Title

Energy Use per Worker-Hour: Evaluating the Contribution of Labor to Manufacturing Energy Use

Authors

Zhang, Teresa
Dornfeld, David

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Evaluating the Contribution of Labor to Manufacturing Energy Use

Teresa W. Zhang and David A. Dornfeld
Laboratory for Manufacturing and Sustainability
Department of Mechanical Engineering
University of California at Berkeley

Abstract

Energy use is an important metric of environmental impact and manufacturing efficiency. However, a major component of energy analysis has yet to permeate life-cycle analysis methodology: the energy use associated with human labor. This paper presents a straightforward method of estimating the energy demands of an hour of industrial labor based on readily available national statistics. In the United States, this estimate yields 64 MJ of primary energy use per worker-hour (EPWH). These results can be applied to inform and expand the applications of process-based and hybrid economic input-output life-cycle assessment.

Keywords:
Energy use; Labor; Major Manufacturing Countries

1 INTRODUCTION

Energy is an important metric of environmental impact and manufacturing efficiency. A key parameter of life-cycle assessment (LCA) is energy consumption, as it can dominate environmental impacts such as global warming potential, carcinogenic emissions, and acidification potential. Energy assessment is also effective as an indicator of manufacturing efficiency. As yield, manufacturing cycle efficiency, process capability, and other manufacturing performance metrics improve, energy use per unit output decreases accordingly.

The metric of energy use was popularized largely due to the work of Howard Odum, who has written numerous books on energy and environmental accounting since the 1970's including [1],[2], and [3]. In [4], he presents several methods of quantifying the energy use of labor, in terms of metabolic energy, national fuel share, national emergy share, and as a function of the level of education enjoyed by a worker.

Boustead and Hancock also discuss the energy use of labor in the form of caloric content of food consumed [5]. Calculated as such, they ultimately conclude that the energy contribution of human labor to energy use is negligible.

We argue that the energy associated with human labor must include the energy of infrastructure in addition to that of food, where infrastructure includes housing, transportation, health care, etc. If defined in this way, the energy use of labor can be a significant contributor to manufacturing energy use.

Like economic input-output (EIO) LCA, the methodology presented herein aims to quantify environmental impacts that may not be included in process-based LCA. Because both EIO-LCA and the energy use of labor take a top-down approach, presenting averages for an industry or country, they do so without tremendously increasing the work of LCA practitioners.

Energy use of labor and EIO-LCA should not be applied to the same component of analysis because many sources of energy use would be double counted. However, energy use of labor can be very effective if incorporated into hybrid EIO-LCA, as shown in Figure 1, where EIO-LCA is used to assess activity upstream of the process-based analysis. The energy use of labor enriches the horizontal scope of process-based LCA, while EIO captures vertical supply chain impacts.

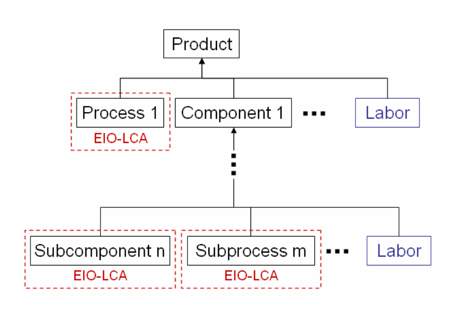

Figure 1: Schematic of process-based LCA and energy use of labor applied in series with economic input-output LCA.

In addition to improving the accuracy of LCA, evaluating the energy use of labor can be applied to extend the decision making capabilities of LCA. The energy use of labor enables us to quantify and inform decisions that introduce or reduce workers, deal with the location of a plant, or involve labor intensive process steps. Detailed examples of such applications are given in Section 3.

Hannon [6], Kakela [7], Pindyck [8], Welsch [9], and Kemfert [10] thoroughly document the substitutions of energy, labor and/or capital equipment that occur under various scenarios, yet until now, the degree to which these substitutions should occur has not been possible to ascertain.

The energy use of labor consequently helps address the disparities between environmental and economic accounting. Environmental analysis largely ignores labor, while the cost of labor factors very heavily into economic analysis. Evaluating the energy use of labor can help reduce the gap between those who prioritize environment and those who prioritize economics.

Finally, human capital, like environmental capital, has externalities that can be passed from a manufacturing system to society at large. For example, manufacturers who pay workers less than a livable wage rely on social programs to support their workforce. The energy use of labor is a tool with which we can begin to account for the environmental externalities of labor.

2 ESTIMATES OF ENERGY USE PER WORKER-HOUR

Three straightforward methods of estimating energy use per worker-hour (EPWH) are presented to produce a lower bound, an upper bound, and a value appropriate for use in life-cycle assessment. As shown in Table 1, the methods are respectively derived from human metabolic activity, total primary energy supply, and non-industrial energy supply.

Method	EPWH (MJ)
Metabolic Activity – Lower Bound	0.5
Primary Energy Supply – Upper Bound	100
Non-Industrial Energy Supply – Recommended for Life-Cycle Assessment	64

Table 1: US estimates of energy use per worker-hour.

2.1 Metabolic Activity

A lower bound estimate of energy use per worker-hour is given by human metabolic activity. An active individual can expend 2800 kilocalories per day or, on average, 0.5 MJ per hour. However, this method fails to consider the much greater amount of energy embodied in and used in the infrastructure employed to support labor. Nor does this consider efficiency losses from food production to digestion.

2.2 Primary Energy Supply

An upper bound estimate is given by amortizing a country or region's energy supply across its worker population and over the number of hours in a year.

In *Environmental Accounting*, Odum calculate the national fuel share per person based on the general population [4]. Based on 1993 data, he concluded that 967 MJ are expended per capita per day or approximately 40 MJ per capita per hour.

However, not all members of the general population are productive workers at any given time. Just as a machine tool must be manufactured and have an end of life, a worker must have a childhood and an end of life. By amortizing energy use over the worker population, we account for the full life cycle of the worker. We therefore allocate energy use over the worker population, as opposed to the general population, to give us a better estimate of the contribution of labor to the energy use of a production system.

This upper bound estimate considers all the infrastructure and services that go into supporting a worker in terms of primary energy. Primary energy is measured in the units of tons of oil equivalent (TOE). Unlike final consumption in the form of refined fuels or electricity, primary energy captures all transformation and distribution losses.

However, energy use per worker-hour calculated based on primary energy cannot be used as a component of process-based life-cycle assessment because this method double counts industrial energy use.

2.3 Non-Industrial Energy Supply

A better estimate of energy use per worker-hour for the industrial sector is derived from non-industrial energy supply, which includes all primary energy except that supplied to industry, as given by Equation 1.

$$EPWH = \frac{TPES - IPES}{population \times hours / year} \tag{1}$$

where *TPES* is a country or region's total primary energy supply and *IPES* is industrial primary energy supply. *IPES* can be replaced with primary energy supply to other sectors of the economy or specific industrial sectors, such as the petrochemical sector, to reflect a particular product or process.

Energy use per worker-hour, in terms of primary energy, captures the energy mix and efficiencies in transformation and distribution for a given region. However, *IPES* is not always readily available, so we approximate it using industrial final consumption (*IFC*) and total final consumption (*TFC*) of energy as follows

$$IPES = TPES \times \frac{IFC}{TFC} \tag{2}$$

This assumes the ratio of final consumption to primary energy supply for industry is representative of the ratio of final consumption to primary energy supply for the country. Countries with industries that consume disproportionately more primary energy than the country at large are penalized by this assumption, resulting in a larger value of EPWH.

The International Energy Agency (IEA) regularly compiles and publishes values for *TPES*, *IFC*, and *TFC* from each country or region in its purview [11],[12]. As defined by the IEA, the industrial sector includes mining, smelting and construction but does not include transportation used by industry. The most current data available reflects 2004 activity.

The International Labour Organization (ILO) is a branch of the United Nations that similarly compiles employment statistics on an annual basis [13]. Worker populations include civilian workers over an employment age, which is typically 14-16 years of age. Though there are disparities in what each country reports, data from the IEA and the ILO is likely more reliable than data compiled from each country directly.

Of the three methods discussed, amortizing non-industrial energy supply yields the most accurate estimate of energy use per industrial worker-hour for use in process-based or hybrid economic input-output life-cycle assessment. This method is applied and discussed in the remainder of this paper.

3 APPLICATIONS

The energy use of labor in the United States is significant relative to the energy use of a machine tool and of labor in other major manufacturing countries and regions. The energy use of labor may also be used to more accurately evaluate labor intensive processes and industries.

3.1 Man vs. Machine

Though there are significant differences between the capabilities of a worker and a machine tool, it is an interesting exercise to compare their relative energy demands. In the US, electricity production from primary energy is approximately 35% efficient [14]. This conversion factor is used to compare primary EPWH with machine tool electricity use.

As shown in Figure 2, the 2.9 kWh of electricity equivalent EPWH that we equate to 30 MJ of primary EPWH is comparable to the power consumption of an automated milling machine but is considerably less than that of a production scale machining center [15].

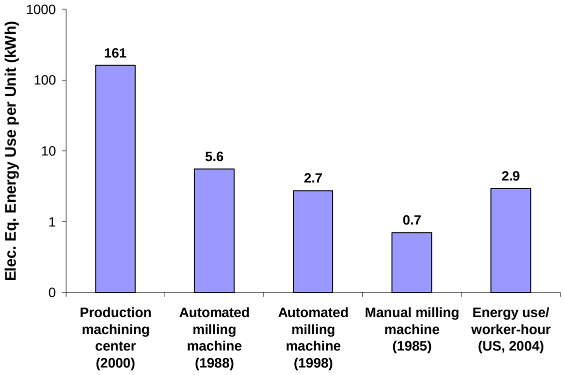

Figure 2: Electricity equivalent energy use per worker-hour in the US based on 2004 data as compared to the hourly electricity requirements of four common milling machines produced in the years indicated, adapted from Dahmus [15]. Note the semi-log scale.

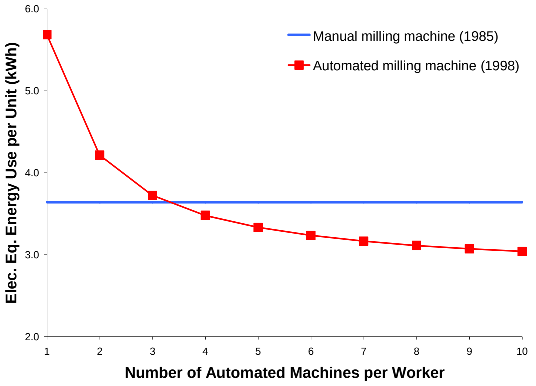

Figure 3: Electricity equivalent energy use, including labor and machine operation, for manual and automated machine configurations.

Dahmus [15] presents a thorough analysis of machining, including material production, cutting fluid preparation, and operation of all components of the milling machine itself. We can obtain an even more complete assessment of total energy use by expanding the analysis to include labor.

Assuming the manual milling machine requires one worker to operate, a worker-hour contributes 2.9 kWh to the 0.7 kWh the machine consumes directly each hour. The actual energy impact of manual milling is therefore five times greater than previously thought. As a component of process-based LCA, this higher energy use may be reflected in a wide range of products and services.

A decision making application of energy use per worker-hour is shown in Figure 3 for Dahmus' milling machines. If a worker is able to operate four or more machines at a time, it is advantageous from an energy point of view to employ the automated milling machine even though it directly uses four times more energy per hour than the manual milling machine. Energy use per part will scale with production rate for each machine.

3.2 Major Manufacturing Countries

The methodology discussed in Section 2.3 can be easily applied to any region with records of *TPES*, *IFC*, *TFC*, and worker populations, such as those reporting to the International Energy Agency [11],[12] and the International Labour Organization [13]. Major manufacturing countries demonstrate a wide range of energy use per worker-hour values, as shown in Figure 4 and Table 2.

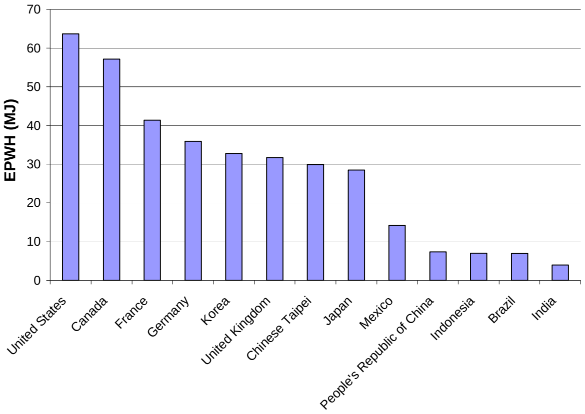

Figure 4: Primary energy use per worker-hour in major manufacturing countries and regions [11],[12],[13].

These differences can be attributed to a complex set of factors. A very important factor is undoubtedly population. With the exception of the United States, the five most populous countries evaluated represent the countries with the lowest values for energy per worker-hour.

There is also an inverse relationship between EPWH and ratio of industrial final consumption to total final consumption. For the countries evaluated, this ratio ranges from 19% for the United States to 41% for China. In general, the more a country expends in manufacturing, the less energy is expended per worker-hour. These trends may suggest relationships between service and manufacturing economies and development, or they may simply be attributed to the calculation of EPWH.

Country	Total Primary Energy Supply	Industrial Final Consumption	Total Final Consumption	Worker Population (million)	EPWH (MJ)
	(EJ/year)				
Brazil	8.6	2.9	7.2	85	7.0
Canada	11	2.4	8.5	16	57
China, People's Republic of	67	18	44	610	7.4
Chinese Taipei	4.4	0.93	2.7	11	30
France	12	1.6	7.2	25	41
Germany	15	2.2	11	37	36
India	24	4.0	17	520	4.0
Indonesia	7.3	1.1	5.5	95	7.0
Japan	22	4.3	15	64	29
Korea	8.9	1.6	6.0	23	33
Mexico	6.9	1.1	4.4	41	14
United Kingdom	9.8	1.4	6.9	28	32
United States	97	13	67	140	64

Table 2: Data for Figure 2 [11],[12],[13]. Note that as defined by the IEA, the People's Republic of China does not include Chinese Taipei. Exajoule (EJ) = 10^{12} MJ.

The necessity of excluding industrial energy use from the calculations, as discussed in Section 2.3, is observed when comparing net importers and net exporters. For example, consider the $214 billion trade deficit between the United States and China in 2006. Energy used in China to manufacture goods for sale in the United States does not contribute to the Chinese EPWH. Meanwhile, energy the United States imports in the form of products can be captured by process-based LCA.

For simplicity, these results do not consider geographic differences in the number of workers employed for any given task or the purchasing power and related energy consumption of industry workers compared to the general population.

3.3 Labor Intensive Processes

Without quantifying the energy use of labor, it is easy to underestimate the environmental impacts of labor intensive processes, such as those used in product installation, maintenance, repair, and recycling.

For example, energy payback time analyses for solar cells often do not consider panel installation, even though it is a major component of their financial cost. Evaluating the energy use of labor is necessary to determine the impact of expensive and labor-intensive solar cell installation on energy payback time.

Labor-intensive sorting processes for recycling are another important application of the energy use of labor. It is important to know the degree to which the energy expended in sorting processes counteracts the energy savings of recycling. There many benefits to recycling outside of energy savings, but the ratio of energy inputs, including that of labor, to energy savings can serve as a measure of efficiency for recycling operations.

3.4 Labor Intensive Industries

The degree of labor required between industries can vary dramatically. Agriculture, handcraft, textile, and service industries are especially labor-intensive. These industries have typically not been the subject of life-cycle analysis, even though their products are consumed in relatively large quantities. Process-based LCA would in fact grossly underreport the environmental costs of a service or an entirely handmade product.

It is also interesting to note that new industries, such as the renewable energy and nanotechnology industries, typically employ more workers per unit output than more established industries [16]. Emerging industries may present problems for LCA practitioners seeking to perform comprehensive assessments. As EIO-LCA data is not yet available for the industry in question, new technologies must be assessed using process-based or hybrid EIO-LCA. Evaluating the energy use of labor is therefore especially valuable to accurately assess the environmental impacts of new technologies and industries.

3.5 Price of Forms of Energy

The prices of various forms of energy are well documented and understood. It is interesting from an economic and social point of view to understand how labor of a given sector is priced with respect to other forms of energy.

4 DISCUSSION

Amortizing non-industrial energy supply produces a simple estimate of energy use per worker-hour. However, there are questions regarding how to apply this information.

At first glance, Figure 2 appears to present a strong argument for the exportation of labor-intensive industries. Yet, energy savings in labor can be easily overturned by energy use in transportation. Intercontinental shipping can consume 1.8 MJ per container-mile, based on industry standard emissions of 85 g CO_2 per container-km [17]. In the United States, a container truck expends 750 MJ per mile [18], in addition to the energy use of the operator. Energy analysis may be a useful tool for siting manufacturing facilities, but the energy requirements of both labor and transportation must be considered.

However, industrial final consumption does not include industrial transportation. This means that the energy use of industrial transport is not subtracted from Equation 1, and is therefore encompassed by energy use per worker-hour. If used in conjunction with process-based LCA, energy use per worker-hour double counts the energy use of industrial transportation. This is a major drawback of this technique that must be addressed to be used with process-based transportation inventories.

It is also not entirely straightforward to decide the number of worker-hours to evaluate in life-cycle assessment. An employee may work eight hours a day, but he or she will continue to expend energy outside of work. Manufacturers reap the rewards of the energy expended during worker-hours in the form of value added to their products and should be responsible for a proportional amount of energy. For the purposes of process-based life-cycle assessment, we recommend calculating the energy corresponding to the number of hours actually worked.

However, one can argue that employers, as a whole, are responsible for the economic activity and corresponding energy consumption employees enjoy outside of work as a result of their hours worked. While the economic activity of both employer and employee are required to sustain manufacturing, consider a factory that employs all workers for only four hours a day. Twice the numbers of workers are needed compared to an identical factory employing workers for eight hours a day. Though these half-time employees would be compensated less and enjoy less economic activity, it is doubtful that their energy demands would be half of that of their full-time colleagues.

Another factor to consider is the effect of feedback. A facility built in a low energy use per worker-hour area may find that its presence spurs economic activity, development, and in turn, increased energy use per worker-hour. It is important to note that energy use, industrial activity, and population can change over time. To be meaningful, energy use per worker-hour should reflect up-to-date statistics.

5 CONCLUSION

Evaluating energy use per worker-hour is a simple and effective way to improve the accuracy and scope of life-cycle energy analysis. This paper makes note of energy use per worker-hour as it compares to a machine tool and to worker-hours in other major manufacturing regions. The potential applications of the energy use of labor in life-cycle assessment are exceedingly broad.

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7 REFERENCES

[1] Odum, H. T., 1971, Environment, Power, and Society, Wiley-Interscience, New York.

[2] Odum, H. T., Odum, E. C., 1976, Energy Basis for Man and Nature, McGraw-Hill, New York.

[3] Odum, H.T., 1983, Systems Ecology: An Introduction, Wiley and Sons, New York.

[4] Odum, H. T., 1996, Environmental Accounting: Emergy and Environmental Decision Making, Wiley and Sons, New York.

[5] Boustead, I., Hancock, G. F., 1979, Handbook of Industrial Energy Analysis, Wiley and Sons, New York.

[6] Hannon, B., Stein, R. G., Segal, B. Z., Serber, D., 1978, Energy and Labor in the Construction Sector, Science, 202: 837-847.

[7] Kakela, P. J., 1978, Iron Ore: Energy, Labor, and Capital Changes with Technology, Science, 202, 1151-1157.

[8] Pindyck, R. S., 1979, Interfuel Substitution and the Industrial Demand for Energy, The Review of Economics and Statistics, 61/2:169-179.

[9] Welsch, H., 1996, Recycling of Carbon/Energy Taxes and the Labor Market, Environmental and Resource Economics, 8:141-155.

[10] Kemfert, C., Welsch, H., 2000, Energy-Capital-Labor Substitution and the Economic Effects of CO_2 Abatement, Policy Modeling, 22:641-660.

[11] International Energy Agency (IEA), 2006, Energy Balances of OECD Countries, Organization for Economic Co-operation and Development (OECD). 2004 data.

[12] International Energy Agency (IEA), 2006, Energy Balances of non-OECD Countries, Organization for Economic Co-operation and Development (OECD). 2004 data.

[13] International Labour Organization (ILO), 2006, Yearbook of Labour Statistics 2006, 65th issue. United Nations (UN).

[14] Energy Information Administration (EIA), 2005, Annual Energy Review 2005, US Department of Energy (DOE).

[15] Dahmus, J. B., Gutowski, T. G., 2004, An Environmental Analysis of Machining, In Proceedings of the ASME International Mechanical Engineering Congress and RD&D Expo, November 13-19, 2004, Anaheim, California USA.

[16] Kammen, D. M., Kapadia, K., Fripp, M., 2004, Putting Renewables to Work: How Many Jobs Can the Clean Energy Industry Generate? Renewable and Appropriate Energy Laboratory Report.

[17] Brutsaert, K., Maritime Engineer, JWD Group, DMJM Harris, Personal communication, February - March 2007.

[18] Gaines, L., Stodolsky, F., Cuenca, R., 1998, Lifecycle Analysis for Heavy Vehicles, In Air and Waste Management Association Annual Meeting.