CSTEP

Machine Level Energy Efficiency Analysis in Discrete Manufacturing for a Sustainable Energy Infrastructure

Technical report 2009011

December 2009

Appeared in the proceedings of the Second Annual International Conference on Infrastructure Systems and Services: Developing 21st Century Infrastructure Networks, Chennai, organized by The Center for Study of Science, Technology and Policy (CSTEP), in collaboration with the Technical University of Delft (Netherlands) and the Next Generation Infrastructures Foundation (NGIF) and the IEEE.

CENTER FOR STUDY OF SCIENCE TECHNOLOGY AND POLICY

Machine Level Energy Efficiency Analysis in Discrete Manufacturing for a Sustainable Energy Infrastructure

S.S. Krishnan, *Senior Member, IEEE*, N. Balasubramanian, Eswaran Subrahmanian, V. Arun Kumar, G. Ramakrishna, A. Murali Ramakrishnan and Ajay Krishnamurthy

***Abstract*— Sustainable economic development necessitates a careful design of the energy infrastructure. The energy infrastructure is primarily composed of energy producers on the supply side, the energy consumers on the demand side and the network which connects them. The increasing energy demand, the spiraling cost of capacity addition and the global climate change scenario have put the energy infrastructure under enormous pressure. Reducing the demand by leveraging energy efficiency techniques is a major viable option towards redesigning the energy infrastructure. Energy efficiency analysis provides a basis for developing a detailed trajectory towards reduced energy consumption and sustainability. We present results of energy efficiency analysis at the machine level in the manufacturing sector which is a major user of the energy infrastructure.**

I. Energy Infrastructure and Manufacturing

The energy infrastructure is a critical requirement for accelerated economic growth. The hectic pace of economic growth witnessed in many countries of the world such as India, has placed enormous pressure on the energy infrastructure. The energy demand is growing rapidly and the capacity additions are lagging behind. The global climate change scenario has magnified the energy demand problem since energy generation is largely based on fossil fuels and will continue to do so into the foreseeable future. Sustainability of human society has been brought sharply into focus due to the realization that "Business as Usual" (BAU) cannot continue much further due to the rapid depletion and degradation of the environment.

A study by the Indian Council for Research on International Economic Relations that looked at the relationship between an infrastructure indicator and performance of the manufacturing sector in India showed that there are strong disparities across states, with Maharashtra, Gujarat, Punjab and Tamil Nadu being best equipped in terms of infrastructure (Figure 1) [1]. Barring Punjab, these are also the states in which the manufacturing sector contributes significantly to the states' GDP. Figure 2 show the relationship between manufacturing share and state of power availability. It is clear that states with better availability of infrastructure have seen a higher growth of manufacturing.

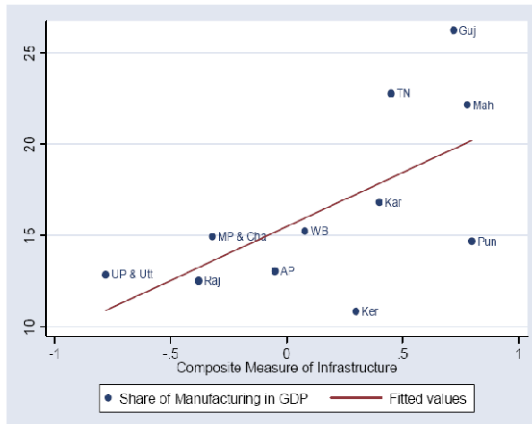

Figure 1. Significance of Infrastructure for the Manufacturing Sector

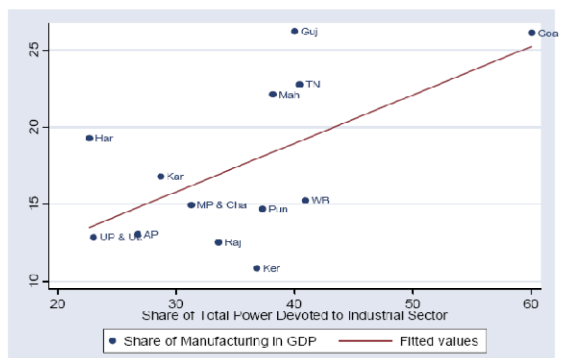

Figure 2. Significance of Power for the Manufacturing Sector

A UNIDO background paper on manufacturing concludes that the comparison of energy-use intensities by country groups and individual countries also supports the proposition that there still remains significant potential to reduce energy-use intensity and the associated CO_2 emissions [2]. According to a report by the World Energy Council [3], the Kyoto Protocol objectives and, more recently, the constraints on energy supply have increased the attention given to energy efficiency policies. Beside market instruments: voluntary agreements, labels, information dissemination and others, regulatory measures are effective where the market fails to give the right signals (e.g. buildings or appliances).

Manuscript received September 9, 2009.

All authors are with the Center for Study of Science, Technology and Policy, CAIR Building, Raj Bhavan Circle, Bangalore 560 001, India (First three authors' email: ssk@cstep.in, nbalu23@cstep.in, sub@cstep.in)

978-1-4244-5791-5/09/$25.00

Energy efficiency (EE) techniques provide a powerful tool with which energy demand can be controlled and reduced in energy consuming components of the energy infrastructure. The Bureau of Energy Efficiency (BEE) in India estimates [4] a large amount of avoided capacity additions attributed to savings in electrical energy demand side consumption as shown in Figure 3.

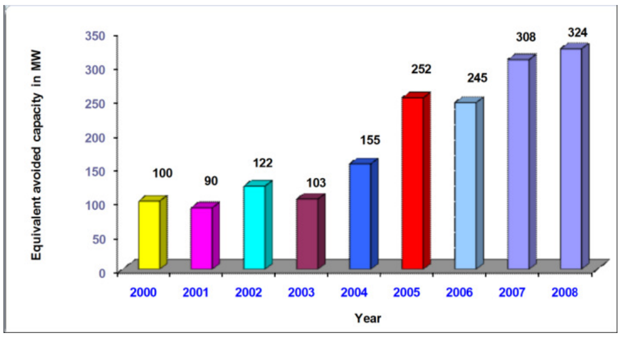

Figure 3. Electrical Energy Saving in terms of Equivalent Avoided Capacity in MW (2000-2008, BEE)

A draft report of the expert committee of the Integrated Energy Policy of the Planning Commission [5], Government of India, states that the importance of energy efficiency and DSM has clearly emerged from the various supply scenarios and is underlined by the rising oil prices. Efficiency can be increased in energy extraction, energy conversion, energy transportation, as well as in energy consumption. It may be noted that a unit of energy saved by a user is greater than a unit produced, as it saves on production losses, transport and transmission and distribution losses. Thus a "Negawatt" (a negative megawatt), produced by reducing energy need saves more than a Megawatt generated.

The Integrated Energy Policy report [5] showed that at 8 percent growth rate we will nearly double our capital stock in nine years. Energy using equipment and appliances will also spread rapidly. Thus, the manufacturers of equipment and appliances should be targeted to force the pace of energy efficiency improvement. The Super Energy Efficient Refrigerator Project in the US is a successful example shown in Figure 4.

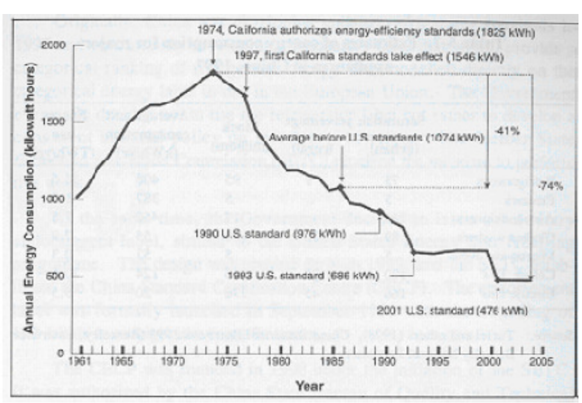

Figure 4. Reduction in the Energy Consumption of Refrigerators sold in the United States of America

The increasing competition among manufacturers has resulted in greater emphasis on high performance and low cost for products. The issues of environmental sustainability and global warming have lead to increased awareness of energy consumption in the product lifecycle. The energy consumed in the entire product lifecycle has become an important design criterion and this paradigm will assume an ever increasing role during product design in the years to come.

An International Technology Research Institute (ITRI) study asked, Is "environmentally benign manufacturing" (EBM) an oxymoron [6]? Manufacturing has a large impact on the environment among industrial activities in the US and similarly worldwide. Manufacturing industries are dominant in their environmental impact in such areas as toxic chemicals, waste, energy, and carbon emissions [6]. It is fairly clear that manufacturing—and in particular metals processing and polymer processing and other energy-intensive processes—deserve our attention for their potential impacts on the environment.

II. A SUSTAINABLE MANUFACTURING MODEL

Manufacturing is commonly thought of as a simple open system into which flows various resources for conversion, and out of which flows products, wastes and pollution. However, one could take a much more extensive view of this problem [6]. If we take the systems view of manufacturing, and track the consequences of manufacturing and design decisions throughout the entire product development cycle, this would take us through (1) raw materials production, (2) manufacturing, (3) the use phase, and finally to (4) the end-of-life phase. This is a far broader view of manufacturing than the one that simply looks at the consumption, wastes and pollutants occurring at the factory. These two different views of manufacturing can be seen in Figure 5.

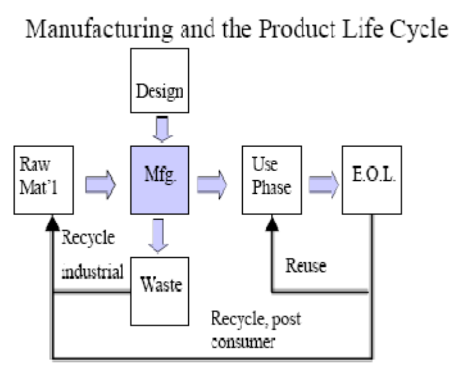

Figure 5. A closed systems view of manufacturing showing all major activities and reuse and recycle paths. Source [6]

A process model of sustainable manufacturing has been presented by researchers at the Center for the Study of Science and Technology (CSTEP) [7]. In this model, shown in Figure 6, the major process activities are represented. Each of these activities has an impact on the environment where an impact can be defined as a material or energy flow in either direction. Some activities such as raw material mining, energy production, manufacturing, use phase, recycling and others have a direct impact on the environment. For example, a car has a direct impact during its use phase. Some activities such as the design process and the maintenance and end-of-life analysis have an indirect impact in that these activities have the potential to substantively alter the direct impact of other activities. This study shows that for a completely sustainable manufacturing model, all the processes must interact with the environment through the sustainable infrastructure layer. They define sustainability analysis to be the set of all activities that can reduce the impact of activities on the environment. Some activities listed under sustainable analysis are energy efficiency, material and energy flow, waste flow, total environmental impact and their associated technical, economic and other analyses.

The Sustainable Manufacturing (SM) Process Model also details the sequence of processes that occur in the life cycle of manufacturing. The raw material mining and energy production feed the manufacturing plant with required inputs. Inputs also come in from design processes which drive the manufacturing process. The product is also subject to routine and periodic maintenance analysis checks which may feedback with retrofit activities that modify or upgrade the plant. When no further retrofits are deemed to be cost effective, then the end-of-life has been reached and this leads to recycling activities which may partition the material into those that can used up in a next round of manufacturing and those that need to be disposed of in an environmentally benign manner.

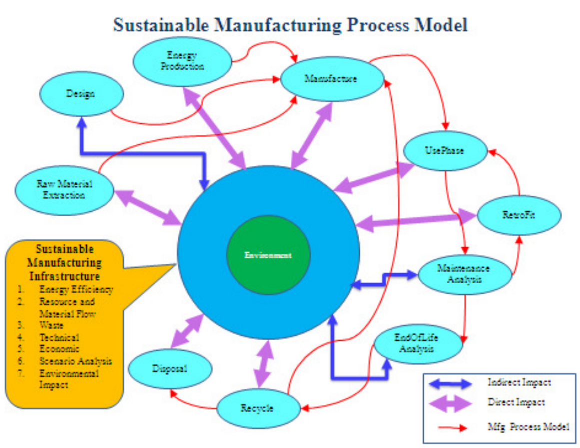

Figure 6. A systems view of the sustainable manufacturing process model

The CSTEP researchers [7] also provided a component view of the sustainable manufacturing infrastructure shown in Figure 7. This view represents all of the stakeholders who comprise the SM infrastructure. Each of the institutional stakeholders forms an aggregation relationship, in UML terminology, with the SM infrastructure. This report states that sustainability cannot be described as a separate activity that can be taught, trained, learned or practiced independent of the target domain. Sustainability has to be integrated into the various activities that comprise the current economic processes of human endeavor. In SM, sustainability analysis has to be incorporated into the different components shown in the SM infrastructure model. Each activity of the SM process model has to perform its entire repertoire of sub-activities while treating sustainability considerations as an additional factor. This may be treated in various formulations by different components as an optimization function, a hard constraint, a soft constraint, a policy option, a policy mechanism guideline, a compliance target parameter or in other ways such as a modification of societal preferences, value systems and demands. However, the fact remains that in a systems view of the SM process model, sustainability needs to be urgently integrated into the current set of activities.

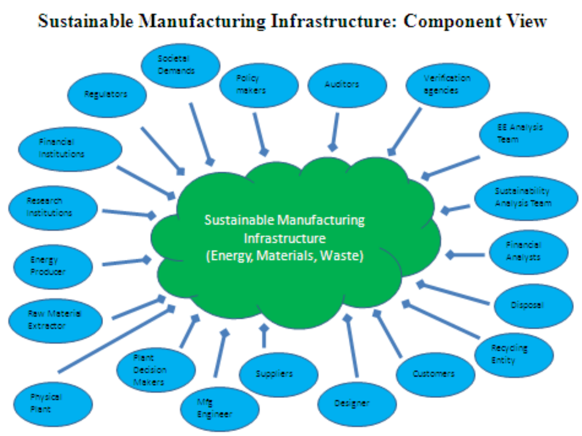

Figure 7. A component view of the sustainable manufacturing infrastructure model.

III. ENERGY EFFICIENCY IN MANUFACTURING

The energy consumed by a manufacturing process is a major direct measure of its impact on the environment. The energy consumed usually translates to the amount of energy that has been produced from fossil-fired plants or captive generators. The energy consumed by a process thus has a strong link with the amount of fossil fuels consumed and therefore to the depletion and degradation of the environment and also to climate change issues as a fallout of the resulting CO_2 emissions [7]. The sustainability benefits are further magnified given that reducing a unit of energy consumption on the demand side has a multiplier effect and results in a savings of about five to ten units of raw input energy on the supply side.

Energy intensity is a major indicator of the energy consumption of a manufacturing process or plant. This typically refers to the amount of energy consumed to produce a unit weight or volume of a product. This value usually is associated with energy efficiency as well in an inverse relationship. Hence, if the energy intensity of a process is high, its energy efficiency is low and vice versa. The energy intensity is also referred to as the Specific Energy Consumption or the SEC of a process [7].

The CSTEP Report mentions that the goal of increased energy efficiency has multiple driving factors. The first is the gap in the energy demand and supply components of the energy infrastructure. Capacity additions are extremely capital and labor intensive and are long term projects with significant negative impact on the environment. Secondly, the global warming and climate change scenario places a responsibility on any sustainability infrastructure to tightly measure, audit, verify, control and mitigate CO_2 and GHG emissions. The Sustainable Manufacturing Model has to focus on energy efficiency as a core activity since energy consumption has a major impact on the sustainability measure of any aspect of human endeavor [7].

In their paper [8], NIST researchers, proposed the idea of introducing sustainability in terms of energy efficiency into computer aided process planning to complement cost, quality and time to arrive at alternate sustainable plans or schedules in identified manufacturing processes. They also sought to initiate dialogue regarding the potential usefulness of the energy readings of manufacturing equipments and to identify collaboration opportunities.

Usually the series of production steps involved in manufacturing are automated in the case of high throughput processes [9]. For some processes each of these steps can be integrated into a single piece of equipment. For example, a modern milling machine can include a wide variety of functions including work handling, lubrication, chip removal, tool changing, and tool break detection, all in addition to the basic function of the machine tool, which is to cut metal by plastic deformation. The energy required by the additional functions can be a large fraction of the total energy consumption of the machine. At lower production rates the machining contribution is even smaller. This behavior is also found in other processes. In general, there is a significant energy requirement to start-up and maintain the equipment in a "ready" position. Once in the "ready" position, there is then an additional requirement which is proportional to the quantity of material being processed.

IV. ENERGY REQUIREMENTS IN PLASTICS MOLDING

Injection molding appears to be on the same order of magnitude in terms of energy consumption when compared to other conventional manufacturing processes [10]. For instance, processes such as sand and die casting have similar energy requirements (11-15 MJ/kg). However, the impact of injection molding seems insignificant when compared to processes used in the semi-conductor industry, such as chemical vapor deposition and atomic layer deposition. This is not entirely accurate and in order to understand the real impact of a manufacturing system one has to consider how widespread its use is in the economy. Injection molding is one of the predominant manufacturing processes, and its use is increasing daily in growing economies like China and India. Energy related emissions refer to those emissions originated from the generation of electricity necessary to run the processes.

Figure 8 portrays the power requirement for a hybrid and an all-electric machine both running the same part with a cycle time of 14 seconds [10]. Simple inspection reveals substantial energy savings from using all-electric over hybrid technology. Note that the curve for a hydraulic machine would be even higher than that of the hybrid. For hydraulic and hybrid machines SEC seems to exhibit a decreasing behavior with increasing throughput, as portrayed in Figure 9. This derives from spreading fixed energy costs over more kilograms of polymer as throughput increases. The power in a hydraulic and hybrid can be described as:

$$P = P_0 + k\dot{m} \qquad (1)$$

where,

$$P_0 = fn(hydraulic\ pumps, computer, etc.)$$

k = *extra SEC to process the polymer*

where Po is the fixed power requirement (power required when the machine is on, but not processing any polymer), $\dot{m}$ is the throughput or process rate, and k is a processing constant. In terms of SEC, this formula can be expressed as:

$$\frac{P}{\dot{m}} = \frac{E}{m} = SEC = \frac{P_0}{\dot{m}} + k \qquad (2)$$

As throughput increases, SEC approaches the constant k as observed in Fig. 9.

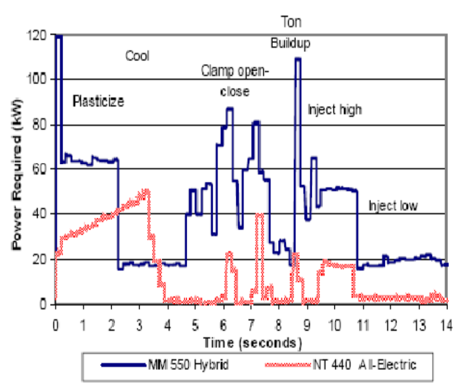

Figure 8. Energy consumed in the injection molding cycle of a hybrid (electric screw drive) and an all-electric machine. Source: [10].

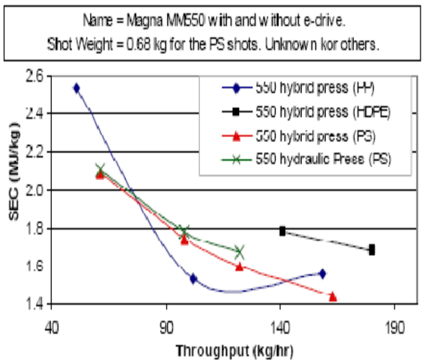

Figure 9.SEC vs. throughput for a Magna MM550, hydraulic and hybrid. There is no inclusion of the efficiency of the electric grid. Source: [10].

V. ENERGY MEASUREMENTS DURING PLASTICS PROCESSING

Energy consumption depends on a variety of different factors [11]:

a. Type and characteristics of the plastic (for instance, each material has a different melting temperature)
b. Design, complexity, and size of the end product. The greater the pressure on the mold, the more energy is consumed.
c. Each technique used for the shaping of the product has its own SEC, depending on heating, molding and cooling.
d. The higher the quantity of production, the lower the SEC.
e. The cycle time determines how long the pump or electrical motor is switched on during the molding process.
f. Size of the machine
g. Frequency of use of the mold
h. Outside temperature (there is a 10 per cent higher consumption in the summer)

a. Energy Consumption in Injection Molding:

We have carried out energy measurements for a variety of hydraulic injection molding machines. A summary of the SEC across different machines is shown in Figure 10. It is observed that there is a wide band of SEC across different machines and across different material flow rates.

We have made the following observations:
The SEC tends to rise initially and then stabilizes at a lower value as the total material processed increases.

1. The SEC tends to be higher for lower flow rates and lower for higher flow rates.
2. The final summary graphs also show how the machines perform with respect to each other while comparing SEC to flow rate/throughput.

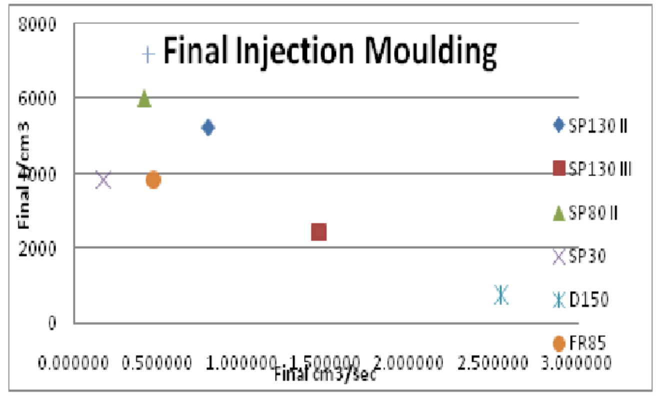

Figure 10. SEC for multiple Injection Molding machines as a function of throughput

3. The general SEC values for IM are between: 1 - 7 MJ/kg, assuming a grid efficiency of 33%.
4. Across machines, it is observed that some machines have lower SEC values for a given throughput.

b. Energy Consumption in Compression Molding

We have also carried out energy measurements for a variety of compression molding machines. A summary of the SEC across different machines is shown in Figure 11. It is observed that there is a wide band of SEC across different machines and across different material flow rates. We have also made the following observations:
The SEC tends to rise initially and then stabilizes at a lower value as the total material processed increases

1. The SEC tends to be higher for lower flow rates and lower for higher flow rates.
2. The final summary graphs also show how the machines perform with respect to each other while comparing SEC to flow rate/throughput.
3. T he general SEC values for CM are between: 1 - 13 MJ/kg. , assuming a grid efficiency of 33%.
4. Across machines, it is observed that some machines have lower SEC values for a given throughput.

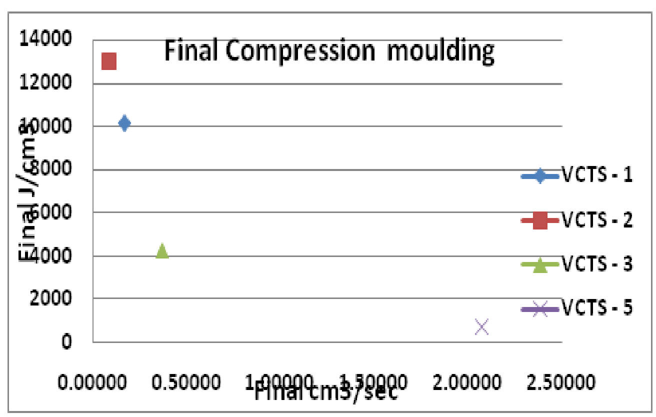

Figure 11. SEC for multiple Compression Molding machines as a function of throughput

VI. ENERGY MEASUREMENTS DURING SHEET METAL WORKING

We have carried out various measurements during sheet metal forming operations. We have performed energy intensity (SEC) calculations using these measurements and have preliminary results that we will present in this section. We have obtained energy consumption data for a wide category of machine tonnage capacities, two examples are shown in Figures 12 and 13.

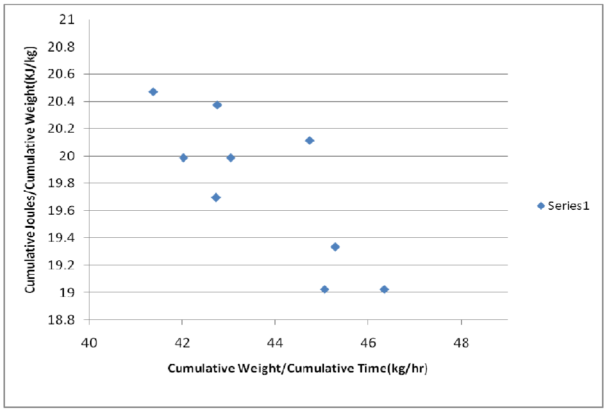

Figure 12. SEC for a 40Ton sheet metal forming machine as a function of throughput

In general the preliminary results show that:

1. The SEC in sheet-metal working is inversely proportional to the throughput. As the throughput increases, the SEC reduces and vice versa.
2. We also observed that the SEC reduces as the total material processed increases, subject to flow-rate changes.
3. The inverse relationship of the SEC to the throughput was also retained when the throughput changed either in the early stage or the middle stages of the entire measurement period.

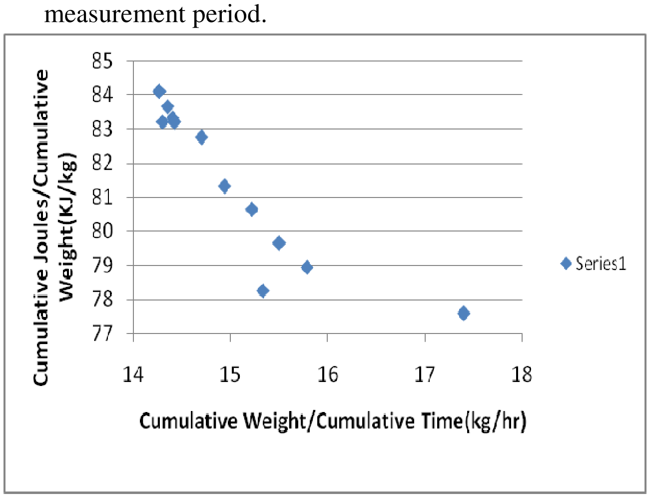

Figure 13. SEC for a 160Ton sheet metal forming machine as a function of throughput

VII. CONCLUSIONS

In this work, we have described a model of sustainable manufacturing and showed a process model for a sustainable manufacturing (SM) infrastructure. We also described the components which make up the SM infrastructure. We identified energy efficiency as an important component of SM which needs to be leveraged to provide maximal sustainability benefits. We have made preliminary measurements and energy efficiency analysis of individual machines in different manufacturing processes such as injection molding, compression molding and sheet metal working. We propose to continue and extend the energy efficiency analysis for more manufacturing processes and to a greater depth and at all levels of a manufacturing plant.

ACKNOWLEDGEMENT

We gratefully acknowledge the cooperation extended to us by NTTF where we carried out the energy measurements described in this paper. We also gratefully acknowledge the SSN Educational and Charitable Trust and the Jamshetji Tata Trust for their support of the above work.

REFERENCES

[1] Rajiv Kumar and A.S. Gupta, "Towards A Competitive Manufacturing Sector," Working Paper No. 203, Indian Council for Research on International Economic Relations, February 2008.

[2] UNIDO, "Energy Use by, and CO2 Emissions from the Manufacturing Sector in Selected Countries," Background Paper, Prepared for Expert Group Meeting: Using Energy Management Standards to stimulate persistent application of Energy Efficiency in Industry, Vienna, Austria, March 21-22, 2007.

[3] "Energy Efficiency Policies around the World: Review and Evaluation Executive Summary," World Energy Council 2008.

[4] G. Pandian, "Role of Energy Efficiency in Policy of India," Bureau of Energy Efficiency, Govt. of India, June 2009. (Accessed August 2009.)

[5] Draft Report of the Expert Committee on Integrated Energy policy, Planning Commission, Government of India, December 2005.

[6] T.Gutowski (Panel Chair), C.F. Murphy (Panel Co-chair) et al, "Wtec Panel Report On Environmentally Benign Manufacturing", *International Technology Research Institute*, April 2001.

[7] S.S. Krishnan and Eswaran Subrahmanian, "An Integrated Systems Model of Sustainable Manufacturing," Center for Study of Science Technology and Policy (CSTEP), Technical Report, July 2009.

[8] M.Mani, S.Rachuri, E.Subrahmanian, K.W.Lyons, R.D.Sriram, "Introducing Sustainability Analysis Early into Manufacturing Process Planning," In *Proceedings of the 14th International Conference on Manufacturing Science and Engineering*, Evanston, IL, USA., October 2008.

[9] T.Gutowski, J.Dahmus, and A.Thiriez, "Electrical Energy Requirements for Manufacturing Processes," in *Proc. 13th CIRP International Conference on Life Cycle Engineering,* Leuven, 2006.

[10] A.Thiriez and T.Gutowski, "An Environmental Analysis of Injection Molding," In *ISEE*, 2006.

[11] Leonardo Energy, "Power Capacity and Utilization Guide, *Plastics Industry Report*," www.leonardo-energy.org, January, 2009, accessed June 16, 2009.