

Electrical Energy Requirements for Manufacturing Processes

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Abstract

This paper collapses the specific electrical energy requirements for a wide range of manufacturing processes into a single plot. The analysis is cast in an exergy framework. The results show: 1) the specific energy requirements for manufacturing processes are not constant as many life cycle analysis tools assume, 2) the most important variable for estimating this energy requirement is the process rate, and 3) the trend in manufacturing process development is toward more and more energy intensive processes. The analysis presented here also provides insight into how equipment can be redesigned in order to be more energy efficient.

Keywords

Energy, Exergy, Manufacturing Processes

1 INTRODUCTION

Manufacturing processes include a wide variety of operations, from subtractive processes such as machining and grinding, to net shape processes such as injection molding, to additive processes such as chemical vapor deposition (CVD) and sputtering. All of these manufacturing processes take material inputs, including working materials and auxiliary materials, and transform them into products and wastes. Similarly, the energy inputs into these processes (primarily from electricity) are transformed into useful work, some of which is embodied into the form and composition of the products and wastes, and waste heat. In addition, the energy inputs usually require fuels and produce emissions. For electrical energy inputs, this occurs at the power station. A manufacturing process, along with material and energy flows to and from the process, is diagrammed in Figure 1.

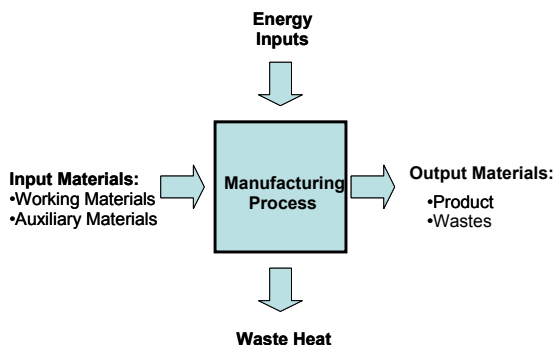


Figure 1: Energy and Material Inputs and Outputs for Manufacturing Processes.

2 EXERGY FRAMEWORK

In attempting to account for the many different flows into and out of a manufacturing process, the thermodynamic concept of exergy or “available work” can greatly simplify the problem. Exergy, as defined by Szargut, is “the amount of work obtainable when some matter is brought to a state of thermodynamic equilibrium with the common components of the natural surroundings by means of reversible processes involving interaction only with the above mentioned components of nature” [1]. For

additional exergy information, see Sato and de Swaan Aarons [2, 3].

Exergy, therefore, measures the potential of materials to do work. Fuels naturally have high values of exergy, but many other working materials, including pure metals, plastics and other organics, can have equally high values. The advantage to using exergy is that it allows material and energy inputs and outputs to be expressed in the same unit, usually joules (J). Secondly, since the development of the concept of exergy is based upon the second law of thermodynamics, and not the first, it is not conserved. Hence this metric provides a measure of what is actually “used up” in the manufacturing process. As a result, a complex energy and material flow problem can be substantially simplified by using exergy analysis. There are two steps: 1) identify the system boundaries, and 2) identify the exergy inputs and outputs. The difference between the inputs and the outputs is the exergy lost. This is given in equation 1.

$$B_{in} - B_{out} = B_{lost} \quad (1)$$

This formulation can be used to account for material transformations, including the conversion of raw working materials into products, wastes, and emissions, and the conversion of fuels (through combustion) into heat (to do work), wastes, and emissions. The concept can also incorporate all other energy sources, for example hydro, solar, electrochemical, and others, but these are of less concern in this paper. In a few cases, the conversion of raw materials and the conversion of fuel will take place in a single physical process, such as the reduction of iron ore to iron by the use of coke. In this case, coke acts not only as a reducing agent but also as a fuel. An example of this can be seen in Baumgartner [4]. However, in the vast majority of cases, the working materials transformation and the fuel transformation will take place as separate, though connected, activities. Perhaps the most straightforward example of this, which in the case of interest here, is the conversion of fuels to produce electricity to power the materials conversion process. This would be true, for example, for machining, grinding, injection molding, electrical discharge machining (EDM), chemical vapor deposition (CVD), and others, which are all powered by a chemical reaction at the power station

that provides the electricity to transform materials at the factory.

In these cases, the separate processes, one involving working materials and one involving fuels, could be combined and evaluated according to equation 1. Or, alternatively, they could be treated separately according to equation 1 and then combined. In this paper, which focuses on the electrical energy requirements, the two activities are considered separately. Furthermore, in looking at the electrical energy requirements, the connection to the actual fuels used is left as a separate exercise which can vary depending on the local electrical grid characteristics. An example later in the paper will illustrate this step.

Finally, in order to fully evaluate the performance of manufacturing processes, the system boundaries for this evaluation should include not only the manufacturing process per se, but also the production of the materials (working and auxiliary non-fuel materials) needed for the process. This allows for an evaluation of both the material exergy requirements for the inputs as well as the potential exergy destruction in working materials during the process. These issues are dealt with elsewhere, and are thus not addressed in the analysis presented here [5].

For the immediate purposes of this paper, the focus is placed on the electrical energy requirements of the manufacturing process. It is convenient to think of a manufacturing process as being made up of a collection of equipment needed to perform the steps of the process. Here only the major piece of equipment that is used for each process, for example the milling machining, is considered. Other auxiliary equipment that would be used with the process, for example a saw and tumbler with a milling machining, could be characterized in the same way as presented for the major piece of equipment. These results for the auxiliary equipment and the major equipment can then be combined to provide a complete picture of the process.

3 ELECTRICITY REQUIREMENTS FOR MANUFACTURING PROCESSES

Manufacturing processes are made up of a series of processing steps, which for high production situations are usually automated. 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 result is that these additional functions can often dominate energy requirements. This is shown in Figure 2 for an automotive machining line. In this case, the maximum energy requirement for the actual machining is only 14.8% of the total. At lower production rates the machining contribution is even smaller. Other processes exhibit this same behaviour. 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. This situation is modelled in equation 2.

$$P = P_o + k\dot{v} \tag{2}$$

Where P = total power, in kW

P_o = idle power, in kW

\dot{v} = the rate of material processing in cm³/sec,

and

k = a constant, with units of kJ/cm³

The specific electrical exergy per unit of material processed¹, B_{elect} , in units of kJ/cm³, is then

$$B_{elect} = \frac{P}{\dot{v}} + k \tag{3}$$

In general, the term P_o comes from the equipment features required to support the process, while k comes from the physics of the process. For example, for a cutting tool, P_o comes from the coolant pump, hydraulic pump, computer console and other idling equipment, while k is the specific cutting energy which is closely related to the work piece hardness and the specifics of the cutting mechanics. For a thermal process, P_o comes from the power required to maintain the furnace at the proper temperature, while k is related to the incremental heat required to raise the temperature of a unit of product.

Evidence for the relationship given by equations 2 and 3 is shown for machining operations in Figures 2 and 3, and for injection molding operations in Figure 4. Other examples are available in the literature. For example, Murphy offers data and a model for the thermal oxidative process used in semiconductor manufacturing which follows the same relationship as in equation 3 [6].

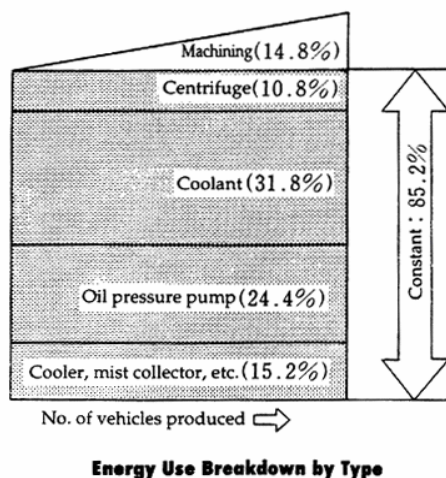


Figure 2: Energy used as a function of production rate for an automobile production machining line [7].

¹ Here electricity is treated as pure exergy. Full exergy accounting would follow this electricity back to the fuels used in the power plant.

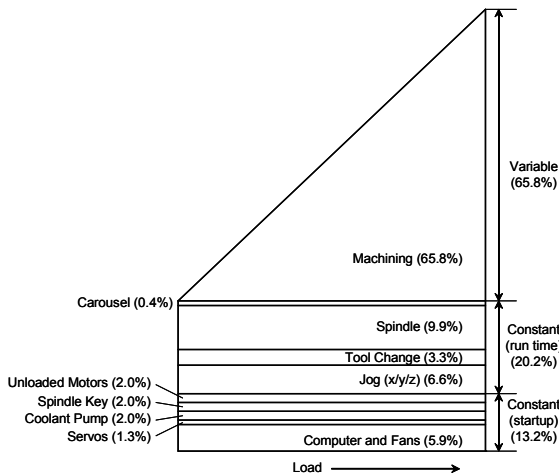


Figure 3: Energy used as a function of material removal rate for a 3-axis CNC milling machine [8].

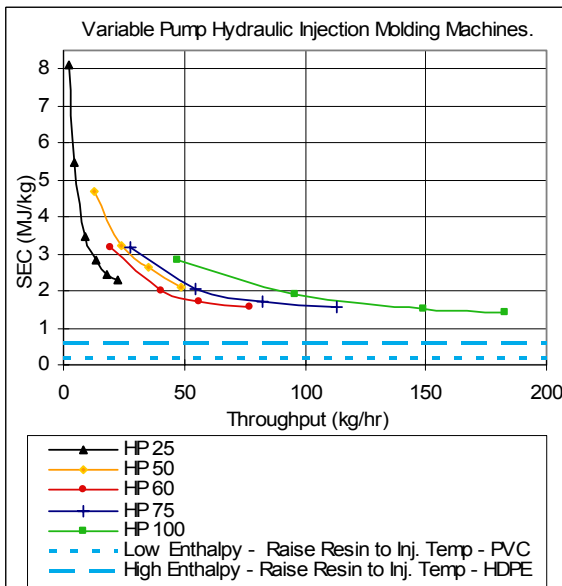


Figure 4: Energy used for various hydraulic injection molding machines as a function of throughput [9].

One important conclusion from this generalization is that the specific exergy of a manufacturing process is a strong function of throughput. Unlike the estimates often made in LCA software, specific process energy (exergy) is not a constant, and can vary substantially; in fact, it is infinite at idle $\dot{v} = 0$. While idling equipment is of course eventually shut down, operating at less than full capacity is not uncommon at all.

A second observation is that over the very broad range of manufacturing processes, the total power requirement for any given process will vary only by one or two orders of magnitude, while the range in material throughput can vary by 10 orders of magnitude or more. That is, electrical standards and shipping convenience have constrained most manufacturing equipment to the range of 5 to 50 kW. On the other hand, new technologies (and low energy prices) have moved manufacturing processes into higher precision and smaller size scales. These new processes, which often operate in the vapor phase, have much smaller throughputs in terms of the unit of material

operated on in a unit of time. The result is a rather orderly progression of manufacturing processes into lower and lower processing rates and higher and higher specific electricity requirements. This trend is displayed in Figure 5 for 36 examples from 10 different manufacturing processes. This figure was constructed from a variety of sources listed in Table 1. Note that an individual process can move up in electricity requirement by operating at a lower process rate. This happens, for example, when a milling machine is used for finish machining versus rough machining, or when a CVD process operates on 1 wafer versus 250 wafers at a time.

Note that the data in Figure 5 may require further modification in order to agree with typical estimates of energy (exergy) consumption by manufacturing processes given in the literature. For example, the data in Figure 5 for injection molding, given by Thiriez, averages about 3 kJ/cm³. Assuming a polymer density of 1 g/cm³ and a grid efficiency of 33%, the yields a specific energy value of 10 MJ/kg. However, most injection molding operations include a variety of additional sub-processes such as extrusion, compounding, and drying, all of which add substantially to the exergy totals. If these additional pieces of equipment are also included they result a value for injection molding of about 20 MJ/kg which agrees with the literature [9, 10, 11].

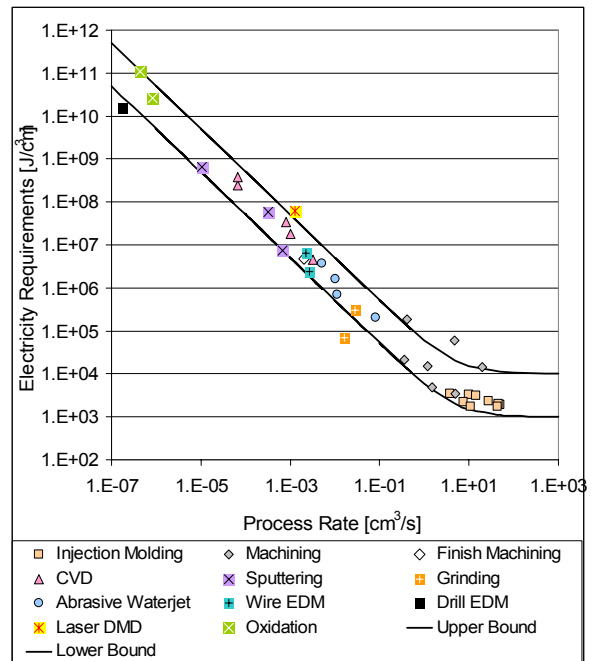


Figure 5: Specific electricity requirements for various manufacturing processes as a function of the rate of material processed.

4 CLOSING COMMENTS

Figure 5 and equation 3 provide a simple conceptual model for estimating the electrical energy requirements for a manufacturing process. This information is needed for Life Cycle Analysis and other environmental accounting problems. The data shows that to a first approximation the most important characteristic of a process is its rate of production. This is because the specific electrical energy requirement is often dominated by the support features of the equipment rather than the actual physical mechanism

of the process. This suggests two important strategies for redesigning manufacturing processes to minimize energy use. The first is the redesign of support equipment. For example, the redesign of machine tools and injection molding machines from hydraulic to all electric has significantly reduced the specific energy (exergy) used by these machines. This is illustrated in Figure 6, where data is plotted for hydraulic and all-electric injection molding machines of similar size [9]. The other strategy is to increase the rate at which the physical mechanism can perform the desired operation. This strategy is illustrated by the significant improvements in cutting tools over the last century which have resulted in reductions in machining times by about two orders of magnitude [12, 13]. The result is higher throughput rates and lower specific energy requirements. It is important to note that these two strategies are often coupled; adding energy consuming support equipment is done precisely because it allows higher throughput.

The data in Figure 5 can also be viewed in a historical sense. In general, the processes in the lower right hand corner of the figure are older, more conventional processes, while those in the upper left hand corner are newer micro-electronics and advanced machining processes. These more modern processes can work to finer dimensions and smaller scales, but also work at lower rates, resulting in very large specific electrical energy requirements. In short, the historical trend seems to be towards more energy-intensive manufacturing processes.

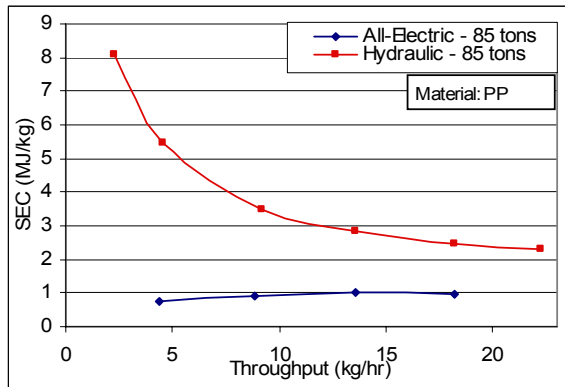


Figure 6: Comparison of specific energy usage for similar sized hydraulic and all-electric injection molding machines as a function of material throughput [9].

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REFERENCES

[1] Szargut, J., Morris, D.R., & Steward, F.R., 1988, Exergy Analysis of Thermal Chemical and Metallurgical Processes, Hemisphere Publishing Corporation and Springer-Verlag, New York, NY, USA.
 [2] Sato, N., 2004, Chemical Energy and Exergy – An Introduction to Chemical Thermodynamics for Engineers, Elsevier, New York, NY, USA.

Process Name	Estimates			Note	References
	Power Required kW	Process Rate cm ³ /s	Electricity Required J/cm ³		
Injection Molding	10.76	3.76E+00	3.41E+03	----	[9]
	26.10	9.77E+00	3.21E+03	----	
	71.40	5.05E+01	1.96E+03	----	
	35.76	1.40E+01	3.09E+03	----	
	47.46	2.70E+01	2.30E+03	----	
	65.34	4.51E+01	1.99E+03	----	
	12.73	7.66E+00	2.20E+03	----	
	13.17	1.09E+01	1.75E+03	----	
Machining	51.41	4.25E+01	1.75E+03	----	[14]
	194.80	2.00E+01	1.42E+04	----	
	194.80	4.70E+00	6.00E+04	----	
	10.65	5.00E+00	3.50E+03	----	
	10.65	1.20E+00	1.50E+04	----	
	2.80	1.50E+00	4.90E+03	----	
	2.80	3.50E-01	2.10E+04	----	
Finish Machining	75.16	4.01E-01	1.87E+05	a	[15, 16]
CVD	9.59	2.05E-03	4.68E+06	a	[15, 16]
Sputtering	16.00	6.54E-05	2.44E+08	----	[6]
	15.00	3.24E-03	4.63E+06	b	[17]
	14.78	9.63E-04	2.66E+07	b	[18]
	25.00	1.65E-03	1.52E+07	d	[19]
Grinding	6.75	1.05E-05	6.45E+08	b	[17]
	19.50	3.25E-04	6.01E+07	b	
	5.04	6.70E-04	7.52E+06	----	
Waterjet	7.50	2.85E-02	3.08E+05	b	[21, 22]
	10.00	1.66E-02	6.92E+04	----	[21]
Wire EDM	16.00	1.04E-02	1.58E+06	----	[23]
	16.00	8.01E-02	2.06E+05	----	
	8.16	1.14E-02	7.15E+05	a	
	8.16	5.15E-03	3.66E+06	a	
Drill EDM	14.25	2.23E-03	6.39E+06	----	[12, 24]
	6.60	2.71E-03	2.44E+06	c	[25]
Laser DMD	2.63	1.70E-07	1.54E+10	b	[26, 27]
Oxidation	80.00	1.28E-03	6.24E+07	b	[15]
	21.00	8.18E-07	2.57E+10	d	
	48.00	4.36E-07	1.10E+11	d	[6]

Notes/Assumptions:
 a = Required power is back-calculated from SEC (in MJ/kg or J/cm³) and throughput (cm³/s).
 b = Power required is assumed to be 75% of rated power.
 c = Power required is equal to rated power since the machine is operating at maximum throughput.
 d = If both idle and run power are provided, the machine is assumed to run 100% of the time.

Table 1: Data for Figure 5

[3] de Swaan Aarons, J., van der Kooi, H., Shankaranarayanan, K., 2004, Efficiency and Sustainability in the Energy and Chemical Industries, Marcel Dekker Inc, New York, NY, USA.
 [4] Baumgartner, S., de Swaan Aarons, J., 2003, Necessity and Inefficiency in the Generation of Waste, Journal of Industrial Ecology, 7/2:113-123.

- [5] Gutowski, T., Dahmus, J., Dalquist, S., Thiriez, A., 2005, Chemical Exergy Models for Manufacturing Processes – Working Paper LMP 1-2006, Massachusetts Institute of Technology, Cambridge, MA, USA.
- [6] Murphy, C.F., Kenig, G.A. Allen, D., Laurent, J.-P., Dyer, D.E., 2003, Development of Parametric Material, Energy, and Emission Inventories for Wafer Fabrication in the Semiconductor Industry, Environmental Science & Technology, 37/23: 5373-5382.
- [7] Gutowski, T., Murphy, C., Allen, D., Bauer, D., Bras, B., Piwonka, T., Sheng, P., Sutherland, J., Thurston, D., Wolff, E., 2005, Environmentally Benign Manufacturing: Observations from Japan, Europe and the United States, Journal of Cleaner Production, 13: 1-17.
- [8] Kordonowy, D.N., 2001, A Power Assessment of Machining Tools, Massachusetts Institute of Technology, B.S. Thesis, Department of Mechanical Engineering, Cambridge, MA, USA.
- [9] Thiriez, A., An Environmental Analysis of Injection Molding, 2005, Massachusetts Institute of Technology, Project for M.S. Thesis, Department of Mechanical Engineering, Cambridge, MA, USA.
- [10] Boustead, I., 2002, Eco-profiles of the European Plastics Industry: PVC Conversion Processes, APME, Brussels, Belgium. Visited: 25 Feb. 2005 <http://www.apme.org/dashboard/business_layer/template.asp?url=http://www.apme.org/media/public_documents/20021009_123742/EcoProfile_PVC_conversion_Oct2002.pdf>
- [11] Boustead, I., 2003, Eco-profiles of the European Plastics Industry: Conversion Processes for Polyolefins, APME, Brussels, Belgium. Visited: 25 Feb. 2005 <http://www.apme.org/dashboard/business_layer/template.asp?url=http://www.apme.org/media/public_documents/20040610_153828/PolyolefinsConversionReport_Nov2003.pdf>
- [12] Kalpakjian, S., Schmid, S.R., 2001, Manufacturing Engineering and Technology, Fourth Edition, Prentice Hall, Upper Saddle River, NJ, USA.
- [13] Sandvik Coromant, 1996, Modern Metal Cutting: A Practical Handbook. Fair Lawn, NJ, USA.
- [14] Dahmus, J., Gutowski, T., 2004, An Environmental Analysis of Machining, ASME International Mechanical Engineering Congress and RD&D Expo, Anaheim, CA, USA.
- [15] Morrow, W.R., Qi, H., Kim, I., Mazumder, J., Skerlos, S.J., 2004, Laser-Based and Conventional Tool and Die Manufacturing: Comparison of Environmental Aspects, Proceedings of Global Conference on Sustainable Product Development and Life Cycle Engineering, Berlin, Germany, 103-110.
- [16] Polgar, K.C., 1996, Simplified Time Estimation Booklet for Basic Machining Operations. Massachusetts Institute of Technology, M.S. Thesis, Department of Mechanical Engineering, Cambridge, MA, USA.
- [17] Wolf, S., Tauber, R.N., 1986, Silicon Processing for the VLSI Era. Volume 1 - Process Technology, Lattice Press, Sunset Beach, CA, USA.
- [18] Novellus Concept One - 200 mm Dielectric System, 1992, Users Guide to 200mm PECVD Processing, Novellus Systems Inc., San Jose, CA, USA.
- [19] Krishnan, N., Earth Institute Research Fellow and Instructor at Columbia University. Personal communication by email: nk2162@columbia.edu. 8 Jul. 2005.
- [20] Holland, H., Technician at AJA International, Inc. Telephone interview. Tel: (781)-545-7365. 9 June 2005.
- [21] Baniszewski, B., 2005, An Environmental Impact Analysis of Grinding, Massachusetts Institute of Technology, B.S. Thesis, Department of Mechanical Engineering, Cambridge, MA, USA.
- [22] Chryssolouris, G., 1991, Laser Machining Theory and Practice. Springer-Verlag, New York, NY, USA.
- [23] Kurd, M., 2004, The Material and Energy Flow Through the Abrasive Waterjet Machining and Recycling Processes, Massachusetts Institute of Technology, B.S. Thesis, Department of Mechanical Engineering, Cambridge, MA, USA.
- [24] Product literature, Sodick Co Ltd, CNC Wire-cut EDM, Model Selection Guide, Japan.
- [25] Product literature, A U -500i A , AU-300iA, AU-700iA & AU-1000iA, Accutex, Accuracy & Technology Leading Company, Accutex International Co., Ltd, Visited: 12 Dec. 2005 <http://www.accutex.com.tw/e_au-300ia.htm>.
- [26] Product literature, "NC Drill EDM Machines" King Edm Ltd. Visited: 12 Dec. 2005 <<http://www.manufacturers.com.tw/showroom-6464-4-5-000009919-0.php>>.
- [27] McGeough, J.A., 1988, Advance Methods of Machining, Chapman and Hall, New York, NY, USA.

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