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The evolving metabolism of a developing economy: India's exergy flows over four decades

Sachin B. Jadhao[a], Aniruddha B. Pandit[a], Bhavik R. Bakshi[b,*]

[a] Institute of Chemical Technology, Mumbai 400 019, India
[b] William G. Lowrie Department of Chemical and Biomolecular Engineering, The Ohio State University, Columbus, OH 43210, USA

HIGHLIGHTS

- Resource use in India is analyzed between 1970 and 2010 in terms of exergy flows.
- Exergy use has been growing fast since adoption of free market policies.
- India's metabolism is lagging that of developed economies by 20 years.
- Resource intensity (exergy use per GDP) has started decreasing recently.
- Opportunities for improvement are in power generation and transportation.

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ABSTRACT

Many developing countries are attempting to develop quickly by increasing utilization of nonrenewable resources. Comparing the national metabolism of developed and developing societies can shed useful light into how efficiently the useful potential of resources is being used to identify potential pitfalls and opportunities for sustainable development. Such analysis may also help avoid and leapfrog over some of the mistakes of developed countries. Such research could assist in finding answers to some critical questions like whether developing societies like India are being more sustainable than developed societies in terms of resource utilization. Comparing historical trends of resource use across multiple societies also sheds light on how the resource mix changes with efforts toward sustainability.

The primary objective of this work is to gain greater understanding of India's economic growth over the last four decades (1970–2010) by analyzing its reliance on useful work or exergy derived from various natural resources. Such insight can help determine whether India is following a path of sustainable development. If the country is not on this path, this work can help identify opportunities for improvement. Acquiring such data was itself a formidable challenge, making this the first database of its type. This paper presents and discusses the trajectories of resource consumption and its conversion into useful work and environmental emissions from economic activities. The results show a significant increase in the country's metabolism as it evolved from a controlled to a more open free-market economy, along with a more recent and gradual improvement in the intensity of exergy use. Comparing the trend of India's metabolism with that of selected developing and developed economies shows India's path to be similar in many ways. Reliance on nonrenewable resources has been increasing and a large fraction of the exergy input gets wasted, as shown by a Grassmann diagram. Results show that opportunities exist for improving efficiency in the utilities and residential sectors. India needs to improve its efficiency at a faster rate than what happened in developed countries since otherwise the global implications due to fast economic growth and a large population can be quite significant.

1. Introduction

Assessment of resources used in society has been popular to address their scarcity and price volatility, and due to increasing awareness about the environmental impact of their use. For sustained economic progress of any society, availability of natural resources is a major concern. Every industrial process can be seen as a transformation of natural resources, expenditure of available energy (exergy) and

* Corresponding author.
E-mail address: bakshi.2@osu.edu (B.R. Bakshi).

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generation of entropy. Most natural resources that modern societies rely on are products of millions of years of work by nature in the form of various geochemical and physicochemical transformations. Utilization of these natural resources at a rate higher than their rate of replenishment is inherently unsustainable since it precludes their availability to future generations. Pressure exerted by anthropogenic activities on the ecosystem has been enormous over the last couple of centuries and even more remarkable in the last few decades. This has certainly contributed to enhanced human well-being, but at the cost of subjecting ecosystem products and services to severe anthropogenic stress. With an increase in population, industrialization and economic growth, pressure on the ecosystem is not likely to subside.

Resource consumption for economic development is a limiting factor but its wastage and excessive use in society can be avoided with proper analysis of its use. Natural resources are generally categorized as fuel (energy) resources and non-fuel (material) resources. But this distinction is not very meaningful, because all the non-fuel material resources play an equally important role for the development of a society. Often, resources like crude oil and natural gas that are considered as fuel (energy) resources are used for producing useful materials, while material (non-fuel) resources like wood and plastic waste get used as an energy source [1]. Hence, to evaluate the performance of a society all the ecosystem products and services (energy, material, ecosystem services) need to be accounted for on a common basis [2].

Exergy analysis has been found to be a useful measure to account for a large variety of resources as it represents the usefulness, quality or potential of the natural resource to cause the necessary change. It has been used by many researchers as a tool for the assessment of resource conversion to useful work to evaluate many national economies [3]. This includes studies by Ayres and coworkers on the US economy, [2–5], and similar studies for other countries such as Turkey [6–7], Canada [8], Sweden [9], UK [10] and Japan [11,12]. Majority of regional and national economies studies focussed on exergy flow in society for one single year. In these studies, the structure of resource utilization and destruction has been discussed for the respective societies. The first analysis was applied by Reistad to US for the year 1970. Goran Wall in 1977 and in 1986 [6] made a systematic attempt; he used exergy analysis as a measure of all (fuel and nonfuel) resources in Sweden. Wall was the first to include exergy of non-fuel resources for the assessment of society [6], and this approach was subsequently applied to societies in Japan [8], and Italy [11]. Another exergy-based study of the Japanese society over the last century concluded that the overall efficiency of Japanese society has declined slightly in last half of the 20th century [7]. Bakshi and coworkers distinguished between industrial cumulative exergy consumption (ICEC) and Ecological CEC (ECEC), where the former accounts only for human activities, while the latter also considers exergy consumption in ecosystems [9]. ECEC is inspired by the concept of emergy and shows the close connection between emergy and cumulative exergy, and is able to account for all kinds of resources, including human labor. Extended-exergy accounting (EEA) also accounts for fuel, non-fuel minerals and also labor muscle power in exergetic terms [10]. Using these methods for analyzing the thermodynamic metabolism of several societies shows the low second law efficiency and resulting resource scarcities. Such studies have focused on USA [4,5,12], U.K. [5,13], China [14–18], Turkey [19,20], Belgium, Portugal [21], Danish society [22]. This work presents the first study on the exergy utilization and destruction of resources used in India.

Each country has a different combination of resource use to satisfy the energy need for anthropogenic activities of the society. Its choice depends on the cost and availability of resource, technology, government policy, local environmental norms and regulations. Ertesvag gave a comprehensive comparison and the analysis of different societies, such as Norway, Sweden, Italy, Japan, Sweden, Ghana, Turkey, Brazil, Canada, Finland, USA based on exergy analysis [23]. These studies show that a large fraction of the total resource that is extracted by society gets wasted. Different thermodynamic approaches have been used for the assessment of the societies. Exergy analysis has also been used to account for environmental emissions and their impact. Because of its advantages over simple material and energy analyses, such as representing all resources in terms of their capacity to do work, exergy analysis has become very popular and has been successfully used for estimating the efficiency of resource utilization and influencing policies.

Developing economies play a major role in the overall energy scenario of the world, and this role is only expected to increase. India is among the world's largest energy consuming societies, accounting for about 3.5% of the global annual energy consumption. Being a developing economy and the second most populated country, it has a huge demand for physical resources. Heavy dependence on fossil fuels to satisfy its energy needs over many years has generated pressure on the availability of resources, which is only expected to increase in the future. Increasing societal awareness regarding environmental emissions and climate change is exerting pressure on the fossil fuel emissions in India. Minimizing the losses associated with society's metabolism can reduce the burden on the available reserves and also help to reduce the environmental emissions and its impact on the environment. Hence it has become imperative to analyze the resource utilization in any national economy.

The main objective of this paper is to evaluate the changes in India's metabolism and evaluate the progress of growth over the last four decades on the basis of useful work derived from the use of natural resources and environmental emissions. Using Wall's approach [6,8,11], this study quantifies the exergy flow of the major resources used in India between 1970 and 2010. This approach quantifies the physical amount of flow into its exergy content for inputs and outputs in key economic sectors. Results of this analysis include information about efficiency trends, which could play an important role in devising policies of resource use and sustainable development in India and other developing economies. The chief novelty of this work lies in its (1) being the first study of its type for India, (2) making available data about exergy flow in India over four decades, (3) providing unique insight about where does India as a developing country stand in terms of its resource utilization compared to developed societies. The rest of this paper is organized as follows. Section 2 summarizes the energy scenario in India, followed by the exergy-based approach in Section 3. Results of this analysis are in Section 4, including trends of resource use and relevant metrics. Finally, Section 5 discusses some of the main findings of this work and includes suggestions for the future.

2. Energy scenario in India

Historically, India has been an agriculture-based economy, but in the past two decades it has embraced the free market and globalization to shift towards one of the world's leading industrial nations. India is among the major resource consumers in the world, being the second largest in terms of population, and with a fast growing economy. It is generally accepted that India, in its quest for economic growth and well-being to provide a reasonable standard of living for its vast population, does have a legitimate right of resource consumption for development. India has become 4th largest energy consumer worldwide. In 2000–2001, total primary energy consumption in India was 3% of the world total energy consumption [24]. Total energy production in India in 2006 was 435.6 million tonnes of oil equivalent (MTOE). The total energy production in low income countries for the same period was 734.4 MTOE, in middle income countries was 6447.4 MTOE and in high income countries was 4663.1 MTOE [25,26]. However, the per capita resource consumption in India is extremely modest. For the year 2004, primary energy consumption was 15.3 GJ per capita as compared to 360 GJ per capita in the US [27]. Resource consumption in India is characterized by the dominance of fossil fuels. Approximately 90–95% of the total energy need is satisfied using fossil fuels, out of which coal