An Environmental Analysis of Injection Molding

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Abstract—**This environmental analysis of injection molding highlights a few important points. The choice of injection molding 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 analyzed are 19.0, 13.2 and 12.6 MJ/kg respectively (including auxiliaries, compounding and the inefficiency of the electric grid). For hydraulic and hybrid machines SEC seems to exhibit a decreasing behavior with increasing throughput. This derives from spreading fixed energy costs over more kilograms of polymer as throughput increases. For all-electric machines SEC is constant with throughput. When the polymer production stage is included in the analysis, the energy consumption values increase up to 100 MJ/kg. The overall injection molding energy consumption in the U.S. in a yearly basis amounts to 2.06 x 10^8 GJ. This value is of similar magnitude to the overall U.S. energy consumption for sand casting, and to the entire electricity production of some developed countries**

Keywords-Injection Molding; Hydraulic; Hybrid; All-electric; Specific Energy Consumption (SEC); Life Cycle Inventory (LCI).

I. INTRODUCTION

Plastic components are integral parts in electrical and electronic (E&E) products. 8.5% of the plastic production is dedicated to this market [1]. Although this number might seem small it is larger than the amount of plastic used for the automotive industry (8%) [1]. In E&E products plastic can represent from 3% of the total weight in medical equipment to 33% in small house appliances and 42% in toys [1]. The majority of this plastic used for E&E products is injection molded in order to attain the specific geometric requirements. Injection molding involves melting polymer resin together with additives and then injecting the melt into a mold. Once the resin is solidified, the mold opens and the part is ejected. At first glance, injection molding may appear to be a relatively benign process with respect to the environment due to its low direct emission levels and apparently low energy consumption. However, when calculating the environmental cost of injection molding one must also take into account the ancillary processes and raw materials used in the process. Aside from the raw material production stage which has substantial emissions, the main metric in the whole injection molding process is energy consumption. The large scale of the injection molding industry makes the environmental impacts of this process especially critical. In other words, a small increase in the efficiency of the process could lead to substantial savings for the environment.

This paper investigates injection molding from an environmental standpoint, yielding a system-level environmental analysis of the process. It provides a transparent process model that includes all major steps involved in the production of injection molded products and shows the dependency of injection molding on the most important process parameters. This paper presents a summary of our findings along with detail on four major issues:

1. Relationship between energy consumption and throughput.
2. Differences in environmental performance between hydraulic and all-electric machines.
3. Role of secondary/subsidiary process in the energy accounting.
4. Environmental scale of injection molding.

II. BACKGROUND

With regards to injection molding life cycle inventories (LCI), much effort has gone into studying the production of raw materials (polymers) as well as the product end-of-life aspects, such as disassembly separation and recycling. Amongst the researchers in this area, it is worth mentioning Ian Boustead, who developed a set of “eco-profiles,” or LCI’s, of the most consumed polymers in the plastic industry. He also created life cycle inventories for injection molded PVC and injection molded polypropylene. The former LCI studied two injection molding facilities in France that produce PVC fittings for pipe drainage systems [2]. The latter LCI studied one facility in the U.K. that produces 12 to 76 g polypropylene components [3]. These studies are product specific, narrowing on one application and one set of processing parameters. In an effort to obtain a range of values typical in injection molding, and thus more breadth of data, this study incorporates measurements from machines processing different products and materials. It also provides a transparent outline of all the sub-processes that make up the injection molding process together with their environmental performance.

Other contributors to the field of injection molding include Mattis et al. 1996 and Boothroyd et al. 2002. Mattis et al. used a 3-D solid modeling environment and numerical analysis to explore the influence of mold design, part design, and some process parameters on the process efficiency [4]. Boothroyd et al., whose goals were to develop design-for-manufacturing guidelines, developed a set of empirical equations predicting machine size and processing time of each stage in the injection molding cycle [5].

If the reader is not familiar with injection molding technology please refer to [6].

III. MACHINE ENERGY CONSUMPTION

The main division in injection molding machinery lies in how the drives in these machines are powered. The oldest and most common injection molding machine type is the hydraulic powered machine. This machine uses one or more hydraulic pumps to power all of the machine's motions. One can have a pump for each drive, a centralized pump driving all motion, or a combination thereof. There are two obvious inefficiencies with hydraulic machines. First, for most machines, pumps continue running even while the machine is idle, consuming power that does not get used in production and thus wasting power. Secondly, there is an intrinsic inefficiency in the architecture of the system. An electric pump transfers work to the hydraulic circuit, which in turn transfers work to the mechanical components. Each transfer of work entails inefficiencies. Why not eliminate one of these transfers? This is where all-electric powered injection molding machines come into place. As their name indicates, these machines use servo motors to power each of the mechanical drives. Basically, one servo motor runs the rotation of the screw, another moves the screw along the injection axis, and a third moves a toggle clamp to close the mold. Aside from the above mentioned main servos, there might be others that run secondary functions. These machines exhibit superior efficiency on average, but are not applicable for high clamping force applications due to the instabilities in the toggle clamp configuration. This is where the hybrid powered machines come into place. A hybrid machine uses both servo motors and hydraulic pumps. The most common configuration is using the hydraulic pump for clamping and servo motors for screw movement. These machines sacrifice some of the all-electric efficiency for the precision of hydraulic clamps. Fig. 1 portrays the power requirement for a hybrid and an all-electric machine both running the same part with a cycle time of 14 seconds. Simple inspection reveals substantial energy savings from using all-electric over hybrid technology. The reader must note that the curve for a hydraulic machine would be even higher than that of the hybrid.

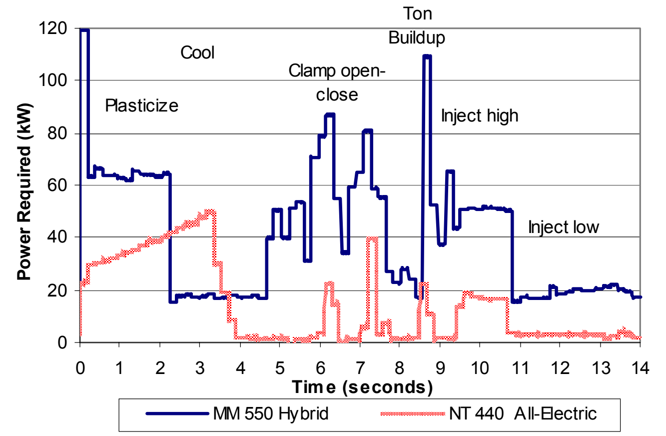

Figure 1. - Energy consumed in the injection molding cycle of a hybrid (electric screw drive) and an all-electric machine. Source: [7].

Thus the choice of machine has a substantial impact on the specific energy consumption[1] (SEC), or energy consumption per kilogram of polymer processed. More than 100 energy measurements and calculations were examined from the three types of machines. This analysis yields average SEC values for hydraulic, hybrid and all-electric machines of 3.39, 1.67 and 1.46 MJ/kg respectively (without accounting for the efficiency of the electric grid).

For hydraulic and hybrid machines SEC seems to exhibit a decreasing behavior with increasing throughput, as portrayed in Fig. 2. 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:

$$\begin{aligned} &P = P_0 + k\dot{m} \\ &where, \\ &P_0 = fn(hydraulic\ pumps, computer, etc..) \\ &k = extra\ SEC\ to\ process\ the\ polymer \end{aligned} \qquad (1)$$

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. 2.

All-electrics on the other hand have very low fixed energy costs (ex: running the computers), and their SEC stays constant as throughput increases, as portrayed in Fig. 3.

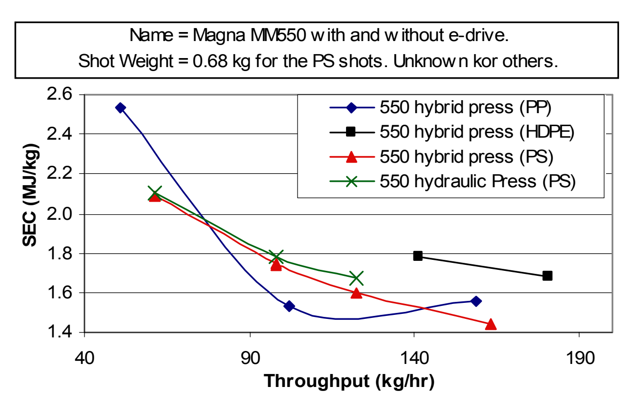

Figure 2. SEC vs. throughput for a Magna MM550, hydraulic and hybrid. There is no inclusion of the efficiency of the electric grid. Source: [8, 9].

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[1] Here we use a common expression, while in fact energy is not consumed but transformed. A more rigorous but less understood definition for SEC would be "specific exergy consumed".

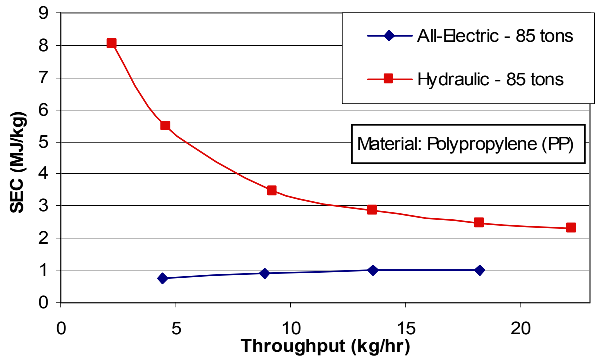

Figure 3. SEC vs. throughput for an all-electric and a hydraulic machine. There is no inclusion of the efficiency of the electric grid. Source: [8].

IV. SUMMMARIZED LIFE CYCLE INVENTORY

In order to develop a successful life cycle inventory (LCI) it is first necessary to establish the boundaries of the system to be analyzed. In the case of injection molding, the overall process starts at the polymer production stage. This stage takes raw materials from the earth and transforms them, with the addition of energy, into polymers. The raw polymer is then shipped in bulk to the compounder which mixes it with additives in order to bestow the polymer with the required properties for its future application. The polymer is then shipped to the injection molder which transforms the polymer into a finished product. The injection molder might also add some additives in the process, such as coloring. After being injection molded and packaged, the product is ready to be used by the consumer (and eventually disposed). The scope of this analysis is “cradle to factory gate” with the exclusion of packaging. Thus it encompasses everything from the creation of the raw materials for polymer production to the injection molding of the product. The system boundaries are portrayed by the dashed square in Fig. 4.

Close to 100 sources were consulted in order to develop this LCI. Most of these sources are not listed in the references section but can be obtained from [10]. The results of the LCI are summarized diagrammatically in Fig. 5. The reader must note that with the exception of the polymer production stage when energy data exhibited variation with type of polymer it was averaged according to the relative amount of polymer injection molded in the U.S.

It is interesting to note how even though the energy consumption for injection molding machinery seems low, when other stages in the process are included the figure becomes substantial. Considering the energy consumption of all stages from the compounder to the injection molder (not including polymer production), hydraulic, hybrid and all-electric machines yield average values for SEC of 19.0, 13.2 and 12.6 MJ/kg respectively. These values take into account the energy

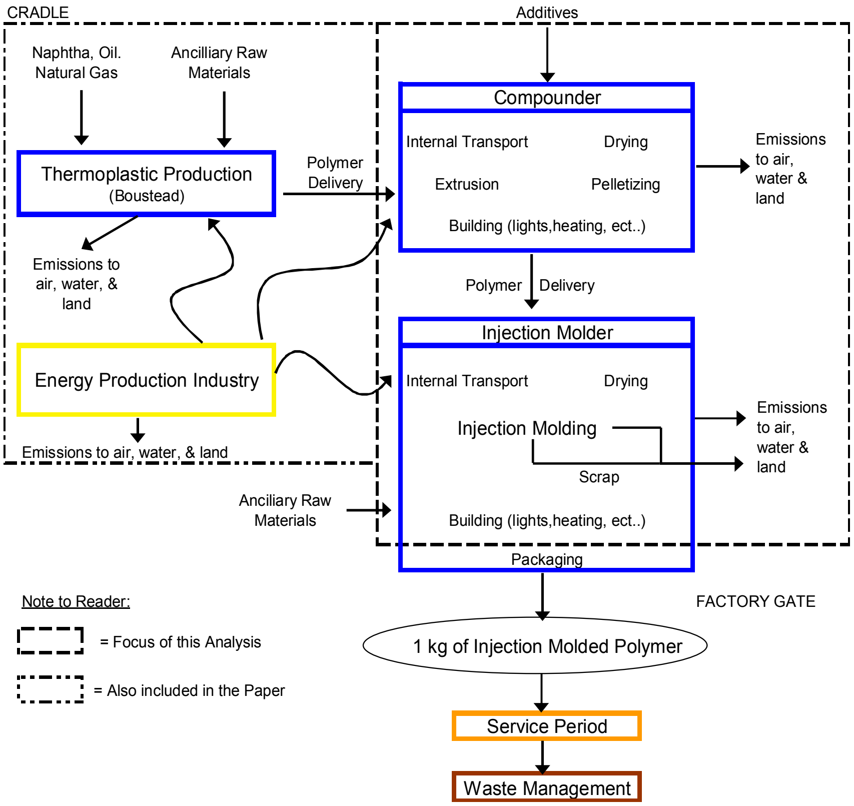

Figure 4. Injection Molding System Boundaries

ENERGY CONSUMPTION BY STAGE in MJ/kg of shot

Thermoplastic Production

							Generic by Amount		Extras	
	HDPE	LLDPE	LDPE	PP	PVC	PS	Consumed	Inj. Molded	PC	PET
avg	89.8	79.7	73.1	83.0	59.2	87.2	81.2	74.6	95.7	78.8
low	77.9	79.7	64.6	64.0	52.4	70.8	69.7	62.8	78.2	59.4
high	111.5	79.7	92.0	111.5	79.5	118.0	102.7	97.6	117.4	96.0

Polymer Delivery	avg	0.19
	low	0.12
	high	0.24

Compounder

	Internal Transport	Drying	Extrusion	Pelletizing	Building (lights, heating, ect..)
avg	0.09	0.70	3.57	0.16	0.99
low	-----	0.30	1.82	0.06	-----
high	-----	1.62	5.00	0.31	-----

Subtotal	avg	5.51
	low	3.25
	high	8.01

Polymer Delivery	avg	0.19
	low	0.12
	high	0.24

Injection Molder

	Internal Transport	Drying	Injection Molding (look below)	Scrap (Granulating)	Building (lights, heating, ect..)
avg	0.04	0.70		0.05	0.99
low	-----	0.30		0.03	-----
high	-----	1.62		0.12	-----

	Injection Molding - Choose One		
	Hydraulic	Hybrid	All-Electric
avg	11.29	5.56	4.89
low	3.99	3.11	1.80
high	69.79	8.45	15.29

Subtotal	avg	13.08	7.35	6.68
	low	5.35	4.47	3.17
	high	72.57	11.22	18.06

		Hydraulic	Hybrid	All-Electric
TOTAL w/ Generic Inj. Molded Polymer	avg	93.60	87.87	87.20
	low	71.65	70.77	69.46
	high	178.68	117.34	124.18

TOTAL w/o Polymer Prod	avg	18.97	13.24	12.57
	low	8.84	7.96	6.66
	high	81.04	19.70	26.54

Notes **Drying** - the values presented assume no knowledge of the materials' hygroscopia. In order words, they are averages between hygroscopic and non-hygroscopic values. For hygroscopic materials such as PC and PET additional drying energy is needed (0.65 MJ/kg in the case of PC and 0.52 MJ/kg in the case of PET)

Pelletizing - in the case of pelletizing an extra 0.3 MJ/kg is needed for PP

Granulating - a scarp rate of 10 % is assumed

Figure 5 - Overall System Diagram. The values above account for the efficiency of the electric grid. Multiple sources. Refer to [10] for an extended bibliography.

burden associated with producing the electricity to power the manufacturing processes[2]. When the polymer production stage is included in the scope of the LCI, the energy consumption values increase up to 100 MJ/kg. In the whole LCI, producing the polymer has the greatest impact on the environment. After the polymer production, injection molding machinery and extrusion have the greatest impact.

With regards to emissions, the majority of emissions come from the polymer production stage. Please refer to [11] if interested in these emissions. In the rest of the LCI, emissions can divided into: energy related emissions and processing emissions. Energy related emissions refers to those emissions originated from the generation of electricity necessary to run the processes. Table 1 presents energy related emissions for the compounder and the injection molder.

Processing emissions arise at the polymer processing sites. These kinds of emissions are small compared to energy related ones. For instance extruding polypropylene generates 0.185 g of volatile organic compounds (VOC's), 0.030 g of particulate matter, 0.0099 g of ketones, 0.0022 g of aldehydes, , and 0.0018 g of organic acids per kg of polymer extruded [12].

V. ENVIRONMENTAL SIGNIFICANCE

When compared to other conventional manufacturing processes, injection molding appears to be on the same order of magnitude in terms of energy consumption. For instance, processes such as sand and die casting have similar energy requirements (11-15 MJ/kg) [13, 14]. However, when compared to processes used in the semi-conductor industry, such as chemical vapor deposition and atomic layer deposition, the impact of injection molding seems insignificant. This is far from the truth, though. In order to understand the real impact of a manufacturing system one has to understand 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. Table 2 presents an estimate of the current quantities of polymer injection molded in the U.S. and in the world. With these values and distribution of the different machine types, the total energy spent in injection molding can be estimated.

According to Snyder, in 2002 29% of the machines sold in the U.S. were electric based rather than hydraulic [15]. With this information, we assume that 70% of the injection molding machines are hydraulic, 15% are hybrids and 15% are all-electric. Table 3 shows the results of the U.S. and global energy estimate.

Stage	SEC (MJ/kg)	Energy Related Emissions				
		CO_2	SO_2	NO_x	CH_4	Hg
		g	g	g	g	mg
Compounder	5.51	284.25	1.26	0.51	10.32	0.01
Injection Modler						
Hydraulic	13.08	674.82	2.98	1.22	24.49	0.01
Hybird	7.35	379.33	1.68	0.68	13.77	0.01
All-Eletric	6.68	344.57	1.52	0.62	12.50	0.01

Table 1 - Energy-related air emissions for the "compounder" stage and the "injection molder" stage. Multiple sources. Refer to [10] for calculation

	Inj. Molded - Million kg/yr	
	U.S. Only	Global
6 Main Thermoplastics	5,571	23,899
All Plastics	12,031	38,961

Table 2. Injection molded polymer totals in kg/year. The subdivision 6 main thermoplastics refers to HDPE, LDPE, LLDPE, PP, PS and PVC. The complete calculation can be found at [1]. The sources used are [16, 17, 18].

Compounder and Injection Molder	U.S. GJ/year	Global GJ/year
6 Main Thermoplastics	9.34E+07	4.01E+08
All Plastics	2.06E+08	6.68E+08

Table 3. Total energy used in Injection Molding. The subdivision 6 main thermoplastics refers to HDPE, LDPE, LLDPE, PP, PS and PVC. The complete calculation can be found at [1].

As can be observed, the overall injection molding energy consumption in the U.S. in a yearly basis amounts to 2.06 x 10^8 GJ. This value includes all steps in the LCI, except polymer production. Including polymer production would increase this number by an order of magnitude. This value (2.06 x 10^8 GJ) is of similar magnitude to the overall U.S. energy consumption for sand casting (1.62 x 10^8- 2.28 x 10^8 GJ, [14]). For the reader to comprehend the scale of the U.S. injection molding energy consumption, Table 4 provides values of the entire electricity production of several countries. Without accounting for the electric grid, the overall injection molding energy consumption in the U.S. amounts to 6.19 x 10^7 GJ/year[3]. This value can be compared with the values in Table 4.

It seems imperative for industry to keep improving the efficiency of the process, since small savings anywhere in the LCI can lead to tremendous energy savings on a national scale. This seems an intelligent move in a time of raising energy prices.

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[2] The electric grid in the U.S. is 30% efficient. Visit [10] for more details.

[3] Equivalent to electricity consumption.

Annual Electricity Production

Smaller than U.S. Injection Molding Totals				Within 1 Order of Magnitude to U.S. Injection Molding Totals			
Country	**GJ/year**	**Country**	**GJ/year**	**Country**	**GJ/year**	**Country**	**GJ/year**
Afghanistan	1.71E+06	Jordan	2.55E+07	Austria	2.19E+08	Iran	4.47E+08
Guatemala	2.22E+07	Nicaragua	8.41E+06	Belgium	2.68E+08	Netherlands	3.18E+08
Honduras	1.37E+07	Nigeria	6.25E+07	Bulgaria	1.49E+08	New Zealand	1.39E+08
Iceland	2.84E+07	Panama	1.78E+07	Czech Rep.	2.52E+08	Poland	4.87E+08
Jamaica	2.26E+07	Slovenia	4.92E+07	Denmark	1.27E+08	Portugal	1.59E+08
				Finland	2.56E+08	Saudi Arabia	4.65E+08
				Greece	1.80E+08	Switzerland	2.47E+08
				Indonesia	3.46E+08	UAE	1.36E+08
				Hungary	1.24E+08	Venezuela	3.15E+08

Table 4 - Selected countries with smaller or similar order of magnitude electricity production to the amount of energy spent injection molding (compounder + injection molder) in the U.S. Source: [19].

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NOTE: for the LCI results not all references that were used in the calculations were listed. If the reader desires to obtain the references please refer to [10].