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A Tool to Estimate Materials and Manufacturing Energy for a Product

N. Duque Ciceri, T. G. Gutowski, M. Garetti

Abstract— **This study proposes an easy-to-use methodology to estimate the materials embodied energy and manufacturing energy for a product. The tool requires as input the product's Bill of Materials and the knowledge on how these materials are processed (or an educated guess); the resulting output represents the sum of all the energy inputs into a product system in the form of a value range on the energy requirements of the product during its beginning of life. This includes extraction of materials, processing, and manufacture of the final product.**

***Index Terms*—Energy, Life Cycle Assessment, Life Cycle Energy**

I. INTRODUCTION

While different methodologies have already been created for this purpose such as the well-known Life Cycle Assessment (LCA) - where one of its main outputs is the energy requirements through the different stages of the product - these studies are very extensive, requiring data that are not easily available and taking a great deal of time to be completed. LCA results in the topic of sustainable manufacturing, by now, have become the "bottom line" of many other studies that represent advances in the subject. A common approach used for performing an LCA involves hiring a consulting firm to conduct the study on a given product. Consultants may use privately owned softwares and databases, methods and assumptions for the analysis involving also the collection of primary data to support their study, resulting on a list of impacts at the unit process level. This resulting database is the Life Cycle Inventory (LCI) providing a detailed description of all of the impacts associated with each process during the life of a product. These studies are then used to provide the client results of the analysis and opportunities for improvement. A review of available Life Cycle estimates however, can show significant disagreement, even between seemingly identical products for studies conducted by reputable practitioners. Additionally, LCAs are so communly used and mis-used, that are becoming a "black box" where people use it not really knowing what is inside of the study. The purpose of this study is to develop a tool that can quickly and transparently estimate the energy requirements for the materials and manufacturing phases of a product. Thus, existing LCI's can be quickly double checked and new products can be estimated even early in the design stage.

II. RESEARCH METHODOLOGY

The main research method used in this project was an extensive literature review involving the research of publicly available data on: 1) materials embodied energy figures, 2) emperical data of energy studies on the most common manufacturing processes, 3) product Bill of Materials (BOM) and 4) published Life Cycle Inventories of products. The first three constitute the main components for the construction of the proposed tool, while the last one serves as the point of comparison to validate the results from the tool and verify the reliability of these estimations. An overview on the results of this review is as follows:

1. MATERIALS EMBODIED ENERGY

The energy that must be commited to create 1 kg of usable material (e.g. 1 kg of steel stock, or of PET pellets, or of cement powder) measured in MJ/kg. In general, the embodied energy of the materials is dominant when compared to the manufacturing energy requirements to process the materials. The database contains a total of 74 entries on the materials embodied energy mainly from two realiable and updated sources [1],[2].

2. MANUFACTURING PROCESSING ENERGY

Data from empirical energy studies is compiled. Figures are given as a range value measured in MJ/kg, categorized in the main type of materials as follows:

2.1. Metals

Studies reporting the energy intensity at the technology level are considered. For instance, in the case of iron casting, the range depending production melting technonologies

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(furnaces): Cupola melting, heel electric induction, batch electric induction. The value reported and used in this methodology is 19 MJ/kg – 29 MJ/kg [3]. Other studies on conventional and advanced manufacturing processes were considered. Table 1 summarises these figures included in this methodology.

TABLE 1. EMPERICAL MANUFACTURING ENERGY STUDIES

Manufacturing Process	Energy Requirement Range (MJ/kg processed)	Source
Coventional Manufacturing		
Machining	5.3 - 7.5	[4]
Milling	1.3 - 2.6	
Grinding	8.8	[5]
Iron Casting	19 - 29	[3]
Sand casting	11.6 - 15.4	[6]
die casting	14.9	[7]
Forging	16.3	[8]
Finish Machining	24	[9]
Advanced Manufacturing		
Waterjet (Nylon)	150 - 214	[10]
Waterjet (Steel)	167 - 238	
Waterjet (Al)	195 - 1670	

2.2. Plastics (Polymers)

This category is treated for plastics that are injection molded. In this process of injection molding, the choice of machine type (hydraulic, hybrid or all-electric) has a substantial impact on the specific energy consumption (SEC). The SEC values for hydraulic, hybrid and all-electric machines used are 19.0, 13.2 and 12.6 MJ/kg respectively [11].

2.3. Composites

A recently published study compiling results from 15 different processes of composite materials is integrated in this methodology [12], including pultrusion (hybrid), reinforced plastics (e.g. spay up, resin transfer molding, glass fabric, autoclave molding) among others. Energy intensities range from 3 to 20 MJ/kg on these various manufacturing processes.

In general, most of these energy figures on conventional manufacturing processes for metals (with the exception of advanced processes, which have higher processing rates and therefore higher energy intensities [13]) plastics and processing of many composites, roughly fall within the range of 1 to 30 MJ/kg. Further in this paper, as an exercise, this range will be applied for the products manufacturing energy in general, to simplify and make a "quick check" of the application of this tool.

2.4. Semiconductors

This category may be the exeption case, where manufacturing processing energy can be as high as the materials embodied energy. Studies on the energy inputs on semiconductors manufacturing are not many and the few existing are grueling to understand and draw a generalization. The complexity of the processes involved during the wafer manufacturing stage (may require upward of 400 distinct process steps [14]) makes evident the scarcity of such studies. In order to derive an estimation on the energy into the electronics manufacturing, the following formally established classification of sub-industries was used [15]: (i) Wafer manufacturing (ii) Chip level packaging (iii) Printed Wiring Board (PWB) manufacture (iv) Board-level assembly (v) Display manufaturing (vi) Final assembly.

From literature, it appears that the energy for semiconductors manufacturing, should be normalized per area of wafer instead of kg per chip. Given that a 2g packaged die contains about 3mg of active semiconductor devices [16]. Moreover, there is also a significant difference between energy intensity in the wafer fabrication of a 200mm and a 300mm wafer. For instance, a recent study by Krishnan et al [17] reported an LCI with a 300mm functional unit (with findings on device fabrication: process and infrastructure = 7100 MJ/wafer), which translates to 1.07kwh/cm2; compared to a 200mm wafer that falls within a the range of 1.4 - 1.59kwh/cm2, reported in the respective studies [18], [16], [19].

Table 2 recaps the findings of six different published studies, on energy of semiconductors manufacturing, as well as the respective study boundaries, compared according to wafer sizes: 150mm, 200mm, and 300mm.

TABLE 2. STATE OF THE ART ON THE ENERGY USE OF WAFER MANUFACTURING

Wafer size - diameter (mm)	Electricity required (kWh/wafer)	Manufaturing Energy Requirement (MJ/Kg)	Material Emboided energy (MJ/Kg)	Calculation Boundaries	Source
200	470	13500	4135	Includes chemicals + Si wafer production + Cu and Epoxy emboided energy: (5.8+2.3+.17)/MJ per 2g chip). Manufacturing is 27MJ/2g chip	[17]
200	440	-	-	Si wafer production + Wafer mfg	[15]
200	499	6067	1956	5% yield core material IC "back-end" production (assumes 25% of mfg energy) Total Energy: 8022MJ/kg (Mat'ls Energy: 1520MJ/kg, Au content: .2 weight % - 435.7 MJ/kg)	[18]
		1214	573	1% yield core material IC "back-end" production (assumes 25% of mfg energy) Total Energy: 1787MJ/kg (Mat'ls Energy: 303MJ/kg, Au content: .1 weight % - 270.3 MJ/kg)	
300	664	1510	2900	Includes chemicals + Si wafer production	[16]
300	583	-	-	"gate to gate" - all materials and energy flows (facility level). Two results depending on the layers of the device: 6 vs. 8 layers (1.56 Kwh/ die vs. 1.87 Kwh/ die)	[19]
150	270	-	-	Device Fabrication (Process and Infrastructure) excludes Si wafer and chemical production	[14]

The energy requirement for each wafer size is estimated with the figures reported on electricity required per wafer[1] and the wafer theoretical weight of yield of core material: 27.8 g (150mm); 53.1 g (200mm); 127.6 g (300mm). The theoretical weight is a reasonable estimate of the actual weight. For a 150mm wafer, the actual finished wafer weight is 28.3 grams[2].

The results for each wafer size are shown in Table 3, as well as the figures used for the remining stages on electronic manufaturing.

TABLE 3. ENERGY CONTENT FOR THE MANUFACTURING OF ELECTRONICS

Categories	Energy requirement (MJ/given unit)	Units	Sources
Wafer manufacturing /Chip level packaging			
150 mm	9.7	kWh/g	[14]
200 mm	8.3 - 9.4	kWh/g	[16],[18]
300 mm	4.6 - 5.2	kWh/g	[17],[20]
Printed Wiring Board (PWB) manufacture			
PWB 1/2 lay 3.75 kg/m2	151	MJ/kg	[19]
PWB 6 lay 4.5 kg/m2	146	MJ/kg	
PWB 6 lay 2 kg/m2	333	MJ/kg	
Board-level assembly			
	120 - 140	MJ/kg	[1]
Final assembly			
	0.2 - 0.3	per chip	[21]
Display manufacturing			
LCD/CRT	2950 - 3750	MJ/m2	[1]
LCD	3563	MJ/m2	[19]
CRT	3169	MJ/m2	

This methodology for estimating the energy into semiconductors manufacturing has been applied to different products, using their BOMs. For example, in the case of a desktop (CPU tower) [22], the total electronics manufacturing results in about 2900 MJ/unit, for which 2780 MJ goes into the wafer manufacturing/chip packaging. This means that about 95% of the energy content is needed in this phase. Therefore, for the purpose of the Life Cycle Energy estimation, it may be safe to neglect the other phases (i.e. PBW manufacture, board assembly and final assembly) when making the analysis.

2.5. Nano-materials

Additionally, the tool also includes data on the nano-materials processing (e.g. Carbon Nanofiber production [23], nano scale fabrication in semiconductors [17]).

3. PRODUCT BILL OF MATERIALS

A total of 46 Bill of Materials from 23 different electronic products are used to try the methodology. Table 4 summarises the products and the source where their BOM is found.

TABLE 4. PRODUCT BILL OF MATERIALS

Product	Sources	Product	Sources
TV	[25]-[30]	Dish washer	[29], [30]
Refrigerator	[25], [29]-[32]	Microwave	[29]
Monitor CRT	[18], [29], [33], [35]	Vaccum Clener	[30]
Laptop	[34], [35]	Printer	[40]
PC (excl. monitor)	[18], [22], [29], [35]	Fax machine	[41]
LCD Monitor	[35]	Cordless phone	[42]
Video (DVD)	[29], [33]	CD player	[42]
PC (incl. Monitor)	[36]	Calculator	[42]
Cell phone	[33], [37]	TV Board / PC Board	[42]
Washing machine	[25], [29], [38]	Hair Dryer	[1]
Digital Copier	[30], [39]	Coffee Maker	[1]
Room Air Conditioner	[25], [30]		

4. PUBLISHED LIFE CYCLE INVENTORIES

Despite the fact that the availability and accessability of these analyses is limited, a total of 9 published product LCIs (i.e. complete empirical studies on a given product) were gathered and used to compare with the results given by the proposed tool. Table 5 summarizes the sources of each study.

TABLE 5. EMPIRICAL PRODUCT LIFE CYCLE INVENTORIES

Product	LCI Published source
PC	[24]
PC (tower)	
CRT Monitor	
Refrigerator	[31]
Washing Machine	[29]
LCD Monitor	[35]
Digital copier	[39]
Hair Dryer	[1]
Coffee maker	

III. RESULTS AND DISCUSSIONS

A diagram comparing the two outcomes for the 9 different products is provided: the resulting Life Cycle Energy analysis from BOM - with the proposed tool against the published LCI, showing that for most products the published LCI figures fall into the range given by the tool estimates. The resulting output represents the sum of all energy inputs into the product in the form of a value range (minimum to maximum). The diagram is read in this way: let us take, for instance, the cathode ray tube (CRT) monitor as an example. An empirical LCI for a CRT monitor reports that the energy required for its materials and manufacturing is equal to 1055 MJ. Our tool is applied to a BOM of a CRT monitor and estimates the energy on those phases to be in the range of 985 and 1455 MJ.

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[1] Assuming all studies based on US power grid. 1kwh = 3.6 MJ.

[2] Personal communication with Wafer Fab Operations Manager at Analog Devices. Cambridge, MA. September, 2009.

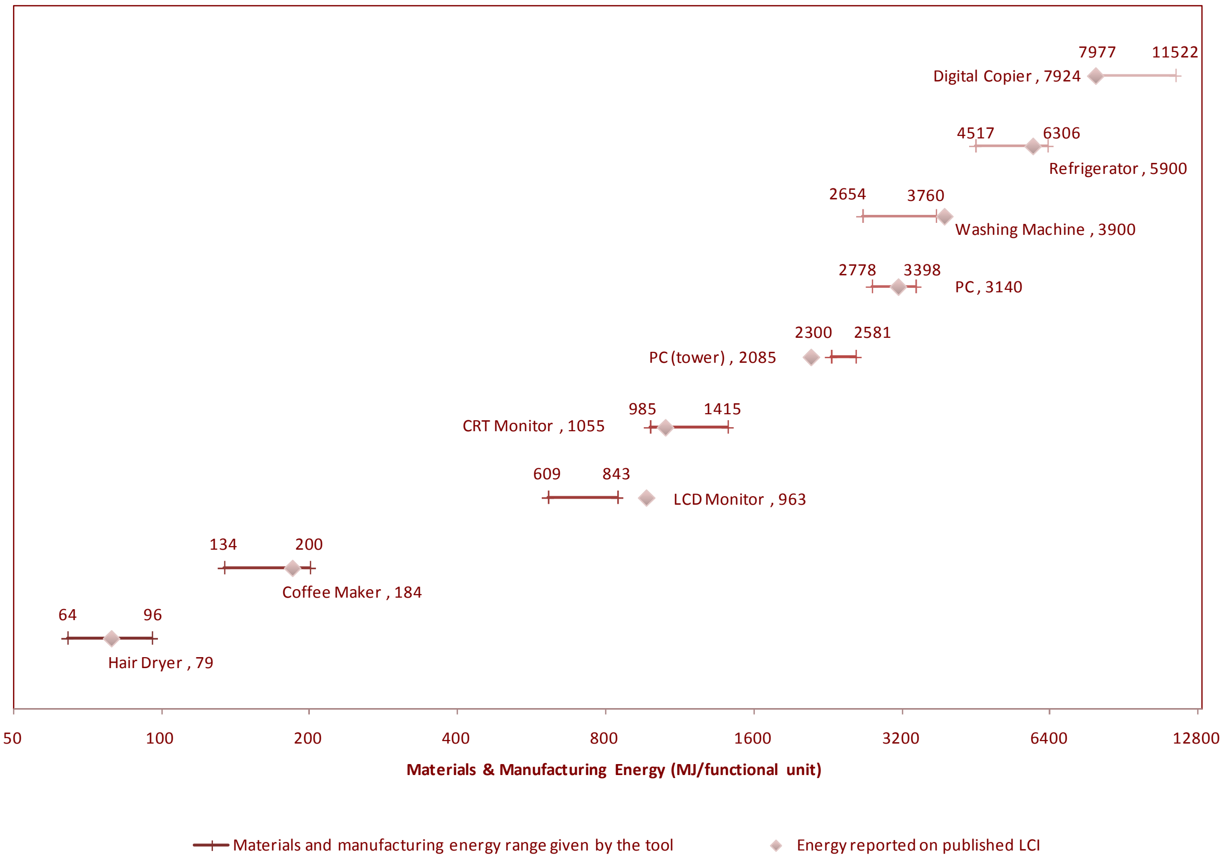

Fig. 1. Comparison of product's matetrial and manufacturing energy calculated with the BOM tool vs. publised LCIs

A simplified version of this tool is also presented. The values taken for energy requirements on materials and manufacturing of each product have been approximated. Materials embodied energy is taken as the 75th percentile of the given range. Manufacturing energy intensities equals to a single number for most processes. As mentioned earlier, most of the manufacturing energy figures on conventional manufacturing processes for metals plastics and processing of many composites roughly fall within the range of 1 to 30 MJ/kg. The processing energy figure of materials for each product has been taken as 15MJ/kg of material processed in general, instead of each of the individual manufacturing processing figure given in the tool; except for electronics (given their high energy intensity), for which the methodology to estimate their energy requirements presented in the semiconductors section of this paper, is used. Figure 2 shows the comparison of the results calculated with this simplified version of the tool against the published LCI energy data for each product. Most products lay around the diagonal line, that represents the y=x values; which means that the tool provides a fair approximation of the emperical number. Products either to the left or the right of the line indicate a slight over (or under) estimation of their energy requirements.

The authors acknowledge the existance of other tools that similarly draw conclusions that are comparable to the presented tool in this paper. There are some issues with transparency, assumptions, discrepancies and generalizations in other tools that affect significantly the analysis. For instance, the methodology presented in [19], which is very well explained and done; nonetheless, there is a significant assumption in this study stating that for electronic products materials account for 25 % of the manufacturing energy. From the results of the different products analysed in this study, the material/manufacturing energy ratio is not constant through out the products, only one of them is close to the 20% ratio.

In general, the main issues with LCA-like methodologies or tools are: (i) product to product variation (ii) variation in the different LCA approaches people use (iii) variations in the boundaries used for the problem, and (iv) various unexplained or only partially explained assumptions. We suspect that most of the variation has to do with the last two statements. Normally, tools can be accurate enough, but often fail on these issues. The proposed tool is accurate enough to give a sense of direction, which is its purpose. For a more thorough analysis, we suggest to use more detailed tools.

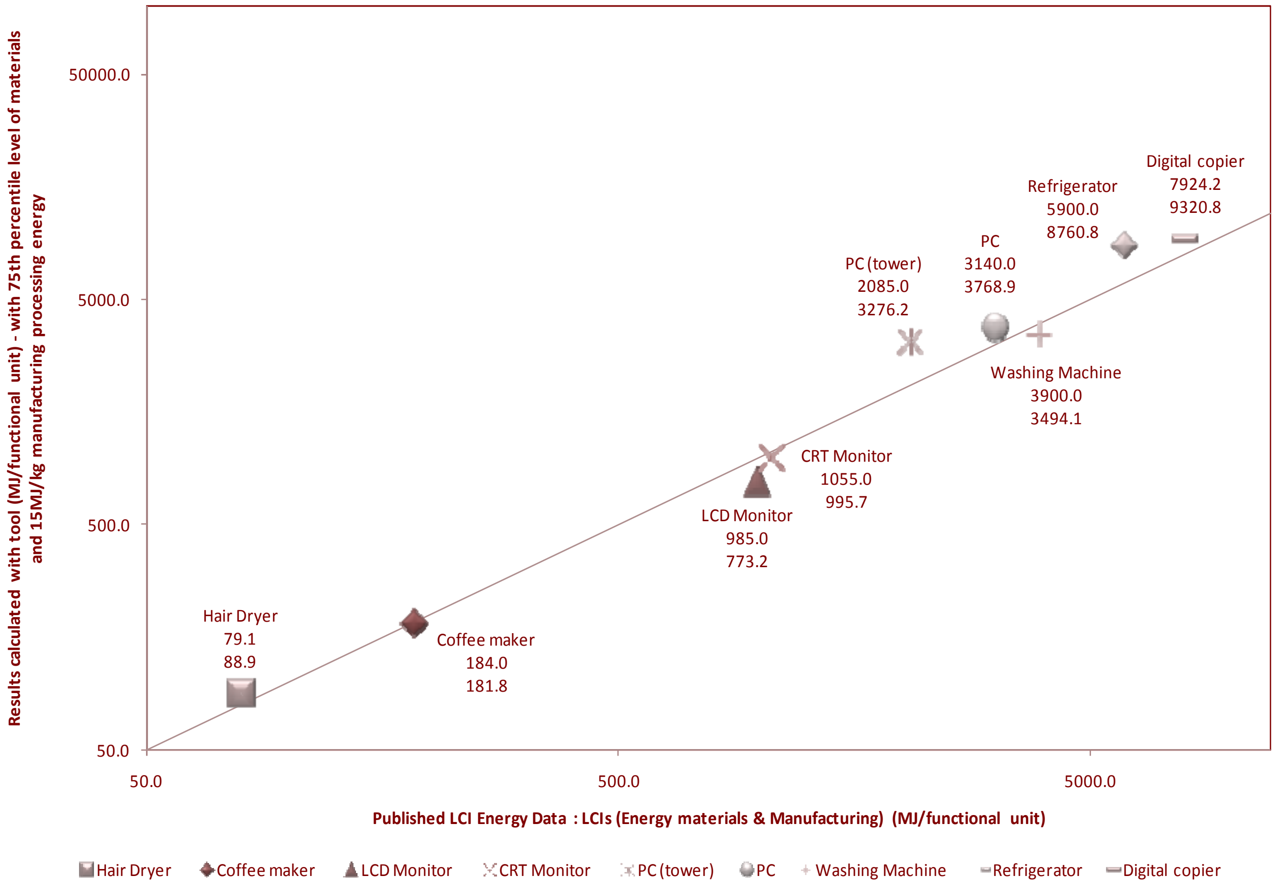

Fig. 2. *Simplified version:* Comparison of product's matetrial and manufacturing energy calculated with the BOM tool vs. publised LCIs (Approximation with 75th percentile of the level of materials embodied energy and 15 MJ/kg for material processing).

IV. CONCLUSION

Preliminary results show that this methodology provides a very good estimate of the energy requirements for materials production provided a sufficiently detailed bill of materials is available. Secondly, the method provides reliable results for conventional manufacturing processes, and reasonable estimates for electronics manufacturing. Given the complexity of the later, the accuracy improves in step with the level of manufacturing process data available. The tool offers the scientific community a two-fold gain: 1) a quick Life Cycle Energy analysis, allowing to estimate the product energy requirements to then be compared with other energy studies in the different life stages (i.e. middle of life and end of life) of the product; 2) an educational tool, allowing the evaluation of the energy requirements of products from a BOM or a dismantled product.

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