Materials Sustainability and the Need for a National Life Cycle Assessment Initiative

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Never in the history of mankind has "Sustainability" become such a critical issue as it has today. Sustainability of life in the universe demands sustainability of natural resources including food, water, clean air and other material resources, sustainability of energy resources and sustainability of environment. However, the term sustainability is interpreted differently by different stake holders. A material scientist looks at sustainability from the prism of raw materials availability, an environmentalist from the perspective of environment, an economist from the point of view of cost, an agriculturist from the viewpoint of food, a biologist from the considerations of sustaining life and so on. Nevertheless today, there are universally accepted definitions for "Sustainability", the most common being that of the *World Commission on Environment & Development which defines sustainability as;*

"forms of progress that meet the needs of the present without compromising the ability of future generations to meet their needs"

Although this definition is broad, simple and elegant, it lacks details. I found a more lucid definition of sustainability in a review paper published by Patzek and Pimentel [1] in a review article in "Critical Reviews in Plant Science" in 2005 which is *given below:*

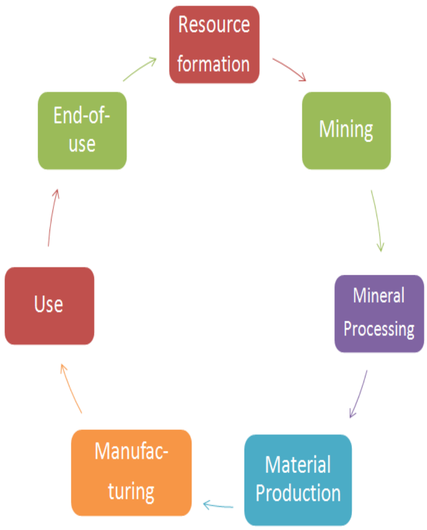
"A ***cyclic process*** is sustainable if and only if it is capable of being sustained, I.e., maintained without interruption, weakening or loss of quality **"forever"** and the **environment** the process feeds and to which it expels its waste is also sustained forever"

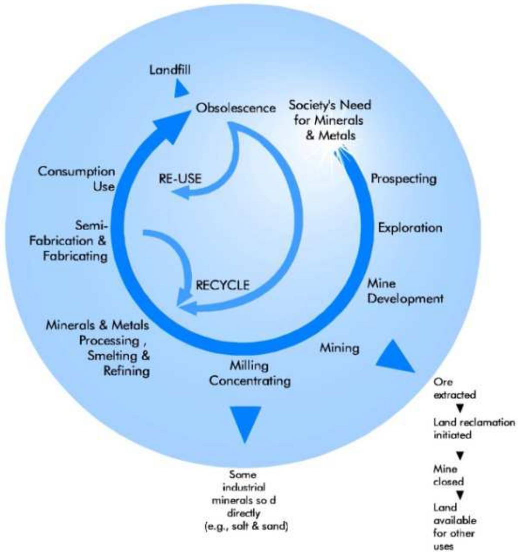
The essence of this definition lies in the three phrases *cyclic, forever and environment*. Although materials sustainability can be evaluated for the full life cycle of the process, practical considerations would warrant that the analysis is carried out *for the part of the cycle which is relevant* within *a finite & defined time period & only changes to the immediate environment is considered.*

Sustainability can be applied to any resource such as food, water, land, natural resources, energy and environment as also processes or practices or services. However, in this article, I would restrict to only sustainability of materials especially in the context of mining, mineral processing and metallurgy.

The full life cycle of a material, more specifically a metal (after the formation of the universe through cosmological evolution) would comprise of ore formation through geological processes, mining, mineral processing, metal extraction, manufacturing, use and end-of-use which could be renovation/rejuvenation& re-use, recycling or burial back to earth and its subsequent geological transformation. Extrapolating the definition of Patzek and Pimentel to this context of materials would imply that:

"The cycle of ore formation, mining, mineral processing, metal extraction, manufacturing, use and end of life stages are maintained without interruption, weakening or loss of quality **"forever"** and no net **environmental** change is brought about by this cycle over a period of time".





The Ideal Material Cycle

The Actual Material Cycle

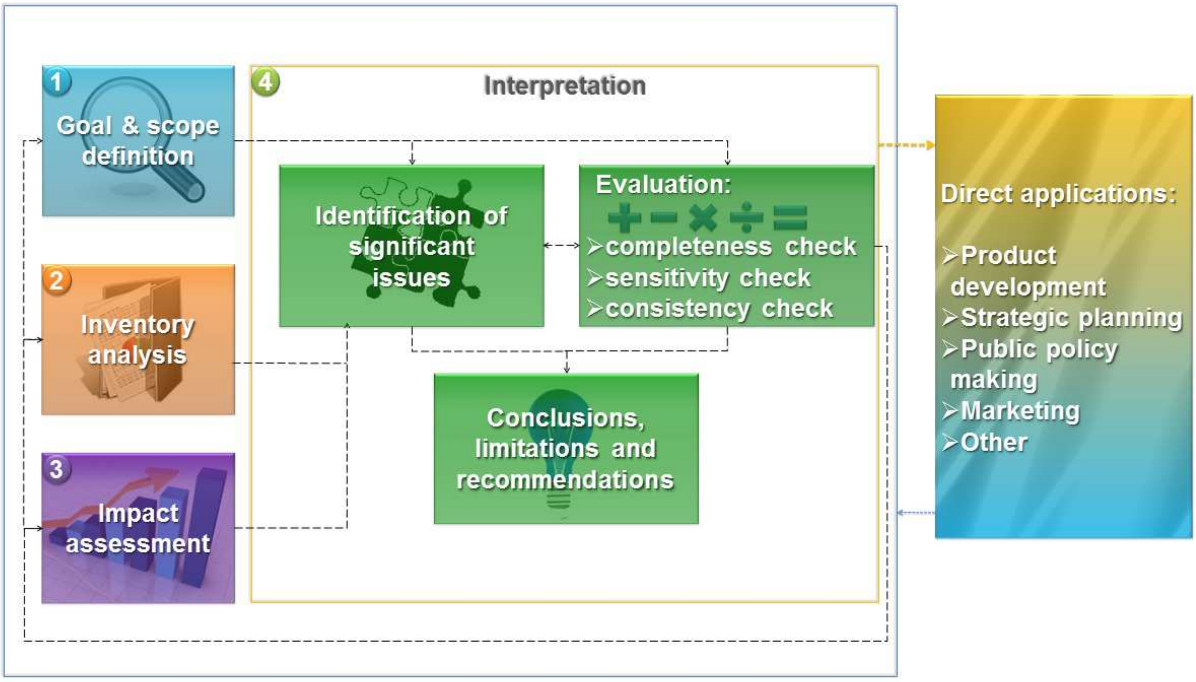
(Fig Reproduced from Sustainable Development & Minerals & Metals. An Issue Paper by Natural Resources, Canada)

I have in the past tried to address the thermodynamic, kinetic and environmental aspects of materials sustainability in terms of laws of thermodynamics, applying rate equations and Le-Chatelier's principle to the materials cycle [2]. However, in this article, my main emphasis will be on how to quantify and measure materials sustainability as well as to how to carry out an objective "Sustainability Analysis". The best method to assess and evaluate sustainability of a product or process cycle is through a "Life Cycle Assessment".

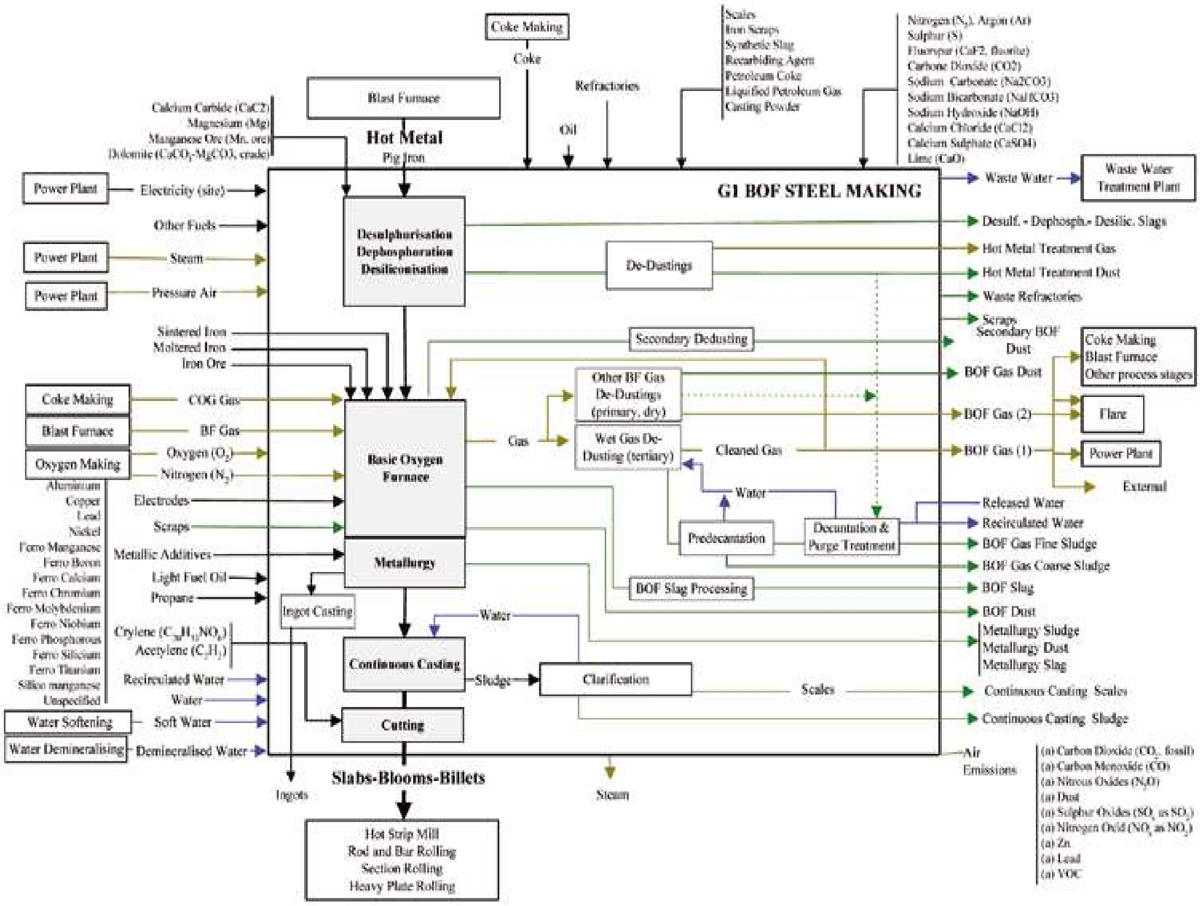
Life Cycle Assessment

Life Cycle assessment (LCA) is a process of compiling and evaluating the inputs, outputs and the potential impacts of a process cycle or product system through its life cycle. Impact analysis can include environmental impact, impact on natural resources, ecological impact, societal impact, economic impact etc. For any material, the life cycle as mentioned earlier will include the stages of mining, mineral processing, metal extraction or production, manufacturing, use and end-of-use.In each stage, there will be a large number of unit processes and product/material/energy flow between these unit processes. A process refers to the transformation of an input to an output and unit process is the smallest element considered in the life cycle analysis for which input and output data are quantified.*There is no single unique method for conducting LCA although 14040 series ISO standards provide guidelines.* The LCA procedure described below is largely based on ISO 14044 –2006 [3].

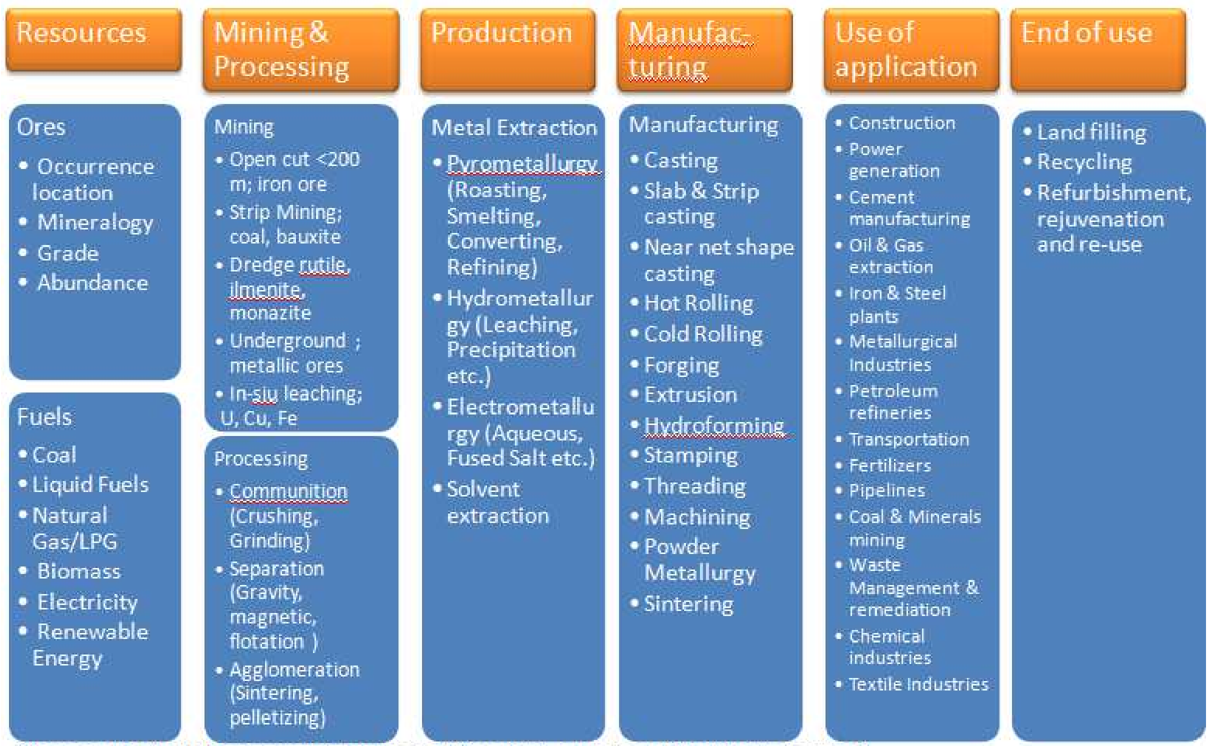
An LCA comprises of four phases"– the establishmentof the goals and scope of the assessment, the drawing up of materials inventory and energy balance for each unit process and for all stages of the life-cycle, evaluation of emissions and discharges for each unit process and for all stages of the process/product life cycle, an assessment of the impact and the identification of actions for improvement".LCA studies are relative in nature and based on a functional or reference unit. The functional (reference) unit can be a unit product, unit mass, unit length or any other physical parameter depending on the goal and scope of the LCA.



Definition of goal includes defining the intended application (eg., product development, strategic planning, public policy making, import-export decisions, marketing etc.) and objective, intended audience and whether the results are to be put up in public domain. The scope would include the description of the product system to be studied, the performance characteristics of the product system, the functional unit, the system boundary, procedures & methodologies to be used, interpretation methods and data requirements. Defining the system boundary involves specifying the unit processes of the system under consideration and the flow between the unit processes in the form of process flow charts. Although, it would be ideal to carry out such a study over the full life cycle ie., from cradle-to-cradle or even cradle-to-grave, in practice because of large differences in the time cycles of the various stages and geographical spread over which the various stages of the product cycle occur, this becomes virtually impossible. Whereas the time taken for the stages of mining, mineral processing, metal extraction and product manufacturing are in days, the use stage can be for tens of years and the resource formation stage takes millions of years. Further, the geographical locations where each of these stages is carried out are different and widely spread. Because of the difficulty in data collection over the vast geographical space and long time cycle, the studies are generally restricted up to the exit gate of the product, leaving out the "Use" and "End-of-Use" stages. It could be either a Cradle-to-Gate analysis or a Gate-to-Gate analysis. A typical "System Boundary" for a Gate-to-Gate analysis of Steel Making through the Blast Furnace – Basic Oxygen Furnace (BF-BOF) route reproduced from a LCA study by World Steel Association [4] is depicted below:



Even a simplified Gate-to-Gate analysis such as the one shown abovehas close to 270 unit processes [4] and one can imagine the level of complexity. Further, as mentioned earlier, the material life cycle has so many stages and each stage has several degrees of freedom as shown below:



Since each stage has several degrees of freedom, any one of them can be used for a life-cycle assessment; Therefore for the same material several LCA's are possible

The life cycle assessment is dependent on location, time, nature of technologies (mining, mineral processing, production and manufacturing technologies), nature of use and the end-of-use option exercised; carrying out a realistic life cycle assessment for the whole cycle from cradle-to-grave becomes virtually impossible.

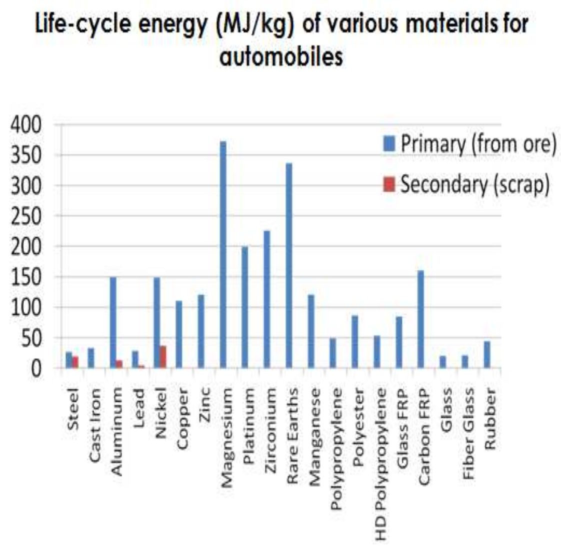
The heart of an LCA study is the creation of a Life Cycle Inventory (LCI) and the impact assessment protocols. In the Life Cycle Inventory phase, an inventory of input/output data is created for each unit process and for all the stages of the life-cycle. It involves the collection of the data for each unit process and the data is normalised against the functional unit. The input data for each unit process includes amount, composition and energy content of all raw material inputs, energy inputs, ancillary inputs and other physical inputs (such as air and water). The output data includes similar information on products & co-products, intermediate products, wastes, releases to air, water & soil and any other form of energy output. Depending upon the nature of the impact analysis carried out, one may require other data such as land use in each unit process, costs of inputs and outputs, noise and radiation generated if any during the process. The life cycle inventory stage includes data collection, data validation, normalising the data against the functional unit, relating the data to each unit process, and data aggregation. Data collection for each unit process can be through measurement, calculation, estimation or taken from literature. Data validation of each unit process can be accomplished through elemental mass balances, energy balances and/or by comparison with literature data. The input and output data if aggregated must also be related to each unit process, allocation of inputs and outputs made to the products & co-products and normalised against the functional or reference unit.

The objective of the Life Cycle Impact Assessment (LCIA) phase is to comprehend and assess the magnitude and significance of the potential impacts of a process/product system through the life cycle of the process/product. Although the most common and relevant impact is the Environmental Impact, life cycle impacts on climate change, human toxicity, eco-toxicity, depletion of natural resources, depletion of energy resources, on land degradation, on water resources and on cost can as well be evaluated based on the life cycle inventory data. The LCIA phase comprises of selecting impact categories, assignment of the LCI results to the selected impact categories, selection of category indicators and characterization models, calculation of the category indicator results and the final impact.After the selection of the impact category, the next step is to assign the LCI results to impact categories. There are LCI results that are exclusive to one impact category and there are LCI results that relate to more than one impact category. For example, concentrations of CO_2 and methane can be assigned exclusively to Global Warming Potential whereas SO_2 contributes to both Acidification and Eutrophication potential and CFC's contribute to both Global Warming Potential and Stratospheric Ozone Depletion Potential. In the assignment of LCI results, distinction must be made between parallel mechanisms (e.g. SO_2 is in parallel apportioned between the impact categories of human health and acidification) and serial mechanisms (NO_xcan be classified partly to contribute to ground-level ozone formation and partly to acidification). The category indicators are quantified representation of the impact category. There are mid-point category indicators that are relevant in the short run and end-point category indicators that are relevant in the long run. For example, if the selected impact category is "Climate Change" reflected by Global Warming, the mid-point category indicator can be Infra Red radiative forcing (W/m^2) and end-point category indicator could be loss of life in years or fraction of species that has disappeared. The relevant LCI data for this purpose would be the output concentrations of CO_2, methane, CFC's and halogens for all the unit processes within the system boundary. Similarly, if one were analyzing the "Environmental Impact" of which one of the parameters is the Acidification potential, then the mid-point category indicator would be pH and end-point category indicator can be disappearance of plant species and the relevant LCI data are concentration of nitrogen oxides, sulphur di oxide, halogens, H_2S etc. The calculation of indicator results or characterization involves the conversion of LCI results to common units and the aggregation of the converted results within the same impact category. For example, for the impact category of "Global Warming Potential", all the output data on CO_2, methane, CFC's and halogens is converted to kg-equivalent of CO_2. Similarly, for the impact category of "Acidification Potential", all the output data on nitrogen oxides, sulphur di oxide, halogens, H_2S etc is converted to kg-equivalent of SO_2. This conversion uses characterization factors. Characterisation models describe the relationship between the LCI results, category indicators and, in some cases, category endpoint(s). Characterisation models have been developed and reported in the literature for most of the impact categories [5-7]. Some of the sources have a collection of characterisation models [8-14].For measuring climate change, there exists a characterisation model developed by the Intergovernmental Panel on Climate Change (IPCC) [5].

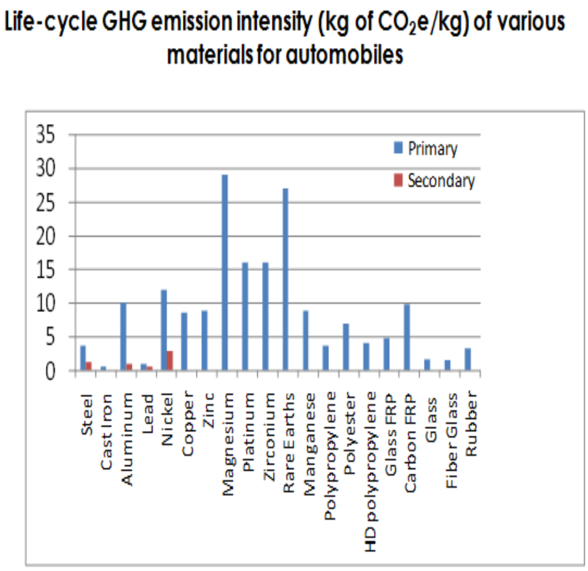
The Life Cycle Interpretation phases comprises of identification of the significant issues based on the results of LCI and LCIA, an evaluation of the completeness, consistency and sensitivity of LCI & LCIA, flagging the limitations and drawing up of conclusions and recommendations. The results are clearly sensitive to the exact assumptionsmade and the LCA results are context specific, place specific, time specific and technology specific.

Among the several types of impact analysis that can be carried out, the most relevant ones from an Engineer or Material Scientist's point of view is Environmental impact, Embodied Energy Analysis, Exergy Analysis, Material Flow Accounting, Embodied water Analysis and Life Cycle Costing.

Embodied Energy is the sum of all the primary energy consumed to produce any goods or services, considered as if that energy was incorporated or 'embodied' in the product itself ie., the primary energy consumed to mine, beneficiate, extract, process, transport, and produce a good (or service). It implies all the energy requirements associated with the production of the good or service. That includes the sum of the direct and indirect energy associated with the product or activity, i.e., all energy must be primary and traced upstream to their origin.One can similarly define embodied water for any product. The life cycle embodied energy of various materials used in automobiles and the GHG emission impact thereof is given below [15]:



Data from Keoleian & Sullivan, MRS Bulletin, 37, 2012, p.368



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Note that steel has one of the lowest life cycle embodied energy among all the materials used in automobiles including Al and Mg. Although light alloys of Al and Mg consume less energy in the "Use" stage compared to Steel, they consume four to six times the energy as Steel in the production and manufacturing process.

Exergy of a system is the maximum useful work possible during a process that brings the system to equilibrium i.e., utilizable energy of the system. After the system & surroundings reach equilibrium, the exergy is zero. Each input to the system is accounted for in terms of its exergy content and each output is evaluated for its exergy content. The ratio of the exergy content of the system's output to the sum of the input exergies is a measure of the maximum conversion efficiency attainable under reversible conditions.

Material input per unit of service (MIPS) is a measure of eco-efficiency of a product or service. The calculation takes into account materials required to produce a product or service. The total material input (MI) is divided by the number of service units (S). The whole life cycle of a product or service is measured when MIPS values are calculated. MIPS method can be used to measure natural resource consumption in 5-categories, viz. abiotic and biotic resources, earth movements in agriculture & silviculture, water and air. Abiotic resources refer to non-renewable resources like minerals, fossil energy sources and soil excavations. Biotic resources refer to renewable resources like plant biomass. Earth movements include mechanical movements and erosion. Water includes surface, ground and deep ground water used by humans. Air is calculated when it is used in combustion processes or chemically or physically transformed.

The life-cycle assessment techniques are in the stages of development as a scientific discipline. However, rapid progress is being made in this field with respect to development of softwares for a complete life cycle assessment, comprehensive Life Cycle Inventory database development, data validation through mass and energy balances, data analysis etc. Today, several softwares and programs including databases such as GABI, SIMAPro, GREET (Greenhouse Gases, Regulated Emissions and Energy Use in Transportation Model), TRACI (Tool for the Reduction and Assessment of Chemical and other Environmental Impacts), BEES (Building for Environmental & Economic Sustainability developed by NIST, US), GEMIS (Global Emission Model for Integrated Systems), USETox etc. are available for Life Cycle Assessment of materials and processes in various applications. However, since the LCI data for any unit process depends on the geography, time at which the data was collected, the nature of technology, the energy mix (extent of renewable&non-renewable energy) in the various countries etc., one can't readily use these databases either out of place or out of context or at a different time. Many countries such as Japan, Korea, USA, Thailand, Germany and Canada have national level LCA programs and/or national level databases which can be used for conducting a LCA study. Analyses such as Embodied Energy Analysis, Life Cycle Emissions Analysis, Embodied Water Analysis, Exergy Efficiency etc. are extremely useful in decision making on technology selection, strategic planning, public policy making and import-export decisions for the government.

India has set itself an ambitious growth rate target in double digits which also includesa significant increase in the growth rate of the manufacturing sector. Any growth in the manufacturing sector will have to be sustainable in terms of the impact on natural resources including energy resources, utilities such as air and water, environmental impact and socio-economic impact. As a country, we should be able to scientifically quantify these to enable decision making on a scientific basis and based on data. It is therefore imperative that India as a country launches a National Life Cycle Assessment Initiative as also creates a country-specific database that will enable a comprehensive life cycle assessment study as a basis of decision making on priority.

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