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THEMATIC ESSAY

Why Socio-metabolic Studies are Central to Ecological Economics

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Abstract: Global material extraction has tripled since the 1970s, with more than 100 billion tonnes of materials entering the world economy each year. Only 8.6% of this amount is recycled, while 61% ends up as waste and emissions, the leading cause of global warming and large-scale pollution of land, rivers, and oceans. This theme paper introduces socio-metabolic research (SMR) and demonstrates its relevance to ecological economics scholarship in India. SMR is a research framework for studying the biophysical stocks and flows of materials and energy associated with societal production and consumption. As one of the core approaches in industrial ecology and ecological economics, SMR is widely conducted in Europe, the United States, Japan, Australia, and China. In India, it is still in its infancy. In this paper, we review pioneering efforts in SMR in India and make a case for advancing the field in the subcontinent.

Key words: Socio-metabolic Research (SMR); Industrial Ecology; Ecological Economics; India; Material Flow Analysis (MFA).

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1. THE GLOBAL RESOURCE CHALLENGE

At the crux of our environmental crisis is the linear, one-way flow of (mostly non-renewable) materials and energy to grow our global economy. Despite improvements in technologies, global material extraction has tripled, exports quadrupled, and per capita material consumption nearly doubled, since the 1970s (UNEP 2016; Schandl *et al.* 2017). For the first time in human history, more than 100 billion tonnes of materials enter the global economy every year, of which only about 8% is recycled, creating an enormous "circularity gap" (Circle Economy 2020). To add to this sustainability conundrum, the 61% that ends up as waste and emissions contributes to large-scale land, river, and ocean pollution as well as global warming, thus compromising the health of our planet and human well-being (UNEP 2015; IPCC 2018).

The third dimension of sustainability is equity. The "costs" and "benefits" of current patterns of resource use are unequally distributed across the world and between current and future generations (Schaffartzik, Duro, and Krausmann 2019; Diffenbaugh and Burke 2019). Industrialized nations, with less than a quarter of the world's population, consume more than 40% of the world's domestic extraction, that is, 17 tonnes of materials and 300 GJ of energy per capita and year, respectively, as compared to 3–5 tonnes and 37–50 GJ in low- to middle-income countries (Krausmann *et al.* 2016). In other words, there are regions of the world or sections of society that engage with harmful, exploitative, and dirty industries and hence pay the cost of current patterns of resource use while others (mostly rich consumers) benefit from them. This distributional aspect of sustainability is often discussed in connection with environmental justice (Martinez-Alier *et al.* 2016).

Humanity's unsustainable patterns of production and consumption, and the resulting pollution, and equity concerns, are central to ecological economics, a field of research founded on the premise that the economy is a subset of the natural world, and, hence, economic activities must adhere to biophysical thresholds (Costanza 1989; Melgar-Melgar and Hall 2020). Pioneers of ecological economics have emphasized this message through several influential works. For example, Kenneth Boulding (1966) urges society to shift from a reckless "cowboy economy" to a frugal "spaceman economy". Georgescu-Roegen (1971) applies the entropy law to the economic process, which resonates strongly with Martinez-Alier and Schlupmann (1987), who emphasize the use of biophysical metrics, such as material and energy flows, as opposed to monetary units, to evaluate economic performance. Meadows *et al.* (1972) warn us of the limits to economic growth that relies on the ever-increasing exploitation of limited resources—this underlies much of Herman Daly's (1977) work on steady state economics. These ground breaking ideas contributed to the vision and formal founding of ecological economics in 1989 (Costanza 1989), which has evolved to include aspects of well-being, justice, and equity (Costanza *et al.* 2020).

A transformation to sustainability requires a drastic reduction in material throughput to levels compatible with the earth's biophysical ability to supply resources and absorb wastes and emissions. This paper introduces socio-metabolic research (SMR) as an approach that quantifies patterns of resource use by economies, allowing researchers to identify systemic risks and vulnerabilities, social inequalities, and potential for transformation or collapse. We describe the theoretical underpinnings, research approaches, and applications of SMR, with a focus on India and its potential for the sustainability.

2. SUSTAINABILITY AS A PROBLEM OF THE SOCIETY-NATURE INTERACTION

Sustainability problems (some would call them crises) often result from the way society interacts with its natural environment. As such, sustainability is a social, as much as it is an ecological, challenge. Therefore, we need a heuristic and cross-disciplinary model that sufficiently captures the dynamic interaction between the biophysical planet and the social world and, in doing so, relates social and economic development to environmental change. In this respect, the model of the society–nature interaction developed by the Vienna school of social ecology is persuasive (Figure 1). The starting point in the model is to conceive of "society" not only as a group of rational actors or a human population, but as one that also includes biophysical elements—livestock, buildings, infrastructure, and machines, collectively referred to as "material stocks"—that are deliberately created and maintained by a given population for its survival and well-being. Society reproduces itself biophysically and culturally over time through a system of mutual feedback loops and is, thus, a "hybrid" between cultural and natural spheres of causation (Fischer-Kowalski and Weisz 2016).

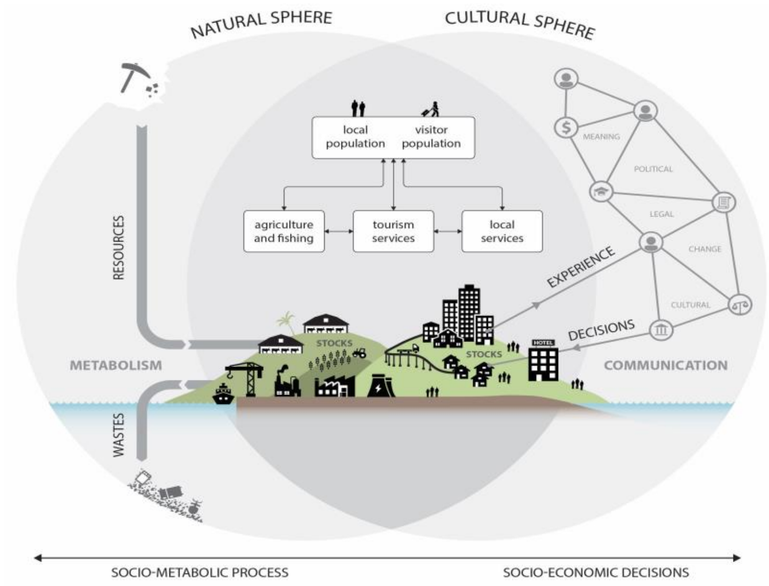

Figure 1: Heuristic Model of Society–Nature Interactions (adapted from Fischer-Kowalski and Weisz 2016)
Source: Simron J Singh | Illustration support from Lodewijk Luken

Biophysical reproduction is carried out via a process referred to as "social metabolism" (the "natural sphere" in Figure 1). As in biological metabolism, a given society organizes material and energy flows through its natural environment and by way of trade for its sustenance and reproduction. Some material and energy becomes waste (outflows), while the rest of the flows are net additions to "stocks". Stocks provide critical societal services such as housing, food, energy, transport, health, and education. Stocks, in turn, need to be maintained through flows, creating a dynamic feedback loop referred to as the "material stock–flow–service" (SFS) nexus (Haberl *et al.* 2017). The size and composition of resource throughput in a socio-economic system characterizes its "metabolic profile" and is indicative of the pressure an economy exerts on the environment.

Just as metabolism influences a person's body (leading to obesity or diabetes), the process of social metabolism alters land and sea (mining, urbanization, fishing, and agriculture) and, over time, causes changes in ecosystems, the atmosphere, and biogeochemical cycles. Seven of these earth system pressures[4] have been quantified and designated as "planetary boundaries". Of these, four are found to be well outside the safe operating space for humans at present—for example, climate change and loss of biodiversity are currently causing existential crises (Steffen *et al.* 2015). The cumulative impacts of past and ongoing changes to the natural environment have assumed a global proportion. Climate disruptions, sea-level rise, hurricanes, and possibly even pandemics are examples of ecosystem disservices, against which society needs to protect itself and adapt by altering existing patterns of social metabolism.

Materials and energy such as food, fossils, metals, and minerals that humans extract from nature, however, do not always flow on their own. They are deliberately mobilized by humans based on values, ideologies of development, and expectations in the social world. They are manifested and reinforced through institutions, laws, policies, education, cultural norms, the economy, and discourse (the "cultural sphere" in Figure 1). As humans interact with the natural world, they generate experiences, favourable or unfavourable. These feed back over time into the symbolic/cultural sphere; existing practices are confirmed, or new meaning and insights about environmental risks and uncertainties are generated (for example, through the recognition of ecosystem disservices), leading to renewed expectations and rules.

3. SOCIO-METABOLIC RESEARCH AND ITS APPLICATIONS

SMR studies focus on the biophysical aspects of society–nature interactions on different spatial and temporal scales. In other words, SMR offers a research framework for systematically studying the stocks and flows of materials and energy associated with societal production and consumption. As such, SMR has become one of the core systems approaches in scientific disciplines such as industrial ecology and ecological economics (Molina and Toledo 2014; Haberl *et al.* 2019). The research encompasses a broad range of traditions such as urban metabolism, the multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM), material and energy flow analysis (MEFA), environmentally extended input–output analysis (EE–IOA), and related approaches such as life cycle assessment (LCA), the ecological footprint and integrated assessment models (IAM) (for an excellent review of SMR traditions, see Haberl *et al.* [2019]). Gerber and Scheidel (2018) consider MEFA and MuSIASEM the two major socio-metabolic approaches that are foundational to ecological economics. While

[4] The seven planetary boundaries are climate change, biosphere integrity, land-system change, freshwater use, biochemical flows, ocean acidification, and stratospheric ozone depletion.

MEFA seeks to establish a mass balance of biophysical stocks and flows through socio-economic systems, MuSIASEM draws on the theory of complex hierarchical systems to integrate diverse socio-economic and metabolic dimensions at multiple scales into its analysis.[5]

This paper focuses on material flow analysis (MFA), an accounting method that describes (in quantitative terms) the physical dimensions of an economy: what quantity and quality of materials (including energy carriers) are domestically produced, imported, transformed, used, and discarded? MFA is one of the core methodologies that quantifies resource use at the global, national, or sub-national scales and indicates anthropogenic pressures on the environment (Dittrich, Giljum, Lutter, and Polszin 2012; IGEP 2013; Mutha, Patel, and Premnath 2006; Singh *et al.* 2012). Embedded in the System of Environmental–Economic Accounts (SEEA) (Eurostat 2018), MFA offers a consistent compilation of all resources entering the socio-economic system, changes in biophysical stocks within the system, outflows into the environment (such as wastes and emissions), and exports to other socio-economic systems (Figure 2). Depending on the issue, an MFA can focus on specific flows of interest, such as food and energy, investigate specific chemical substances (substance flow analysis), or track problematic materials such as plastics or e-waste in a system.

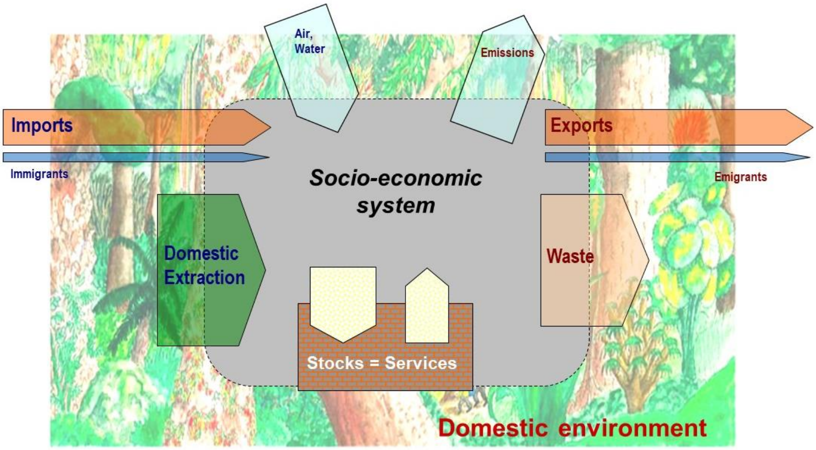

Figure 2: Material Flow Analysis for SMR
Source: Simron J Singh

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[5] MEFA is attributed to the Vienna school of social metabolism (Fischer-Kowalski and Weisz 2016; Haberl *et al.* 2016), and the scholarship on MuSIASEM comes from the Barcelona school of societal metabolism (Giampietro *et al.* 2009, 2012).

Standard headline indicators include direct material inputs (DMI, the sum of domestically extracted raw material and imports), domestic material consumption (DMC, the difference between direct material inputs and exports), physical trade balance (PTB, the difference between imports and exports), material intensity (MI, the ratio of DMC to gross domestic product [GDP]), and resource efficiency (inverse of MI, also referred to as material productivity). DMI and DMC are important metrics for assessing nationwide material flows (UNEP 2016; Eurostat 2018). DMC, measured in tonnes per capita, indicates the average material consumption of the economy and is a useful marker of the impact of population growth and consumption on material use. These metrics allow for a comparison between socio-economic systems to determine system performance, levels of vulnerability, and anticipated risks.

Up until recently, much of SMR focused on "flows" of materials and energy through an economy. The contributions of "flow" studies include mapping trajectories of resource use across space and time. Insights from these studies shed light on past and ongoing resource-use patterns (Schandl *et al.* 2017; Krausmann *et al.* 2016), historical and ongoing transitions from agrarian to industrial modes of production (Weisz *et al.* 2001; Haberl *et al.* 2011), decoupling and eco-efficiency (UNEP 2011; Wiedenhofer *et al.* 2020), progress towards the UN Sustainable Development Goals (SDGs) (Bringezu *et al.* 2016; Eisenmenger *et al.* 2020), and "environmental justice" or the (unequal) distribution of the costs and benefits of social metabolism on different spatial and temporal scales (Healy *et al.* 2013; Martinez-Alier *et al.* 2016; Scheidel and Schaffartzik 2019). More recently, SMR has provided crucial insights on the nonlinearity of society–nature interactions. The findings from SMR suggest that a high quality of life is possible with moderate levels of material use. Using data from multiple countries, researchers have found that human well-being only increases with resource use or emissions up to certain threshold (saturation point), beyond which no clear trends emerge (Lamb *et al.* 2014; Mayer, Haas, and Wiedenhofer 2017).

Interest in the accumulation of "material stocks" within the SMR community has risen in the last decade. "Flow" accounting has revealed that over 50% of extracted resources now go into building stocks, up from 20% in 1900. Scholars have also realized that "stock" patterns and dynamics influence current and future "flows" of resources (first for building and then for maintenance), creating lock-in effects and path dependencies (Krausmann *et al.* 2020). Quite recently, scholars have pointed to the important link between stocks and services. In 2015, 75% of all materials extracted (62 Gt/year) were used either to build up stocks or to operate them to provide societal services such as housing, transport, health, and education (Krausmann, Wiedenhofer, and Haberl 2020). It has become evident that material stocks enable societies to convert resource flows into specific services. Two-thirds of the SDGs depend on infrastructure investment, as it forms the backbone of production and consumption and our daily lives and, hence, the material basis of societal well-being (Thacker *et al.* 2019). The service approach within SMR offers new perspectives and strategies for achieving higher levels of well-being with lower levels of resource use by improving the material intensity of services (Haberl *et al.* 2017).

Another novel contribution of SMR (within both the flow and stock approaches) is the concept of a circular economy (CE), which has recently emerged as an important policy goal and a sustainability strategy in many parts of the world (Geng *et al.* 2013; Ghisellini, Cialani, and Ulgiati 2016). CE departs from the dominant linear (take–make–dispose) economy in favour of a relatively closed, systemic, cyclical, and restorative model (Ellen MacArthur Foundation 2013; Merli, Preziosi, and Acampora 2018; Stahel 2019). CE borrows the idea of cycling resources through society just as nature cycles water, nutrients, carbon, and other essential materials. While loop closing can occur on any scale up to a global one, existing CE research and practice tend to focus on the meso scale, mostly at the level of eco-industrial parks (Salomone *et al.* 2020). Industrial symbiosis, as this sub-field is termed (Chertow 2000), focuses on resource life–extending strategies and the eco-efficiency of goods and services (i.e., reducing resource input per unit of output). Economic and environmental benefits are the primary motivations for more efficient product design, cleaner production, and closing material loops by valourizing waste (Ghisellini, Cialani, and Ulgiati 2016; Stahel 2019; Kirchherr, Reike, and Hekkert 2017; Sauvé, Bernard, and Sloan 2016). MFA techniques are expected to be increasingly applied to entire economies to identify strategies for resource optimizing and sharing between sectors to increase the overall "circularity rate" of the system (Mayer *et al.* 2019; Haas *et al.* 2020).

4. SMR IN INDIA

SMR is widely conducted in Europe, the United States, Japan, Australia, and China. Insights from the research are increasingly playing an important role in policy surrounding national resource security and sustainability. This section will review some of the key works that have used SMR in India, from the national scale to the industry level. Each of these applications offers different insights and perspectives on sustainability.

4.1 SMR at the National Scale

In India, SMR is still in its infancy. Singh *et al.* (2012) published the first comprehensive national MFA account for India, examining the 1961–2008 period. The results show that material use quadrupled (by a factor of 3.8) in this period, driven by an increase in the use of non-renewables, mostly from domestic sources. In 1960, about three-quarters of the total material was biomass, which doubled by the end of the study period. In contrast, fossil fuel consumption multiplied by a factor of 12.2, industrial minerals and ores by a factor of 8.6, and construction materials by a factor of 9.1. Between 1961 and 2008, per capita material use (DMC/cap) grew by 60%, from 3 to 4.3 tonnes/cap/year.

Further work reveals that India's burgeoning manufacturing sector is projected to account for 25% of India's GDP by 2025 (IBEF 2019), supported by the country's various infrastructure and capacity-building initiatives such as Make in India (2014), Delhi–Mumbai Industrial Corridor Project (2006), and Skill India Mission (2015). It is no surprise, then, that the country's material, energy, and water demand is rising sharply, aggravated by challenges in the efficient recovery of used resources, weak market mechanisms for secondary materials, and an imperfectly functioning informal waste sector. SMR enables the quantifiable assessment of resource use in the context of economic productivity as a means of evaluating longitudinal shifts in material and energy consumption and identifying sources of metabolic transition driven by an economy's resource use.

India contributed 5% to the world's manufacturing output in 2017 and ranked fifth among the largest manufacturing nations, after China, the US, Japan, and Germany (UNCTAD 2013). India recorded the second-highest material demand, after China, experiencing an 81% increase between 2000 and 2015 (UNEP-IRP 2018). Despite the surge in India's aggregate material demand, its per capita material consumption in 2015 was still way below global standards at 5.34 tonnes, compared to Australia (38.38 tonnes), China (23.65 tonnes), and the US (21.14 tonnes) (Table 1). The dichotomy of India's expected pace of industrialization and multifarious resource exigencies presents a timely opportunity to take stock of the country's resource-use patterns.

Table 1: Domestic Material Consumption Trends in Top Industrial Regions

Country	DMC (tonnes) per capita in 2015	CAGR* between 1990 and 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: Talwar (2019), based on Dittrich (2014); UNEP-IRP (2018); OECD (2016)
*Compound annual growth rate

Shah, Dong, and Park (2020) compare trade, material flows, and resource efficiency indicators for Bangladesh, India, and Pakistan over four decades from 1978 to 2017. The analyses show India's rising reliance on material imports as a result of increased domestic demand, shifting the nation's status from resource-neutral to resource-deficient. Although India's GDP is accelerating, the authors underscore the importance of trade policy incentives and technological innovation in achieving dematerialization. Figure 3 maps India's material-use trends from 1970 to 2017.

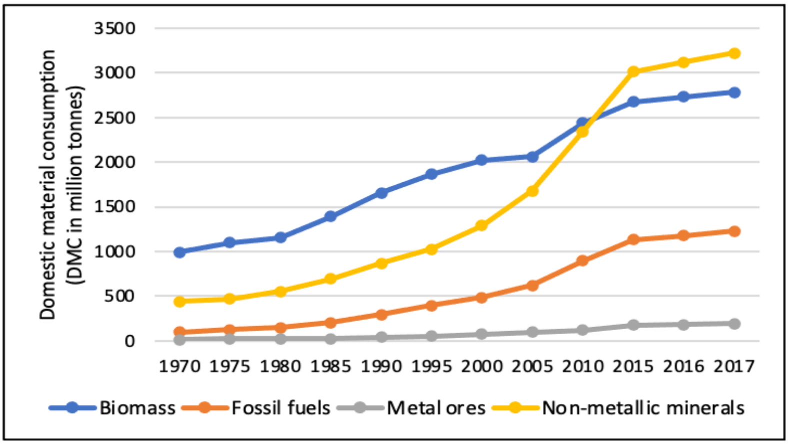

Figure 3: Trends in India's Material Use (1970–2017)
Source: Talwar (2019), based on UNEP-IRP (2018)

Typical patterns of fast-industrializing economies emerge, with increases in the use of fossil fuels (74%) and non-metallic minerals (66%) (Figure 3).

Indeed, the construction, industrial, and agricultural sectors dominate non-metallic mineral use in India, bolstered by ongoing investments in infrastructure building, residential and commercial development, and expanding manufacturing output (Talwar 2019).

The growth in India's resource needs comes at a price. The Global Atlas of Environmental Justice (2021) reports that over 3,400 cases of conflict worldwide arise from inequalities in resource use, including extraction, production, consumption, and disposal. Of these, 343 cases (10%) are from India alone. Drawing on the material flows study that Singh *et al.* (2012) conducted on India and the EJOLT (2021) project, Martinez-Alier, Temper, and Demaria (2016) demonstrate the link between social metabolism and ecological distribution conflicts. Such cases in India include those involving bauxite mining in Odisha, disputes around waste management in Delhi, and ship dismantling in Gujarat. Using domestic household water consumption patterns in Bangalore, Mehta *et al.* (2014) demonstrate that questions about environmental justice are inseparable from those of biophysical sustainability. More recently, Roy and Schaffartzik (2021) analysed land dispossession, exclusion, and injustices associated with the increasing use of coal in India.

4.2 SMR at the Sub-national Scale

SMR at the sub-national scale in India is highly limited. Singh *et al.* (2001) conducted the first comprehensive local SMR (a MEFA) on Trinket Island in the Nicobar district of India in the Bay of Bengal. The study portrays the changing metabolic profile of an indigenous society—the Nicobarese—affected by the development programmes of the Indian state. The Trinket Island case was later compared to the rise in material and energy consumption due to excessive aid following the 2004 Asian tsunami (Singh, Fischer-Kowalski, and Haas 2018). Noll (2015) undertook a socio-metabolic analysis in the Mumbai Metropolitan Region by applying a MEFA to the brick industry. By quantifying the pressure on soil and water due to brick production in the region, he demonstrates the threat to and conflicts with food production, along with other adverse impacts on local communities and the environment.

Local SMR falls within the tradition of "local studies" (Singh *et al.* 2010), a scale viewed as forming the basis of national and global economies. By paying attention to scale interactions, local SMR highlights the role of rural economies in providing critical ecosystem services—provisioning, regulatory, and cultural—to the country. At the same time, they are vulnerable to the socio-ecological impacts of extraction, production, and waste deposition. Local SMR seeks to understand how the "local" is altered by global processes through interventions such as subsidies, markets, legal frameworks, the creation of infrastructure, and the introduction of services such as health and education. Analysis at local scales is gaining importance because it provides insights into local actions and decisions that have cumulative effects on the global environment (Singh and Haas 2016).

The Bangalore Urban Metabolism Project (BUMP 2021), a joint initiative of the Stockholm Environment Institute and the Centre for Public Policy at the Indian Institute of Management, Bangalore, has done pioneering work in quantifying resource use in an urban context. Following a systems approach, a team of researchers led by Deepak Malghan, Vivek Mehta, and Eric Kemp-Benedict adopted SMR to analyse material and energy throughputs in the city of Bangalore. BUMP grapples with urban sustainability challenges to inform better governance that integrates economic efficiency, social equity, and environmental sustainability.

Intensive discussions encompassing CE and resource efficiency in India are in progress. Policy announcements like the Steel Scrap Recycling Policy (2019) and National Resource Efficiency Programme (2019) are important developments for SMR in India. While CE (and its sub-field, industrial symbiosis, with a focus on eco-industrial parks) has been widely researched in China, studies in India are limited in number and scope, despite the manufacturing sector's rising share in economic activity. Previous research on China's CE implementation, success, and impediments notes that policy structure, execution, and monitoring are largely top–down, with the government and state departments playing an active role (Ashton and Shenoy 2015; Ghisellini, Cialani, and Ulgiati 2016; Mathews and Tan 2011; Shenoy 2015). In contrast, an examination of industrial symbiosis networks in India reveals the potential for bottom–up eco-industrial development, with industry actors leading socio-metabolic transitions in critical resource-intensive sectors like manufacturing (Talwar 2019).

Previous studies in India have assessed eco-industrial progress in industrial parks and at the level of regions and states. Singhal and Kapur (2002) propose strategies for incorporating SMR approaches into industrial estate plans by classifying industry types, conducting regional environmental impact assessments for upcoming estates, integrating green industrial townships, and more widely applying environmental management systems to manage park performance. Saraswat (2008) sets out pathways for existing industrial parks to transition to eco-industrial parks to accelerate industrial ecology awareness and circulated toolkits among industry and government actors. Talwar (2019) noted that 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.

Empirical findings from industrial symbiosis research in India demonstrate the extent of material and energy exchanges among co-located firms within industrial settings (Bain *et al.* 2010; Unnikrishnan *et al.* 2004). Bain *et al.* (2010) conducted one of the most comprehensive investigations of industrial symbiosis in India. The authors quantified material flows for 7 resource categories and 11 self-organized symbiotic relationships within a 42-firm dataset from the Nanjangud industrial area in Karnataka. Unnikrishnan, Naik, and Deshmukh (2004) emphasize the need for government and institutional support, shared infrastructure development in industrial parks, and financial incentives for industrial symbiosis development in India. To support eco-industrial development in India, initiatives by agencies like the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), Gujarat Cleaner Production Centre (GCPC), and Indo German Environment Partnership (IGEP) have been instrumental in increasing awareness and the adoption of industrial ecology principles among governments and industries (GIZ and IGEP 2015; Nukala and Meyer 2012).

5. HOW CAN INDIA FACILITATE SMR TO LEVERAGE ITS FULL POTENTIAL?

A transition to sustainability—so that citizens can enjoy a high quality of life at the lowest environment cost—would require a fundamental shift in our resource-use patterns and the way we conceive of human development (Fanning and O'Neill 2019; Raworth 2017; Lamb and Steinberger 2017). There is no doubt that India's resource needs will grow in the coming decades as a result of improving material standards of living among a growing population, which will reach 1.7 billion by 2050. The big question is how. Can India source the materials and energy necessary for human development sustainably, without increasing the pressures on the domestic and global environment? India needs a new resource revolution, different from the Green Revolution and Industrial Revolution, both of which relied on an ever-increasing exploitation of natural resources.

To foster a resource revolution, a multilevel perspective combined with innovation in resource use and efficiency is imperative. Systemic approaches need to be favoured over narrow research agendas that, by oversimplifying complex interactions, obscure synergies and trade-offs between various social and environmental goals. Interdisciplinary approaches with the ability to integrate knowledge from the natural and social sciences; provide common definitions and system boundaries; and guide indicator and model development are urgently needed (Haberl *et al.* 2019; Geels 2011, 2018). In this regard, SMR offers a compelling methodological framework along with a suite of tools and indicators that can offer great insight on policy and drive innovation for a global CE. However, there are some barriers to overcome. Shenoy (2015) identifies three key challenges that need attention before SMR can reach its full potential in India.

First is the lack of adequate data. Although the state and central pollution control boards keep records of companies' maximum capacities and track hazardous waste, they do not have records of the actual tonnage of materials used or traded (Bain, Ashton, and Shenoy 2009). In other words, there is no collation of actual material flow data at the city, state, regional, and national levels. While large companies have data on their material consumption, use, and disposal, data on materials recycled are scarce. Most waste streams from a single industry are bundled together and sold (or auctioned) to agents who then separate out the recyclables from the rest (Bain *et al.* 2010; Ashton and Bain 2012). Materials pass through several agents before they are recycled, and the number of agents they pass through depends on the type of material, point of recycling, value, and storability. Much of the disaggregation of recyclables happens via the informal market and, hence, there is low to no traceability of data (Medina 2007).

Second is that the development of SMR lacks adequate funding, training, and public awareness. Despite recent developments in research and development in the renewable energy sector and green tech (Singh 2019), increased funding for training and research is needed to develop SMR before it can effectively contribute to innovative solutions that optimize resource flows and improve material efficiency.

Third is the lack of data and information on externalities, that is, harmful effects not internalized in the production costs of enterprises. For example, during mining operations, only the labour costs of removing forest cover and topsoil, not the disregarded materials, are accounted for. Several production processes, even in large industries, entail social and environmental externalities unique to the specific sector and local context. These unaccounted resources are relevant to thoroughly understanding socio-metabolic pathways and their future potential (Hulten, Bennathan, and Srinivasan 2006).

Ecological economists can and must play a bold and crucial role in the new resource revolution in India. This entails strategic partnerships between academia, businesses, and the public sector. Fostering interdisciplinary and transdisciplinary research and training around SMR; building the capacity of large, medium, and small enterprises; promoting resource innovation on multiple scales; and fostering a culture of sufficiency and efficiency are some of the key ingredients. As Costanza *et al.* (2020) has argued, ecological economics as a field of research has the potential to guide us into a future we all want, one that is prosperous, just, equitable, and sustainable.

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