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WORKING PAPER

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in Indian Manufacturing Industries**

**Akhilesh Kumar Sharma
Tiyasa Mishra**

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4 Vasant Kunj Institutional Area, New Delhi – 110 070

Phone: +91 11 3510 4511 | *E-mail:* info@isid.org.in | *Website:* <https://isid.org.in>

November 2024

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Understanding the Relationship between Material and Energy Efficiencies in Indian Manufacturing Industries

Akhilesh Kumar Sharma* & Tiyasa Mishra**

Abstract: With the globally growing environmental challenges, there is a strong need to focus on adopting sustainable technologies across economic activities. The manufacturing sector is one of the major contributors to emissions, energy consumption, and waste generation. With technological innovations and the adoption of appropriate technologies in manufacturing industries, the reduction in energy consumption and material inputs can improve economic output as well as environmental sustainability. In a developing country like India, many industries are highly energy and material-intensive and waste-generating. This study aims to understand trends and variations in the energy and material efficiencies in Indian manufacturing industries over time and to assess the causal relationship between these efficiencies. Using the KLEMS Database for the period 1980-81 to 2019-20 for 13 broad manufacturing sectors, this study finds that though energy efficiency has increased in all sectors over time, material efficiency has declined in many sectors over time. Interestingly, there is a negative correlation between energy efficiency and material efficiency in the case of many sectors highlighting the need to focus on the adoption of appropriate technologies to increase energy and material efficiencies simultaneously and achieve sustainable production in the manufacturing sector in India. Without this, it might be difficult to achieve sustainable production in industries.

Keywords: Energy Efficiency; Material Efficiency, Sustainable Production, Manufacturing Sector, India

JEL Classification: P28, Q01, L60

* Assistant Professor, Institute for Studies in Industrial Development, New Delhi, India.

** Corresponding Author, Research Scholar, Indian Institute of Technology, Kharagpur, India.

Acknowledgement: An initial version of the paper was presented at the ISID's 2nd Annual National Conference on India's Industrial Transformation: Towards a Competitive, Inclusive and Sustainable Manufacturing Sector, held during 21-23 November 2024. Authors are thankful to the comments from discussants and participants.

For the complete working paper, please contact the author(s) at akhilesh@isid.org.in; aksbhu2608@gmail.com; & tiyasamishratm@gmail.com

1. Introduction

With the globally growing environmental challenges, there is a strong need to focus on adopting sustainable technologies across economic activities. The manufacturing sector is one of the major contributors to emissions, energy consumption, and waste generation. The energy efficiency-related voluntary and mandatory policy measures have declined energy intensity¹ in recent years, further leading to energy demand neutralization (Dasgupta and Roy, 2017). In a developing country like India, many heavy industries are highly energy-intensive and are focussing on energy-efficient techniques of production (Dutta and Mukherjee, 2010). These techniques can be implemented if there is a shift in fuel consumption patterns and focus is given to technological advancements and price changes (Tandon and Ahmed, 2016). Further, rejected products resulting from the manufacturing process are a major source of energy inefficiency and wastage. Hence, a reduction in the number of rejected products in the manufacturing process is environmentally useful apart from energy saving and profitability (Kaushik et al., 2016).

The extraction and processing of raw materials for manufacturing purposes can be harmful to the environment due to adverse effects such as acidification, climate change, and biodiversity loss (Pothen, 2017). The characteristics and optimization of raw materials are important and act as decisive factors for product quality as well as cost (Dhumal et al., 2017). The availability of raw materials depends on the location of the manufacturing industries. Localization is important not only because of the production of raw materials but also due to the availability of waste materials useful for manufacturing as well as the availability of raw materials from the neighboring areas (Thingo, 1985). Therefore, waste management and treatment systems are of high importance for the alternate raw materials to be extracted from waste (Sadala et al., 2019). The location of the manufacturing industries can affect the transportation of raw materials as well (Duflo et al., 2012).

Manufacturing industries can move towards cleaner production by adopting alternative raw materials and energy sources, and by reducing adverse environmental impacts such as greenhouse gas emissions. These industries can reduce the adverse effects through comparison between the emissions released by the imported and domestically produced raw materials used in the manufacturing processes (Mikulcic et al., 2016). Redesigning of the machines used in the manufacturing process can help in increasing energy efficiency to some extent.

With adoption of improved technology in the manufacturing sector, the rate of growth in both energy and material intensities have declined over time although their absolute values have increased. The positive result of this is the industrial ecology. However, in developing countries, this can be disadvantageous leading to stagnation in human and capital resources in the manufacturing sector (Ross, 1992). The industrial ecology can be

¹ Energy intensity measures the amount of energy consumed to produce one unit of economic output by a sector or an economy. It serves as an indicator of energy efficiency — the lower the energy intensity, the higher the energy efficiency.

progressed through the initiatives undertaken by the human participants involved in the manufacturing process and the internal characteristics of the firms (May et al., 2017).

Widespread application of the best available technologies and improvement in recycling processes can improve the energy efficiency of material production (Gutowski et al., 2013). However, the existing studies have not determined trends, patterns and empirical relationship between energy efficiency and material efficiency in major industries particularly in the case of developing countries like India. Moreover, the comparison of energy efficiency with other countries has also been ignored for the development of newer technologies.

Given these research gaps, this paper aims to understand trends and variation in the energy and material efficiencies across different Indian industries over time and to assess the relationship between energy efficiency and material efficiency in the case of major Indian industries. It also emphasizes emerging issues such as changing production structures and the adoption of sustainable production technologies in Indian manufacturing industries.

The study is based on the KLEMS Database, Reserve Bank of India for the period 1980-81 to 2019-20. This time horizon has been chosen to capture the positive outcomes and the limitations of the present study. Using a longer time horizon can lead to the capturing of unintended outcomes (Basu & Maciejewski, 2019). Fifteen major manufacturing industries have been considered in this study based on their importance identified from existing literature and also prioritizing their importance in recent years. This study finds that though energy efficiency has increased in all sectors over time, material efficiency has declined in many sectors over time. Interestingly, there exists a negative correlation between energy efficiency and material efficiency in the case of many Indian industries. This fact highlights the need to focus on the adoption of appropriate technologies to increase energy and material efficiencies simultaneously and achieve sustainable production in the manufacturing sector in India.

The rest of the sections include a review of the literature and conceptual framework; data sources and methodology; results and discussion; and concluding remarks, limitations, and future scope.

2. Review of Literature and Conceptual Framework

Sustainable production is defined as creation of goods and services using processes and systems that are non-polluting, boosting conservation of energy and natural resources, ensuring social and economic wellbeing, and promoting workers' health (LCSP, 1998; Veleva and Ellenbecker, 2001; Hesran et al., 2019). Structural changes including the sectoral composition of economies, trade, international fragmentation of production, technological change, innovation, and demand can lead to sustainable production (Savona and Ciarli, 2019). Increased use of technologies can lead to better infrastructure that can further

contribute to sustainable production in both direct and indirect ways (Jamwal et al., 2021). Environment-related technologies can lead to reducing energy demand which can save energy and ensure energy efficiency (Paramati et al., 2022). Technologies that enhance energy efficiency in production contribute to reduced greenhouse gas emissions, thereby supporting the goal of environmental sustainability (Ayres et al., 2017). The long term environmental sustainability of the manufacturing sector of a country can be achieved through the reduction in greenhouse gas emissions (Ayres et al., 2007).

The reduction in energy consumption as well as energy costs can improve the overall economic viability of a firm/industry. The structural changes and convergence of energy intensities are crucial for manufacturing industries (Kepplinger et al., 2013). The determination of energy intensity becomes important to understand the impact of economic activity on emissions and to develop an energy-economy perspective model (Miketa, 2001). Technological progress and input price can act as drivers of energy efficiency (Dasgupta and Roy, 2015).

At the micro level, manufacturing industries portray a positive relationship between energy efficiency and total factor productivity. Similarly, at the macro level, there exists a negative relationship between energy intensity and GDP per capita for the manufacturing sector (Cantore et al., 2016). Following the Environmental Kuznets Curve (EKC), to increase the economic growth of the nation, without hampering the energy efficiency, renewable energy can be useful. Renewable energy prevents energy disorders and reduces carbon emissions of the Indian manufacturing industries (Zhang et al., 2020).

Technological improvement has led to the use of renewable raw materials that can contribute to sustainable production (Diercks et al., 2008). Further, the focus on dematerialization has led to decreased material use (Bernardini and Galli, 1993). Improvement in the design of materials/commodities for increased durability is useful for ensuring sustainability (Fletcher, 2012). Innovations, inventions, and adoption of new technologies can play a crucial role in determining material use intensity (Saranga and Phani, 2009).

Improvement in material efficiency can reduce the volume of industrial waste and resource consumption. Better waste segregation, higher recycling rate, and increasing success rate of waste management initiatives are results of improvement in existing state of material efficiency (Shahbazi et al., 2017). The usage of renewable raw materials in manufacturing industries has become significant by influencing competitiveness, characteristics of derived products, and ecological effects. These also help in opening up of wider spectrum of synthetic methods and finished products (Baumann et al., 1988).

In general, a complete lifecycle of a product can provide the alternative product design option to ensure material efficiency (Nathani, 2009). The material efficiency usage by the Indian manufacturing industries acts as a crucial factor in ensuring sustainable development in the long run. Increase in usage of raw materials possesses a threat towards its availability. The scarcity of resources and raw materials may arise due to both short-

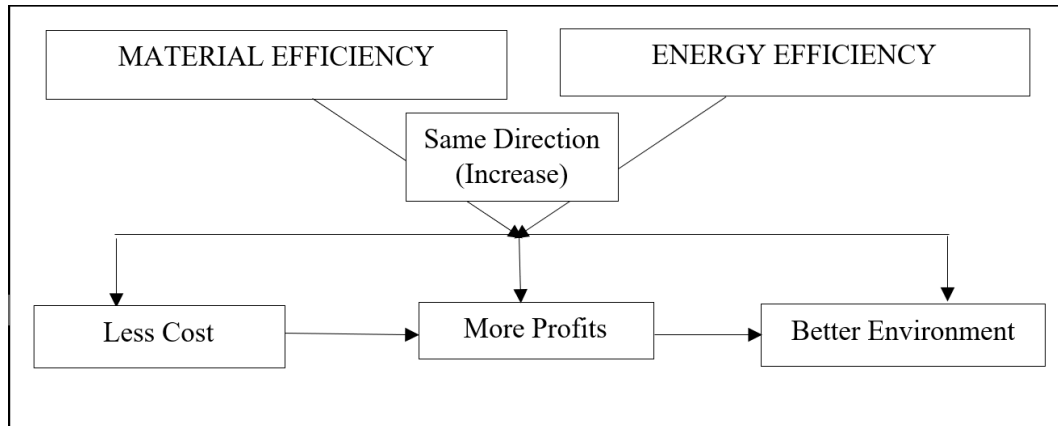
term factors such as external shocks, export restrictions, unplanned investment, etc. and also due to long-term factors such as non-renewable extracted resource depletion. However, extensive use of raw materials by the industries may lead to shortage in both renewable and non-renewable resources in near future. According to the fixed stock paradigm (used for non-renewable resources), the demand for non-renewable resources (flow variable) exceeds the supply of the same (stock variable) which leads to depletion and scarcity at some point even if there is continuous production of the non-renewable resource. According to the sustainable yield paradigm (used for renewable resources), although the supply of renewable resource is not a stock variable, however, due to the increasing demand of such resources, at some point of time, demand will exceed the sustainable supply of resources leading to shortage (Soderholm & Tilton, 2012).

From the above literature, it can be mentioned that to ensure material efficiency and energy efficiency, the Indian manufacturing industries should focus on shifting from non-renewable to renewable energy sources and from non-biodegradable to biodegradable raw materials in order to minimize environmental degradation and ensure economic growth and sustainable development in the long run.

The terms 'material intensity' and 'energy intensity' are just the opposites of the terms 'material efficiency' and 'energy efficiency' respectively. More of material consumption leads to more of material trade which further lead to more energy intensity, although not proportionately (Zheng et al., 2011). Thus, material intensity can have a strong impact on energy intensity of the manufacturing industries. This also considers material intensity to be of higher value than that of energy intensity (Liu et al., 2006).

To promote sustainable development in manufacturing industries, focus should be given to reducing energy intensity and increasing energy efficiency (Oak, 2017). The energy consumption pattern has changed a lot over the years. Technical change and energy conservation in manufacturing industries have not been fully effective due to energy price decreases, huge time consumption for technological upgradation, and improper research and development related to emerging energy technologies. Moreover, sometimes, non-energy inputs can increase energy consumption (Mukhopadhyay and Chakraborty, 1999). For achieving sustainable production, technological change should facilitate growth in both energy efficiency as well as material use efficiency. Therefore, the direction of variation in energy efficiency and material efficiency is very crucial in determining the sustainability of production structure in industries. The magnitude of positive change in the sustainability of production structure is much greater if energy efficiency and material efficiency of an industry increase simultaneously than the opposite directional change in them. Consequently, it may have a significant positive effect on cost reduction and profit earning of an industry. Figure 1 illustrates the environmental and economic benefits obtained due to simultaneous increases in energy efficiency and material efficiency in an industry.

Figure 1: Conceptual framework depicting the beneficial relationship between energy efficiency and material efficiency for manufacturing industries



Source: Authors' design based on related literature review

Reduction in usage of energy-intensive materials can lead to material efficiency. Usage of less materials and reduction in emissions prove to be complementary to each other (Hernandez et al., 2018). Potential efficiency improvements in the manufacturing sector are required to reduce the amount of energy consumption during the production of materials. Material recycling and efficiency are good for the environment as well. This recycled material can replace the primary one and thus can reduce the amount of emissions. This process can be considered as a broader version of sustainability in the long run (Gutowski et al., 2013). An industry also requires indirect energy to carrying out the production processes. Energy is directly consumed by the production processes to manufacture a product or a component. This direct energy includes the minimum energy required to carry out the production process. The indirect energy is required by the supporting and auxiliary activities for the production process. Therefore, with reduction in waste materials in the production process i.e. increase in material efficiency, energy efficiency will also be improved. This efficiency can further improve with the co-processing of wastes generated due to the manufacturing activities which means energy efficiency can be ensured through material efficiency by the transformation of waste into alternative fuels (de Queiroz Lamas et al., 2013). Therefore, it can be hypothesised that there exists a positive relationship between material efficiency and energy efficiency (H1).

Over the years, Indian manufacturing industries have shown a faster decline in energy intensity, indicating an improvement in energy efficiency (Dasgupta and Roy, 2017). Dependence on conventional energy sources and lack of optimal resources sometimes act as challenges to energy efficiency in India (Sahoo et al., 2016). The policies taken by the Indian government which include a sustainable development framework for the reduction of greenhouse gas emissions, input substitution, subsidization, taxation, etc. can promote sustainable development in the long run. Most of the studies have focussed on energy efficiency index and energy indicators and measures for energy performance of the manufacturing industries (Bakar et al., 2015; Filippini and Hunt, 2015). However, there are

no studies particularly in the Indian context focusing on both material and energy efficiencies. Given the paucity of literature, there is a lack of knowledge about how material efficiency and energy efficiency have varied over time in the Indian manufacturing industries and what is the directional relationship between them. This study aims to contribute to this discourse.

3. Data Sources and Methodology

The study uses secondary data collected from the KLEMS Database for the period 1980-81 to 2019-20. The KLEMS (K: Capital, L: Labour, E: Energy, M: Materials and S: Services) database, published by Reserve Bank of India's (RBI), provides time series data on output, capital, labour and intermediate inputs (energy, material and services) at all India level including public and private sectors. In terms of broad industrial classification, it has around 27 sectors including 13 major manufacturing industries². The details of the manufacturing industries considered in this study have been shown in the Table 1.

Table 1: Broad Classification of Manufacturing Industries as KLEMS Database

<i>S. No.</i>	<i>Sector Description</i>
S1	Food Products, Beverages and Tobacco
S2	Textiles, Textile Products, Leather and Footwear
S3	Wood and Products of wood
S4	Pulp, Paper, Paper products, Printing and Publishing
S5	Coke, Refined Petroleum Products, and Nuclear fuel
S6	Chemicals and Chemical Products
S7	Rubber and Plastic Products
S8	Basic Metals and Fabricated Metal Products
S9	Machinery, nec.
S10	Electrical and Optical Equipment
S11	Transport Equipment
S12	Other Non-Metallic Mineral Products
S13	Manufacturing, nec; recycling

Source: Authors' compilation as per KLEMS database.

Material efficiency and energy efficiency have been estimated as output/material use and energy efficiency and output/energy use respectively. Higher material or energy efficiency corresponds to lower material or energy intensity. An increase in material or energy

² The industrial classification in the KLEMS database is constructed by building concordance between NIC 2008, NIC 2004, NIC 1998, NIC 1987 and NIC 1970 so as to generate continuous time series from 1980-81 to 2019-20. This classification is very close to the International Standard Industrial Classification (ISIC) revision.

efficiency results in a decrease in material or energy intensity, as less input is required per unit of output. Material use has been measured as Material input at constant 2011-2012 prices (in Crores of ₹) while energy use has been measured as Energy input at constant 2011-2012 prices (in Crores of ₹). Output has been measured as Gross Output at constant 2011-2012 prices (in Crores of ₹). Material as well as energy efficiencies of different manufacturing industries for each year have been calculated. To avoid short-term variations, decadal averages across sectors have been calculated to understand variations in the material and energy efficiencies over time. The correlational values between material and energy efficiencies have been calculated to determine the relationship between the two and a simple regression analysis has been done to capture the effect of material efficiency on energy efficiency³. In order to assess causal relationship between material efficiency and energy efficiency, following equations have been used for panel regression:

$$ME = \alpha + \beta_1 EE + \beta_2 Tech + \beta_3 t + \varepsilon_i \dots\dots\dots(1)$$

$$EE = \alpha + \beta_1 ME + \beta_2 Tech + \beta_3 t + \varepsilon_i \dots\dots\dots(2)$$

Where ME represents Material Efficiency, EE represents Energy Efficiency, Tech represents Technology, t represents time and ε represents error term. α is a constant term while β is coefficient of respective variables. Technology has been measured in terms of capital-labour ratio and time has been measured in terms of year starting as 1 for the year 1980-81. Equations 1 & 2 have been used to understand bidirectional relationship between material efficiency and energy efficiency.

4. Results and Discussions

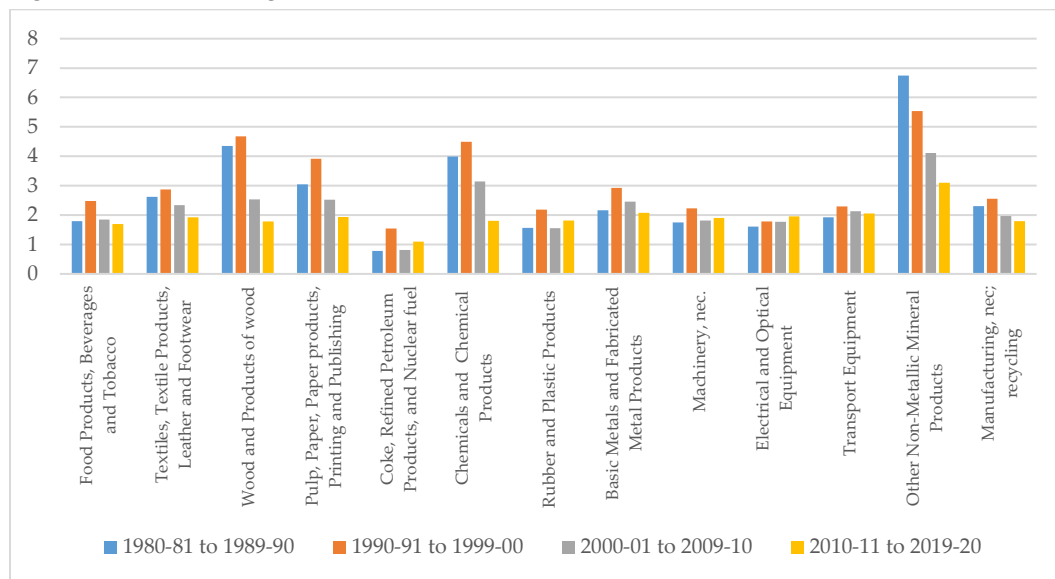
There is significant variation in the decadal average material efficiency in the 13 manufacturing sectors during last four decades i.e. 1980-81 to 2019-20 (Figure 1 and Table A1⁴). In general, material efficiency has increased in 5 sectors including Coke, Refined Petroleum Products and Nuclear fuel; Rubber and Plastic Products; Machinery, nec.; Electrical and Optical Equipment; and Transport Equipment; which indicates a decline in the material intensity in these sectors over time. It implies that lesser amount of material is being used in the production process in these sectors. It also shows decline in the waste generation in the production process in these sectors. Increased material efficiency ensures circular economy through reduction of the generation of industrial waste, the extraction and consumption of resources, and energy demands and carbon emissions (Shahbazi et al., 2016). Dematerialization over the years (in most cases) indicates either a reduction in

³ The correlation analysis here tries to find out the internal and external factors contributing to the outcomes and the regression analysis has been done to capture the associated cause and effect (Walker, 1997). The correlation value lies between -1 and 1. Values -1, 0 and 1 indicate perfectly negative, no linear and perfectly positive relationship between the two variables. Any value between 0 and 0.3 indicates weak positive, 0.3 and 0.7 indicates moderate positive and 0.7 and 1 indicates strong positive relationship. This is just the same for negative values (Ratner, 2009).

⁴ See Appendix for Table A1

material inputs or reduction in waste generated or both. This has resulted in better environmental effects as well (Cleveland and Ruth, 1998).

Figure 1: Decadal Averages of Material Efficiencies across Sectors

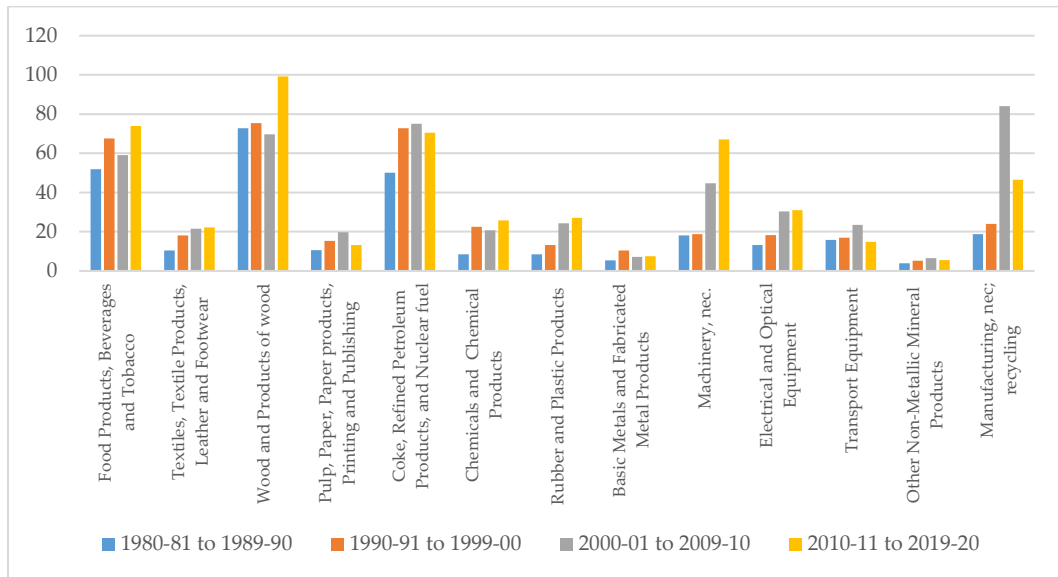


Source: Authors' calculations based on KLEMS Database, Reserve Bank of India

Material efficiency has declined in 8 sectors including Food Products, Beverages and Tobacco; Textiles, Textile Products, Leather and Footwear; Wood and Products of wood; Pulp, Paper, Paper products, Printing and Publishing; Chemicals and Chemical Products; Other Non-Metallic Mineral Products; and Manufacturing, nec; recycling. It indicates that there has been increase in the material use in these sectors to produce the same output over time. It also shows that waste production has increased in these industries over time.

Though there is significant variation in the energy efficiency in all sectors during the four decades, it has increased in all 13 sectors over time in general (Figure 2 and Table A2⁵). It indicates that industries have adopted efficient energy-saving technologies over time. Government policies have also played a significant role in this regard. Higher energy prices might have also compelled industries to adopt energy-saving technologies to reduce the cost of production. However, high energy prices alone have not been sufficient in energy conservation. These have been supported by the higher quality of labour force (Mukherjee, 2008). Exports and firm size also promote energy efficiency of the manufacturing industries to some extent (Macharia et al., 2022).

⁵ See Appendix for Table A1

Figure 2: Decadal Averages of Energy Efficiencies across Sectors

Source: Authors' calculations based on KLEMS Database, Reserve Bank of India

From Figure 2, it is clear that the Other Non-Metallic Mineral Products, and Basic Metals and Fabricated Metal Products industries have the lowest energy efficiency throughout the period. The energy consumption throughout the production process of metals is high due to the low energy utilization capacity of the industry (Guo and Fu, 2010). Some of the industries have almost stagnant or little fluctuating nature of energy efficiency over the years while there is significant increase in the energy efficiency in some industries. The energy efficiency of the textile industry has shown an increasing trend over the years due to its focus on energy-saving methods (Ozturk, 2005).

Some manufacturing industries use raw materials which do not consume much energy. When recycling technology is adopted by the manufacturing industries, repeated use of raw materials occurs with energy consumption. This means that even if the same raw material is used for several years, energy consumption will go on increasing due to its repeated use (Pommeret et al., 2022). On the other hand, when energy is stored and reused in every stage of the manufacturing process, energy consumption will be less even if the usage of raw materials increases (Hadjadi et al., 2019). Therefore, there may not be a linear relationship between energy efficiency and material efficiency in a sector.

From Figures 1 and 2, it is visible that material efficiency is lower than energy efficiency for all the cases. This is a good sign from the environmental perspective because less energy consumption contributes to a lesser amount of environmental damage. The material efficiency of the fuel industry is astonishingly low. This is because the industry uses non-renewable as well as non-recyclable materials for manufacturing processes. But this also leads to a negative result indicating higher material intensity as compared to energy intensity. This means that the industries consume more amount of materials as compared

to energy which further means the recycling of waste materials of such industries is not upto the mark (Frosch & Gallopoulos, 1989).

The correlation coefficient between energy and material efficiencies shows mixed results for the Indian manufacturing industries (Table 2). Ideally, material efficiency and energy efficiency in an industry should increase with adoption of newer technologies which means greater output with lesser inputs. But, it's not always true in reality. Other factors like prices, sectoral linkages and overall growth of the economy play an important role in determining material and energy efficiencies of a sector. Sectors having positive and statistically significant correlation between energy and material efficiencies include Coke, Refined Petroleum Products, and Nuclear fuel (0.35); Machinery, nec (0.38), Electrical and Optical Equipment (0.73); and Transport Equipment (0.39). It indicates that technological changes in these sectors are moving towards sustainable production. Sectors having negative and statistically significant correlation coefficient include Textiles, Textile Products, Leather and Footwear (-0.78); Wood and Products of wood (-0.32); Pulp, Paper, Paper products, Printing and Publishing (-0.28); Chemicals and Chemical Products (-0.57); Other Non-Metallic Mineral Products (-0.54); and Manufacturing, nec; recycling (-0.48). It shows that the net effect of technological adoption in these sectors is lesser in achieving sustainable production.

Table 2: Relationship between Energy Efficiency and Material Efficiency for different manufacturing industries from 1980-81 to 2019-20

<i>S. No.</i>	<i>Sector</i>	<i>Correlation Coefficient</i>	<i>p-value</i>
S1	Food Products, Beverages and Tobacco	0.04	0.80
S2	Textiles, Textile Products, Leather and Footwear	-0.78***	0.00
S3	Wood and Products of wood	-0.32**	0.04
S4	Pulp, Paper, Paper products, Printing and Publishing	-0.28*	0.08
S5	Coke, Refined Petroleum Products, and Nuclear fuel	0.35**	0.03
S6	Chemicals and Chemical Products	-0.57***	0.00
S7	Rubber and Plastic Products	-0.03	0.84
S8	Basic Metals and Fabricated Metal Products	0.11	0.49
S9	Machinery, nec.	0.38**	0.02
S10	Electrical and Optical Equipment	0.73***	0.00
S11	Transport Equipment	0.39**	0.01
S12	Other Non-Metallic Mineral Products	-0.54***	0.00
S13	Manufacturing, nec; recycling	-0.48***	0.00

Source: Authors' calculations based on KLEMS Database, Reserve Bank of India

Note: ***, **, and * show values at 1%, 5%, and 10% levels of significance respectively.

Manufacturing activities should be intertwined with sustainable development goals to ensure that present and future generations will have resources or alternative means to satisfy their basic needs of food, water, and energy. This can reduce environmental impacts

and depletion of conventional energy resources (Carvalho, 2017). In a developing country like India where there are many SMEs, investment towards green organizational innovation and open innovation prove to be effective in the long run. Lean green manufacturing systems positively influence social and environmental performance (de Sousa Jabbour et al., 2020).

High energy efficiency and high material efficiency lead to sustainable development. In a developing country like India with mostly lower quality raw materials used (which can act as contaminant discharges with high energy use), enhancing energy and material efficiencies is good for the manufacturing sector since it leads to a reduction in greenhouse gases, waste generation, climate change, pollution and thus, promotes sustainable development (Zha et al., 2020). Improvement in management strategies and other policies, investments, and export-oriented products can help in sustainable development (Bojnc and Papler, 2011). There should be proper micro and macro level assessment of sustainable development since it acts as a driving force in the twenty first century (Garbie, 2014).

For understanding the causal relationship between material efficiency and energy efficiency, a panel regression analysis has been conducted for equation 1 (See section 3). The results of hausman test shows that the model rejects null hypothesis⁶ indicating unobserved effects are related with the independent variables. Therefore, fixed effect panel regression results have been used for analysis and discussion.

Table 3 shows that the causal relationship between material efficiency and energy efficiency along with other independent variables viz. technology and time. The coefficient of energy efficiency in the model 1 is positive but statistically not significant. However, the negative and statistically significant coefficient of technology in model 1 shows that material efficiency has negative relationship with technology being adopted in the Indian manufacturing industries. The positive and statistically significant coefficient of time shows that material efficiency in Indian manufacturing industries has gradually increased over time but the pace is very slow.

In case of model 2, the coefficient of material efficiency is positive but statistically not significant. It is similar to that of model 1. These two results, positive coefficients but statistically not significant, indicates an absence of a conclusive causal relationship between material efficiency and energy efficiency. The positive and statistically significant coefficient of technology shows that technology adoption has positive impact on energy efficiency in the Indian manufacturing industries. However, the negative and statistically significant coefficient of time shows that energy efficiency has declined over time.

⁶ Prob>chi2 = 0.0000

Table 3: Regression Results – Causal Relationship between Material and Energy Efficiencies

<i>Independent Variable</i>	<i>Material Efficiency</i>	<i>Energy Efficiency</i>
	<i>Model 1</i>	<i>Model 2</i>
	<i>Coefficients (Std. Error)</i>	<i>Coefficients (Std. Error)</i>
Energy Efficiency (EE)	0.340 (0.210)	
Material Efficiency (ME)		0.015 (0.009)
Technology (Tech)	-0.193*** (0.019)	0.020 (0.004)
Time	0.004*** (0.000)	-0.002 (0.000)
Constant	0.439*** (0.022)	0.089 (0.000)
Observations	520	520
sigma_u	0.267	0.056
sigma_e	0.087	0.018
rho	0.904	0.903
R-sq within	0.203	0.449
	between	0.832
	Overall	0.254

Source: Authors' calculations in STATA based on KLEMS Database, Reserve Bank of India

Technological innovations in one manufacturing industry can have a positive impact on other industries as well due to inter-sectoral linkages. Such technological developments can sometimes lead to industrial revolutions and can cause fundamental shifts in society (Steenhuis & Pretorius, 2017). High technology manufacturing creates problem between exploitation and exploration in manufacturing sector (Jayanthi & Sinha, 1998). Manufacturing green technology innovation helps in promoting sustainable economic development (Lee et al., 2022). Indigenous R & D and technology spillover help in decreasing energy intensity resulting in more energy efficiency. Increase in indigenous R&D and technology spillover can help in decreasing energy intensity which leads to more energy efficiency. The major positive drivers of changes in material and energy intensities are the level of exports, export mix, industrial structure, affluence, and population (Wood et al., 2009). Moreover, the natural resources available in a country can also affect material and energy intensities (Efthimiou et al., 2018).

Both energy and material efficiencies are determined by the technology including other factors. However, impact of technology on these efficiencies depends upon the key objectives technological adoption by the entrepreneur and its prices. In general, entrepreneurs focus on reducing energy cost, we have observed a positive relationship

between technology and energy efficiency while, surprisingly, there is negative relationship between technology and material efficiency. But, it highlights the disconnect between technological adoption in Indian manufacturing and material and energy efficiencies. However, it requires a firm level analysis to develop a deeper understanding about the relationship between material efficiency, energy efficiency and technology.

5. Concluding Remarks, Limitations and Future Scope

The study shows that though energy efficiency in manufacturing industries has increased over time material efficiency has not increased in many sectors. Further, the relationship between material efficiency and energy efficiency gives mixed results for the Indian manufacturing industries. The positive value for some industries is beneficial for the economy as it can increase profits, reduce costs as well as save the environment. For some other industries, there exists a negative relationship between energy and material efficiencies indicating technological adoption in these sectors are not supporting growth in these two efficiencies simultaneously, hence have lesser potential to support sustainable production.

High energy efficiency and high material efficiency lead to sustainable development. In a developing country like India with mostly lower quality raw materials used (which can act as contaminant discharges with high energy use), enhancing energy and material efficiencies is good for the manufacturing sector since it leads to a reduction in greenhouse gases, waste generation, climate change, pollution and thus, promotes sustainable development. This study highlights that there is a need to address the issue of declining material efficiencies in many sectors. By focusing on technological innovations, and adoption of appropriate technologies, it can be addressed. Material input qualities need to be improved through appropriate regulations and their implementations.

This study also highlights that there is a need to focus on technologies that can simultaneously increase energy and material efficiencies. Without this, it might be difficult to achieve sustainable production in industries. In the case of Indian manufacturing industries, focus on appropriate technology import, and local research and technological development can foster the adoption of sustainable production technologies. It also requires a broad industrial and environmental policy framework in the country.

Being the first of this kind studies, given our limited knowledge, this study significantly contributes to the knowledge and existing discourse on sustainable production in manufacturing industries in India. However, there is a need to conduct similar exercises at the firm level to develop a deeper understanding and to bring out appropriate policy suggestions.

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7. Appendix

Table A1: Decadal Averages of Material Efficiencies across Sectors

S. No.	Sector	1980-81 to 1989-90	1990-91 to 1999-00	2000-01 to 2009-10	2010-11 to 2019-20
1	Food Products, Beverages and Tobacco	1.79	2.48	1.85	1.70
2	Textiles, Textile Products, Leather and Footwear	2.62	2.87	2.34	1.92
3	Wood and Products of wood	4.35	4.68	2.53	1.78
4	Pulp, Paper, Paper products, Printing and Publishing	3.04	3.92	2.52	1.93
5	Coke, Refined Petroleum Products, and Nuclear fuel	0.78	1.54	0.81	1.10
6	Chemicals and Chemical Products	3.99	4.49	3.14	1.80
7	Rubber and Plastic Products	1.56	2.18	1.55	1.82
8	Basic Metals and Fabricated Metal Products	2.16	2.92	2.46	2.08
9	Machinery, nec.	1.75	2.23	1.82	1.90
10	Electrical and Optical Equipment	1.61	1.78	1.77	1.96
11	Transport Equipment	1.92	2.29	2.13	2.05
12	Other Non-Metallic Mineral Products	6.75	5.54	4.11	3.10
13	Manufacturing, nec; recycling	2.31	2.55	1.97	1.79
14	Electricity, Gas and Water Supply	2.51	3.10	4.28	4.83
15	Construction	3.62	3.13	2.45	2.55

Source: Authors' calculations based on KLEMS Database, Reserve Bank of India

Table A2: Decadal Averages of Energy Efficiencies across Sectors

S. No.	Sector	1980-81 to 1989-90	1990-91 to 1999-00	2000-01 to 2009-10	2010-11 to 2019-20
1	Food Products, Beverages and Tobacco	51.91	67.57	59.10	73.99
2	Textiles, Textile Products, Leather and Footwear	10.50	18.10	21.47	22.20
3	Wood and Products of wood	72.85	75.34	69.69	99.25
4	Pulp, Paper, Paper products, Printing and Publishing	10.60	15.37	19.80	13.15
5	Coke, Refined Petroleum Products, and Nuclear fuel	50.18	72.82	75.16	70.57
6	Chemicals and Chemical Products	8.46	22.60	20.66	25.71
7	Rubber and Plastic Products	8.41	13.21	24.27	27.08
8	Basic Metals and Fabricated Metal Products	5.39	10.38	7.10	7.56
9	Machinery, nec.	18.06	18.73	44.73	67.01
10	Electrical and Optical Equipment	13.20	18.31	30.29	30.99
11	Transport Equipment	15.90	16.96	23.53	14.85
12	Other Non-Metallic Mineral Products	3.96	5.29	6.45	5.53
13	Manufacturing, nec; recycling	18.82	24.06	84.10	46.54
14	Electricity, Gas and Water Supply	4.36	3.18	4.37	5.14
15	Construction	55.46	51.34	44.74	39.33

Source: Authors' calculations based on KLEMS Database, Reserve Bank of India

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4 Vasant Kunj Institutional Area, New Delhi - 110070, India

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