes

1. Renewable Energy Sources (RES) include wind, small hydro, biomass, urban and industrial waste, solar photovoltaic.
2. Water, wind and sun (WWS) refer to RES and large hydro.
3. Units of measurement: Capacity (Giga Watt, GW); Generation (Terawatt-hour, TWh).
4. Hydro projects are classified based on captive power capacity; in India, hydro power plants of 25MW or below capacity are under the aegis of the Ministry of New and Renewable Energy (MNRE) and categorised as small hydro (micro: 100kW or below, mini: 101kW-2MW, small: 2-25MW) (MNRE, 2020). India's large hydro, which falls under the Ministry of Power (MoP), constitutes the fifth highest capacity globally, and has high potential as a renewable energy source. Current estimates are that only 26% the hydropower potential has been exploited (MoP, 2020). Owing to reporting variations by the Government of India and its huge capacity share, this thesis discusses large hydro independently (as a major energy source) and under WWS calculations; whereas, small hydro is represented under RES as well as WWS.

Appendix 11 – Sample of RECP survey at Naroda Industrial Estate in 2000

** attached as separate document (pdf)

Source: NIA Archives, accessed during author field visit in June 2019

Appendix 12 – World Resources Institute survey form for green energy procurement

** attached as separate document (pdf)

Source: NIA Archives, accessed during author field visit in June 2019

Appendix 13 – Co-processing by cement plants in Gujarat, 2009-2017

Table 24: Co-processing by cement plants in Gujarat 2009-2017

Cement Plant	Total 2009-2017 (Million Tonnes, MT)	% change 2009-17
Ambuja Cement Limited	3404440.1	44152%
Ultratech Cement Limited, Kovyaya	2527947.8	3834%
Ultratech Cement Limited, Jafrabad	323498.5	3435%
Sauratra Cement Limited, Porbander	752486.9	801%
Recycling Solutions Pvt Limited, Panoli	37056.9	478%
Shri Digvijay Cement Co. Limited, Jamnagar	273731.3	360%
Sanghi Industries Limited, Kutch	936918.3	247%
Ultratech Cement Ltd, Sewagram - Kutch	598542.0	137%

Source: GPCB (2019)

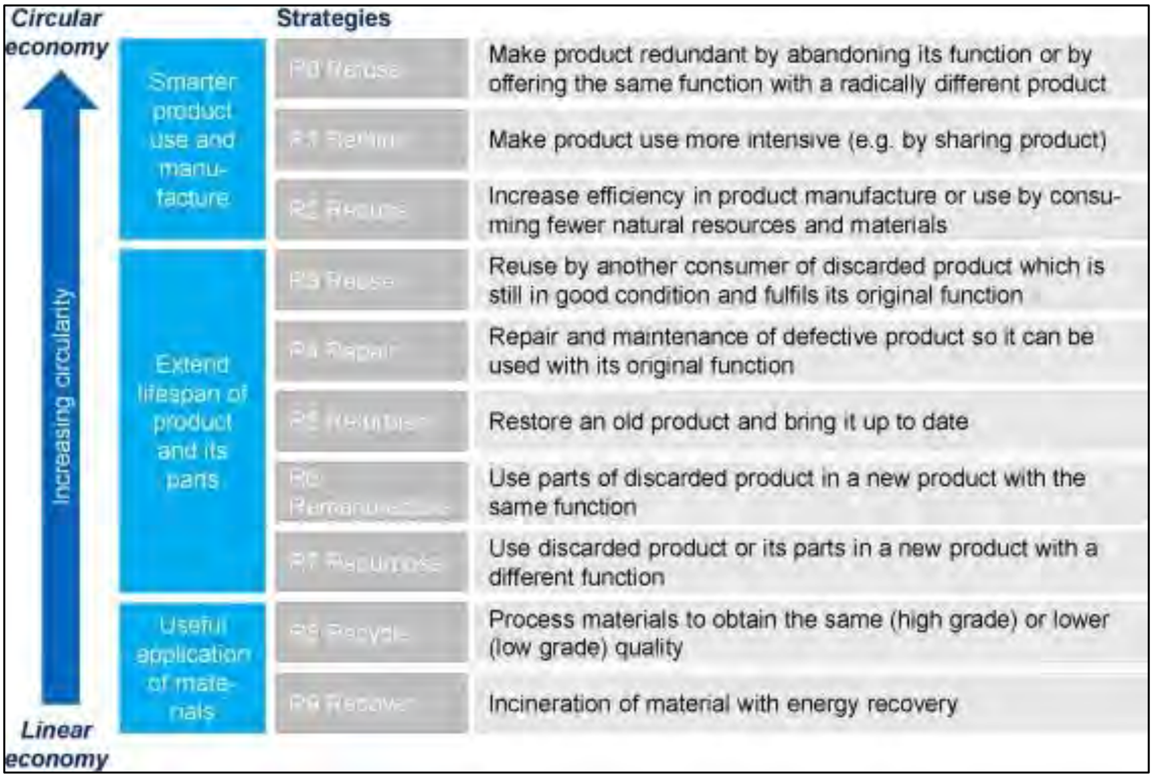
Appendix 14 – Status of co-processing at Nandesari estate, Gujarat

Table 25: Nandesari estate: alternative fuels for co-processing – volume, share and charges

Month/ Year	**2017**			**2018**			**2019**		
	Received (metric tonne)	Sent for co-processing (%)	Charges per tonne (USD)	Received (metric tonne)	Sent for co-processing (%)	Charges per tonne (USD)	Received (metric tonne)	Sent for co-processing (%)	Charges per tonne (USD)
Jan	6205	1.13%		6037	0.02%	195	5825	10.61%	59
Feb	5399	1.25%		5559	2.45%	111	4717	26.22%	59
Mar	6648	0.00%		6397	2.46%	111	5066	23.41%	59
Apr	6685	0.98%		5340	1.93%	111	5966	6.37%	59
May	6651	1.00%		7124	1.16%	78	5665	26.89%	59
Jun	5223	1.19%		7073	2.12%	78	5700	44.87%	59
Jul	1316	4.30%		2347	4.11%	78			
Aug	2587	1.40%		2897	70.39%	59			
Sep	6233	1.23%		7094	6.45%	59			
Oct	6323	0.75%	195	6604	16.59%	59			
Nov	6990	0.66%	195	4960	12.67%	59			
Dec	6489	1.84%	195	5793	29.71%	59			

Source: Author generated, based on data records of Nandesari Environment Control Limited (NECL, 2019)

Appendix 15 – Typology of circular economy strategies



Source: Kirchherr et al. (2017)

Appendix 16 (pages 281-282) removed from Open Access version as they may contain sensitive/confidential content.

Pages removed from Open Access version as they may contain sensitive/confidential content.