

An Environmental Analysis of Injection Molding

by

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Bachelor of Science in Mechanical Engineering (2004)
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Submitted to the Department of Mechanical Engineering in Partial
Fulfillment of the Requirements for the Degree of

Master of Science in Mechanical Engineering

at the

Massachusetts Institute of Technology

May 2006

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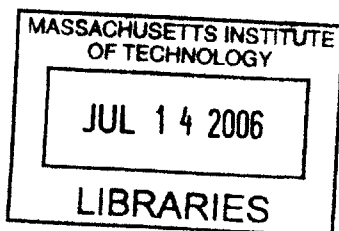
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ABSTRACT

This thesis investigates injection molding from an environmental standpoint, yielding a system-level environmental analysis of the process. There are three main objectives: analyze the energy consumption trends in injection molding machinery, explore the environmental performance of different technological alternatives, and provide a transparent life cycle inventory (LCI) identifying the mayor players in terms of environmental impact.

The choice of injection molding machine type (hydraulic, hybrid or all-electric) has a substantial impact on the specific energy consumption (SEC), energy used per kg of processed polymer. 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. As viscosity and specific heat capacity increase so does SEC. Finally, SEC varies greatly with part shape. The thinner and the greater the projected area of the part the greater the SEC.

When the polymer production stage is included in the analysis, the energy consumption values increase up to 100 MJ/kg. After polymer production, injection molding and extrusion have the greatest environmental impact in the whole LCI. The overall injection molding energy consumption (excluding polymer production) in the U.S. on a yearly basis amounts to 2.06×10^8 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

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ACKNOWLEDGMENTS

This research was supported by the National Science Foundation Award DMI 0323426.

I would like to thank my advisor, MIT Professor Timothy Gutowski, for his patience, guidance in this topic and help in making me see problems from multiple perspectives. Thanks also to Jeffrey Dahmus for his support and for answering that wave of questions one gets at the start of a topic.

In the making of this report multiple people in industry were consulted. I would specially like to thank David Voisard , Special Projects Manager at MHI Injection Molding Machinery, and Mark Elsass, Cincinnati Milacron Supervisor for Technical Service, for providing essential data and always being available for consultation. Thanks also to Dr. Robin Kent, Managing Director of Tangram Technology Ltd., for his advise on building energy consumption, to Daniel Ward, Project Engineer at Husky Injection Molding Systems Ltd. , for providing data on hot runner systems, to Jeff Tester, Professor of Chemical Engineering at MIT, for his help on modeling the U.S. electric grid, to John Radovich, Engineer at Davis-Standard, for providing data and clearing my doubts on extruders, to Bob Newton, New England Representative for the The Conair Group Inc., and Brian Shreffler, Service Technician for The Conair Group Inc., for consultations on resin driers, and to Bert Bras, Mechanical Engineering Professor at Georgia Institute of Technology, for his suggestions on polymer production energy consumption.

I would also like to thank my parents for being the pillars on which I stand. Thank you for giving me so much and expecting so little in return. Thank you also to my girlfriend Paige for her love and support. It has been an honor spending all this time with you. Thank you to all my close friends for your advice and all the fun times. They say friends are the treasures in life. I am a rich son of a gun. Thank you also to Tango for being more than human.

Finally I would like to thank God for opportunity and strength to face all these challenges. Thank you for giving me such an enriching life.

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CHAPTER 1

INTRODUCTION

Injection molding is one of the most widespread manufacturing processes in use today. This process involves melting polymer resin together with additives and then injecting the melt into a mold, cooled by air or water. Once the resin is solidified, the mold opens and the part is ejected. From car bumpers to contact lenses, injection molding offers great versatility in the features of its products. It can be used to make highly complex shapes in a single operation in minimal time. Injection molding's ability to manufacture complex parts allows for reductions in the part count of a design. Its short cycle time implies high throughputs. Injection molding produces parts in a consistent repeatable way, allowing for easy automation.

At first glance, injection molding may appear to be a relatively benign process with respect to the environment due to its low emission levels and relatively 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 must be mentioned that by "injection molding", this paper refers to conventional plastic injection molding. Thus other processes such as gas assisted injection molding, water-assisted injection molding, and metal injection molding, are not included in this analysis. This paper is mainly structured in two parts. The first part provides a detailed analysis of injection molding process. This part includes a review of the types of machines available, an energy consumption breakdown for an injection molding machine, energy consumption trends, and the accompanying theoretical models forecasting empirical trends. The second part of this paper steps back and looks at the whole life cycle inventory from "cradle to gate" for injection molding. This LCI permits the analysis of the economical significance and overall environmental impact of the process. The data presented in this paper is intended to represent the injection molding industry in the U.S.

CHAPTER 2

BACKGROUND

Previous research conducted in the field of injection molding mainly focused on machine specific features and on optimizing the process parameters to increase throughput, energy efficiency, part quality, and etc. Several studies have modeled the process using theoretical energy-based models, numerical analysis, and even software such as MOLDFLOW®. Examples of these studies include Mattis et al. 1996 and Boothroyd et al. 2002. The former analyzed the influence of mold design, part design, and process parameters on the process efficiency, which is closely related to its environmental impact. The latter developed a set of empirical equations predicting machine size, processing time of each stage in the injection molding cycle, and the costs of machinery and molds, all as a function of part dimensions and process parameters. Neither of these studies provides an environmental analysis of the process.

Regarding life cycle analysis of injection molded products, 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 life cycle inventories (LCI), 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 [Boustead Conversion PVC]. The latter LCI studied one facility in the U.K. that produces 12 to 76 g polypropylene components [Boustead Conversion PE]. As can be observed, these studies are really product specific. In an effort to obtain a range of values typical in injection molding, and thus more breadth of data, the current study will incorporate measurements from machines processing different products and materials. When these measurements are not available, careful estimates will be devised.

CHAPTER 3

THE INJECTION MOLDING MACHINE

This part of the analysis focuses its attention on injection molding machinery. In the second part of the paper, a summary of the results is provided within the systematic context of the injection molding LCI.

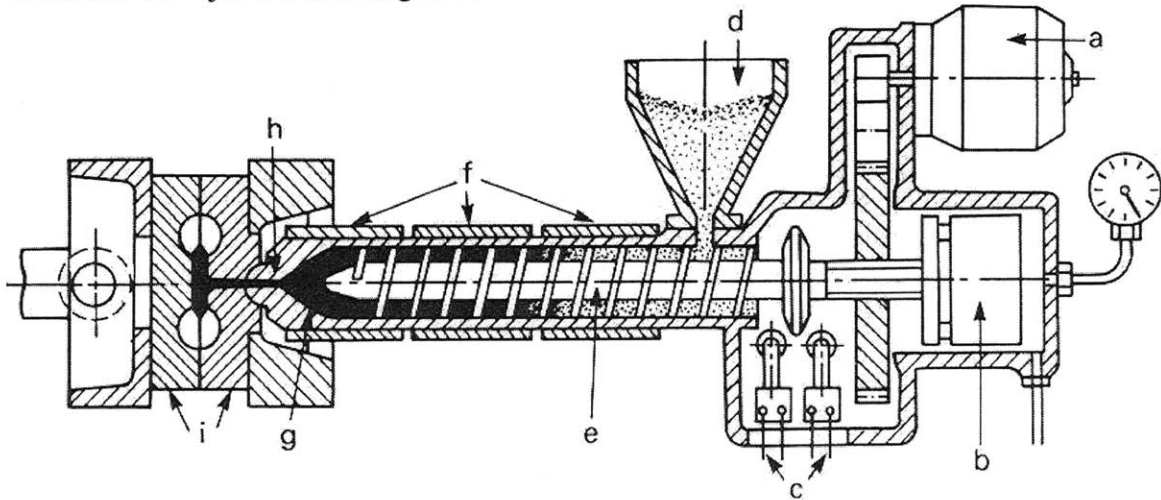


Figure 1 - Diagram of a Generic Hydraulic Screw Injection Molding Machine. Source: [Brydson 1990]. (a) Motor that rotates the screw. (b) Hydraulic drive for advancing/retracting the screw. (c) Left limit switch controlling holding pressure. Right limit switch for setting maximum screw stroke. (d) Resin hopper. (e) Screw. (f) Injection heaters. (g) Melted polymer. (h) Nozzle/gate. (i) Mold or die platens.

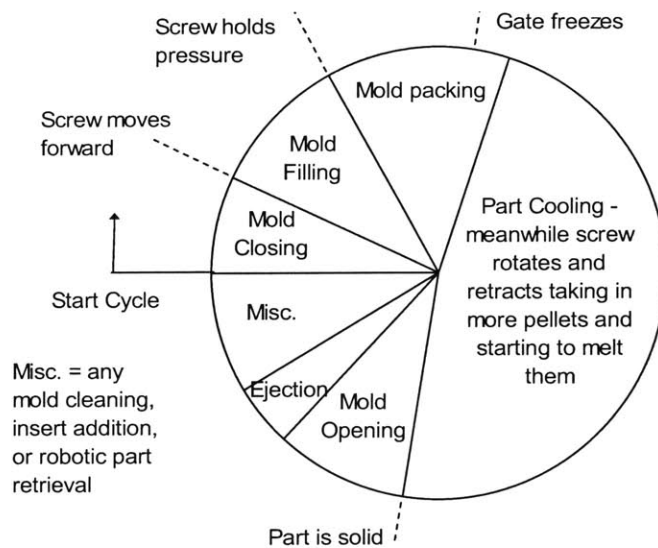


Figure 2 –Representation of Injection Molding Cycle. Adapted from: [Brydson 1990].

Figure 1 above gives an idea of the architecture of an injection molding machine, Figure 2 portrays a typical molding cycle. The injection molding cycle starts when the mold platens (i) close, forming the negative of the part to be molded. It must be mentioned that the mold basically consists of a sprue, a runner system, a gate, and a mold cavity. The sprue transports the molten polymer from the injection nozzle to the runner system. The runner consists of flow channels that distribute the molten polymer to several gates in a complex part, or to multiple connected parts in a multi-part die. In the case of a simple one-part mold, runners are generally not needed. A gate is the interface right before the molten polymer enters the mold cavity. Once the mold is closed, the molten polymer (g) is ready to be injected. The screw (e) advances forcing the melt into the mold. Since the melt decreases in volume as it solidifies, the screw must hold a substantial pressure after injection to ensure that the mold is completely full. Once the mold has been packed, the gate (h) freezes and the molten polymer inside the mold is left to cool. If substantial cooling is needed, the mold might incorporate water channels to improve the heat transfer rate. While the melt is cooling, the screw retracts and rotates in order to start melting the next batch of pellets. As the pellets are fed, pressure starts building next to the nozzle. Once the polymer in the mold has solidified, the mold opens and the part is ejected. In some instances, push rods are used to help eject the part. In the case of intricate geometries, the mold might need side-pulls in order for the part to be released. A side pull is a section of the mold opening in a direction perpendicular to injection. The table below offers an energy breakdown on how energy is spent in a hydraulic injection molding machine. As can be observed, the main contributors to energy consumption are plasticizing, clamp, and heaters, although idle consumption may sometimes be substantial.

Product	Plasticizing	Injection	Clamp	Ejector	Idle	Heaters	Cycle Time (s)
Dairy Container	53%	8%	24%	0%	0%	15%	6.45
Medical Ayringe	46%	5%	8%	2%	29%	15%	23.1
Pail	50%	10%	13%	0%	15%	11%	18.25
Closure	66%	7%	12%	3%	0%	12%	16.75

Table 1 - Energy breakdown in percentages for a Husky Hydro-Mechanical hydraulic injection molding machine (model G300 RS 70/60). Source: [Schad 2001]. Plasticizing is basically melting the polymer by means of rotating the screw. Clamp includes clamping and clamp movement.

Injection molding machines consist mainly of two main parts: the injection unit and the clamping unit. The injection unit is in charge of feeding, melting, and injecting the polymer into a mold. The clamping unit opens and closes the mold, and supplies adequate pressure when injection takes place, allowing for no molten polymer to escape the mold. It seems logical that injection molding machines are characterized by their injection capacity and their clamp tonnage. Injection pressures can range from 3 to 200 MPa¹ and clamp tonnage from 5 to 10,000 tons [Muccio 1994].

In order to complete the injection molding cycle portrayed in figure 2 the injection molding machine needs drives for the following functions:

- 1.) Clamp open and close (and any further adjustment in the case of toggle clamps).

¹ 500 to 30,000 psi.

- 2.) Screw forward and retract (injection & screw decompression)
- 3.) Screw rotation (screw recharge)
- 4.) Ejection pins forward & retract (Part eject)
- 5.) Any side pull mold movement.

Each function needs an energy source. If more than one function needs to be used simultaneously then more than one energy source is needed. Energy sources include motors driving pumps, accumulators, and electric motors driving gearing, etc [Ferromatik Milacron 2001]. It is the use of these energy sources that marks the environmental performance of an injection molding machine as will be seen.

As previously mentioned, this part of the report thoroughly investigates injection molding machines. This section will start by presenting a variety of injection molding machinery together with a brief review of their performance. It will then provide an explanation of energy consumption trends observed in hydraulic, hybrid, and all-electric injection molding machines. The section finalizes with a supplemental subsection explaining other energy saving devices available for injection molding. The reader should note that specific energy consumption, or energy consumption per kg of processed polymer will be used as the metric for energy consumption. This metric is abbreviated by SEC.

3.1 The Evolution of Injection Molding Machines

3.1.1 Hydraulic Machines

In 1872, John and Isiah Hyatt patented the first injection molding machine [Rubin 1972]. The first injection molding machines were nothing more than an arbor press used to push a plunger through a heated barrel containing molten polymer, pushing the polymer from the barrel into a mold. The mold was then allowed to cool and out came the first accurate, repeatable, and three dimensional plastic parts [Muccio 1994]. As the machines developed, they became known as plunger injection molding machines, since their injection units used a plunger to inject the plastic. In these machines, an electric motor runs a pump that increases the pressure in a hydraulic cylinder pushing the plunger forward. Conduction coils are used to heat and melt the polymer. These machines also incorporate agitators in the barrel to improve the homogeneity of the shot. The main problem with this machinery is that since the heat transfer efficiencies are low it takes extended time and large quantities of energy to melt the polymer.

In the years after World War II, the reciprocating screw injection molding machine (portrayed in *figure 1*) was invented as a solution to the above mentioned problems [Brydson 1990]. This type of injection unit design has been dominant since the 1970's [Rubin 1972]. What has changed since then is the nature of the drivers moving the screw.

As the injection units were developed, two types of clamping architectures appeared: toggle clamps and hydraulic clamps. Toggle clamps use mechanical advantage to lock

the mold in place. The mechanical advantage is created by means of linkages that are bent in the mold-open position and straighten up for mold-closed position, providing the necessary resistance to withstand injection pressures. Originally, the movement in the links was powered by means of a hydraulic pump. Toggle clamps allow for fast motions and positive clamping action with no pressure loss. On the negative side, they allow little variation in the clamping pressure and require frequent maintenance of linkages and pins. Hydraulic clamps use one or more pumps to power a hydraulic cylinder which in turn moves mold platens and provides the necessary pressure to withstand injection pressures. Hydraulics allow for a variety of clamping forces, and since they are simpler (less moving parts) they are easier to maintain. On the negative side, it has variations in system pressure due to different oil viscosity. It is also more inefficient due to the large amounts of oil moved. Hydraulic clamps became very popular in the 1980's. Some systems, such as hydromechanical clamps, are a mix of the two devices. This system basically uses mechanical toggles for the major platen movement and a hydraulic cylinder for the final stages of the movement and to withstand injection pressures [Muccio 1994]. While toggle and hydraulic clamps have experienced little change in their mechanics, the motors and pumps driving them have undergone drastic modifications.

Before 1980, energy was cheap, leading machine producers to make injection molding machines with motors and pumps for each function in the machine. In other words, the machine had parallel hydraulic circuits. This gave the consumers the most capability and performance. However, only 10-15 % of all costumers actually took advantage of this capability. The efficiency of these machines was low, since when this capability was used, motors and pumps sat idling waiting for their turn to actuate. About 20% of the rated power is needed to idle a large induction motors running pumps. Since the machine generally does not run at rated powers, this idling loss ends up being 20-40% of the energy to make the part. When energy became a driving factor, machines were built with a single set of pumps that were shared by the several functions. In other words, the machines then had a sequential hydraulic circuit. This represented energy savings on the order of 25-30% [Ferromatik Milacron 2001]. *Table 2A* provides a comparison between two 700-ton presses, portraying energy savings in the order of 30%. The reader must note that the long cycle times in this example do not require the capability of the 1973 press. Thus it was penalized for having the extra horsepower necessary for this extra capability.

Until early 1980's, pumps were fixed displacement pumps, pumping the same amount of oil no matter if the oil was used to do work or re-circulated back to the tank (wasted energy). Variable volume pumps are capable of varying their hydraulic output to match the specific flow requirements. In other words, these valves can "de-stroke", which means that no oil is pumped when it's not needed. The reduced average outputs of these pumps allows for smaller motors, as shown in the *Table 2B*. The more idling, the greater the advantage of these pumps over fixed displacement pumps. In the case presented in *table 2B*, the energy consumption is almost halved. As a rule of thumb, fixed displacement pumps are easier to maintain and variable volume pumps are more efficient. [Rosato 2000 & Ferromatik Milacron 2001].

Pressure and flow control pumps create yet another option to reduce the energy consumption of hydraulic injection molding machines. These pumps are a special type of variable pumps that control the flow and pressure of the oil in the hydraulic circuit to meet the specific flow requirements. These pumps replace proportional flow and pressure valves that control the speeds of the hydraulic cylinders in the machine. They also add pressure drops throughout the circuit increasing the efficiency of the machine. They are especially utilized in small machines. In large machines, the circuits get too complicated to use these pumps. These pumps also receive the name of servo-pumps and

Parallel vs. Sequential	Parallel Circuit	Sequential Circuit
Machine size (ton)	700	700
Year Made	1973	1985
Power (hp)	100	75
Shot Size (kg)	0.49	0.49
Cycle Time (s)	38.8	37.0
Throughput (kg/hr)	45.35	47.62
Power Draw (kW)	55.6	38.9
SEC (MJ/kg)	4.41	2.94
Material	PS	PS

(A)

Fixed vs. Variable	Fixed Pump	Variable Pump
Machine size (ton)	75	85
Power (hp)	25	20
Shot Size (kg)	0.09	0.09
Cycle Time (s)	30.7	29.6
Throughput (kg/hr)	10.31	10.69
Power Draw (kW)	6.7	3.55
SEC (MJ/kg)	2.35	1.20
Material	Nylon	Nylon
Part Type	Cup	Cup

(B)

Pump Comparison	Fixed Pump	Variable Volume Pump	Servo Pump	Electric Machine
Power (hp)	50	50	50	4 servo motors
Shot Size (kg)	0.31	0.31	0.31	0.31
Cycle Time (s)	35.5	35.0	34.5	34.8
Throughput (kg/hr)	31.75	32.20	32.47	32.29
Power Draw (kW)	23.4	20.0	11.5	5.7
SEC (MJ/kg)	2.65	2.24	1.27	0.64
Material	ABS	ABS	ABS	ABS
Capability	Sequential	Sequential	Sequential	Parallel

(C)

Variable Speed Comparison	Variable Volume Pump	Variable Speed Drive on Motor	Electric
Machine size (ton)	300	300	300
Shot Size (kg)	0.25	0.25	0.25
Cycle Time (s)	32.9	32.9	31.8
Throughput (kg/hr)	27.57	27.57	28.53
Power Draw (kW)	18.3	13.7	6.3
SEC (MJ/kg)	2.39	1.79	0.80
Material	Surlyn	Surlyn	Surlyn
Part Type	Golf Ball Covers	Golf Ball Covers	Golf Ball Covers

(D)

Table 2 A, B, C & D – Comparisons between different hydraulic pump options. Energy consumption figures do not take into account the efficiency of the grid. Source: [Ferromatik Milacron 2001].

display very fast response times [Rosato 2000 & Ferromatik Milacron 2001]. *Table 2C* compares the performance of a servo-pump injection molding machine to that of a fixed pump, variable volume pump, and all-electric machines.

In an effort to reduce energy consumption, variable AC or DC drives have been implemented on the electric motors running the pumps. These drives allow for the slowing or stopping of the electric motor during low flow requirements or during idling. Energy savings are specially observed for machines running under-capacity or with long cycle times. For machines with cycle times on the order of a minute or higher, these devices can save up to 30-40 % of the energy consumed. *Table 2D* shows how with a cycle time of barely 30 seconds, a 25% energy saving is observed [Ferromatik Milacron 2001]. Some people in industry classify this machine architecture as a hybrid machine.

3.1.2 Electric and Hybrid Machines:

The mid 1980's saw the birth of the all-electric injection molding machine in Japan. Before this date, the majority of injection molding machine pumps were powered with AC induction motors and accumulators. The birth of the all-electric meant replacing these pumps by electric servomotors. In addition, these all-electric injection molding machines have a servo motor for each function of the machine. This provides the capabilities of an independent pump machine, but without the idling inefficiencies. The motors turn off when they are not being used. When in use, this system is also more efficient than electric motors running pumps. This is due to the fact that fewer steps are needed to transform the energy into useful work. A typical hydraulic electric pump transforms electricity into energy, transfer this energy to the pump oil, which in turn transfers the energy to a mechanical component that does work. The all-electric shortens this chain by eliminating the pump oil. In other words, the all-electric servomotors transform electricity into energy transferring it directly into a mechanical movement [Rosato 2000 & Ferromatik Milacron 2001]. The energy efficiency of all-electrics can be witnessed in *tables 2C, 2D* and *3A*, where all-electric designs offer 50% reduction in the energy consumed by the best hydraulic alternative tested. Some cases, as shown in *table 3B*, reveal savings on the order of 75%!

Hybrid injection molding machines provide the middle ground between hydraulic and all-electrics. As their name indicates, they are mixes of all-electrics and hydraulics. In other words, their injection unit is electric or hydraulic, and the clamping unit is the opposite of the injection unit. Some hybrids though have a hydraulic and all-electric drives in the same unit. For instance, a clamping unit could have servo driving a toggle for main platen movement, and then a hydraulic pump for the last steps in mold closing and to provide the necessary force to withstand injection pressure. The most common type of hybrid has an all-electric injection unit and then a hydraulic clamp². Basically, the electric drive rotates the screw independently of the pumps that are moving the clamp. *Table 4A* illustrates the power reduction experience when the injection unit of a hydraulic

² This configuration of hybrid tends to be called Electric Screw Drive.

	Hydraulic	Hydraulic	All Electric
Machine size (ton)	550	500	NT550
Shot Size (kg)	16.90	14.40	12.00
Cycle Time (s)	11.4	14.8	8.0
Throughput (kg/hr)	151.93	99.32	154.20
Power Draw (kW)	97.6	65.7	51.4
SEC (MJ/kg)	2.31	2.38	1.20
Material	PP	PP	PP
Part Type	Fork	Fork	Fork

(A)

	Hydraulic	All Electric	All Electric
Machine size (ton)	500 MJ	500 ME	500 ME
Shot Size (kg)	0.056	0.056	0.056
Cycle Time (s)	45	45	40
Throughput (kg/hr)	4.48	4.48	5.04
Power Draw (kW)	26.07	5.71	5.96
SEC (MJ/kg)	20.94	4.59	4.25
Material	TPP black	TPP black	TPP black
Part Type	Seal	Seal	Seal

(B)

Table 3 A & B- Hydraulic vs. all-electric. Energy consumption figures do not take into account the efficiency of the grid. Source for 3A: [Ferromatik Milacron 2001]. Source for 3B: [Voisard Energy Cost Comp. File].

is replaced with a servo-electric injection unit. The greater the hydraulic requirement of the screw the greater the saving achieved by going to an electric screw, since one can downgrade the pump to a smaller one. *Table 4B* compares a full-hydraulic, a hybrid (electric screw drive), and an all-electric, showing how the hybrid saves energy compared to the hybrid, but not as much energy as an all-electric. It must be noted that the SEC values in this table are relatively low because PET is dried to a high temperature, entering the IMM at 160°C. The machine just needs to raise the temperature to 290 °C to process it.

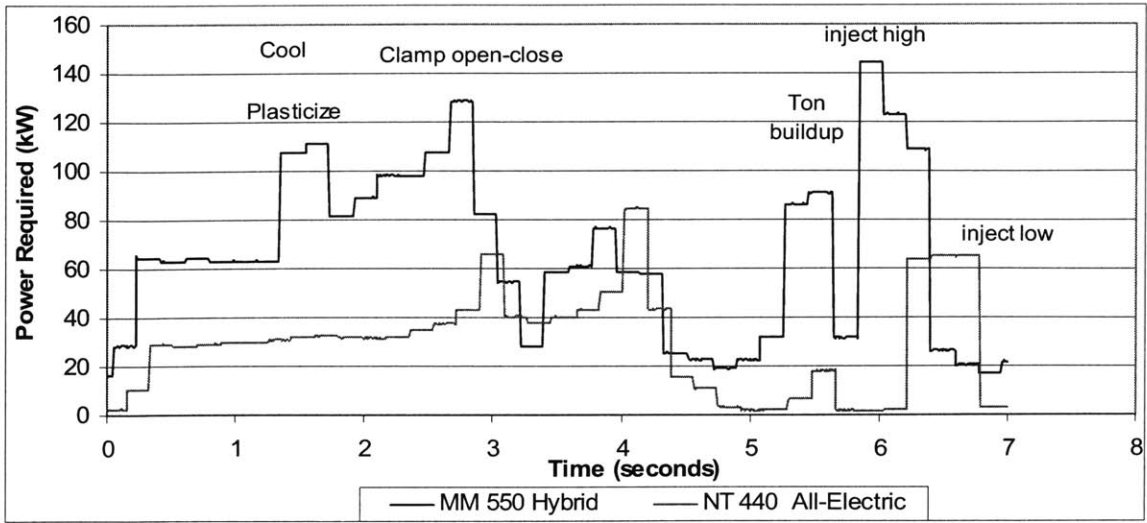
Injection Unit	Full Hydraulic	Hyd w/E-drive
Power (hp)	100	100+120 edrive
Screw diameter (mm)	90	90
Screw RPM	210	210
kg/hr	318.82	363.27
Pump Motor (kW)	104	15
E-Drive Motor (kW)		69
Total kW	104	84
Material	PS	PS

(A)

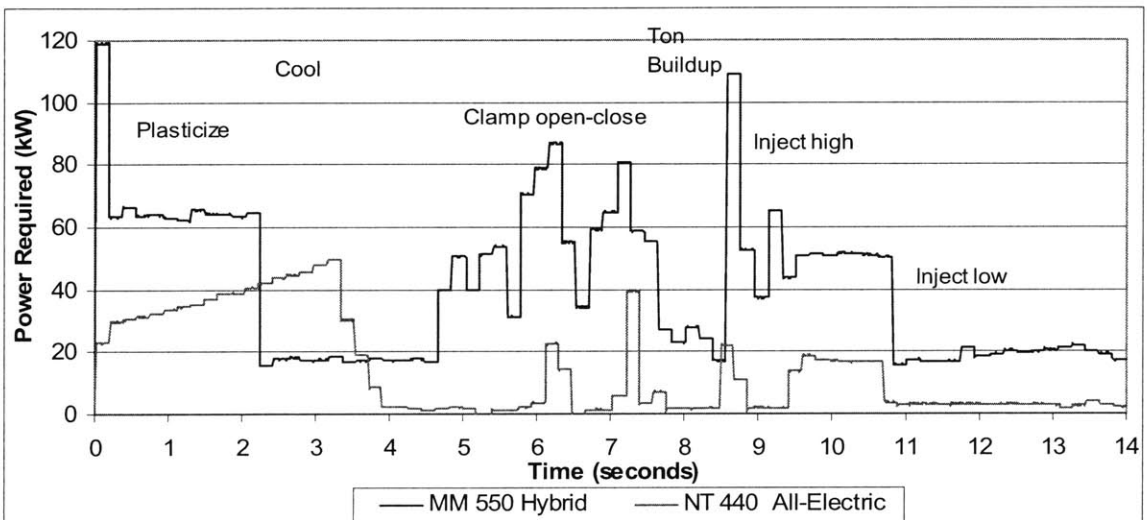
	Husky Full Hydraulic	Milacron Electric Screw Drive	Powerline All Electric
Machine size (ton)	550	MM550E	NT550B
Shot Size (kg)	0.93	0.91	0.94
Cycle Time (s)	17.7	18.1	15.8
Throughput (kg/hr)	188.66	180.50	213.15
Power Draw (kW)	130.6	84.2	63.6
SEC (MJ/kg)	2.49	1.68	1.07
Material	HDPE	HDPE	HDPE
Part Type	5 gal bucket	5 gal bucket	5 gal bucket

(B)

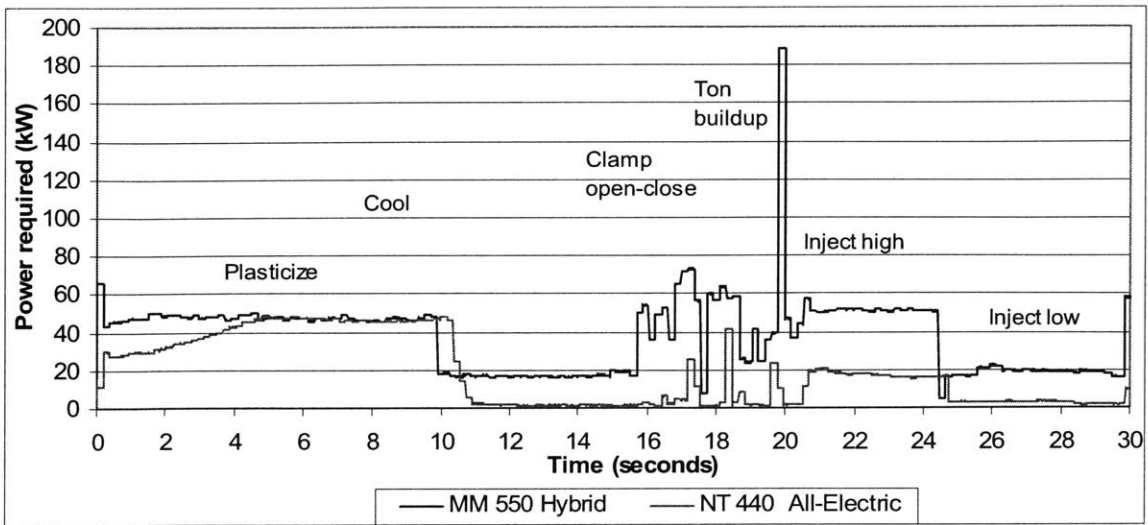
Table 4 - A - Comparison of the injection unit in a hybrid with that of a hydraulic. B – Comparison between hydraulic, hybrid and all-electric. Source: [Ferromatik Milacron 2001].



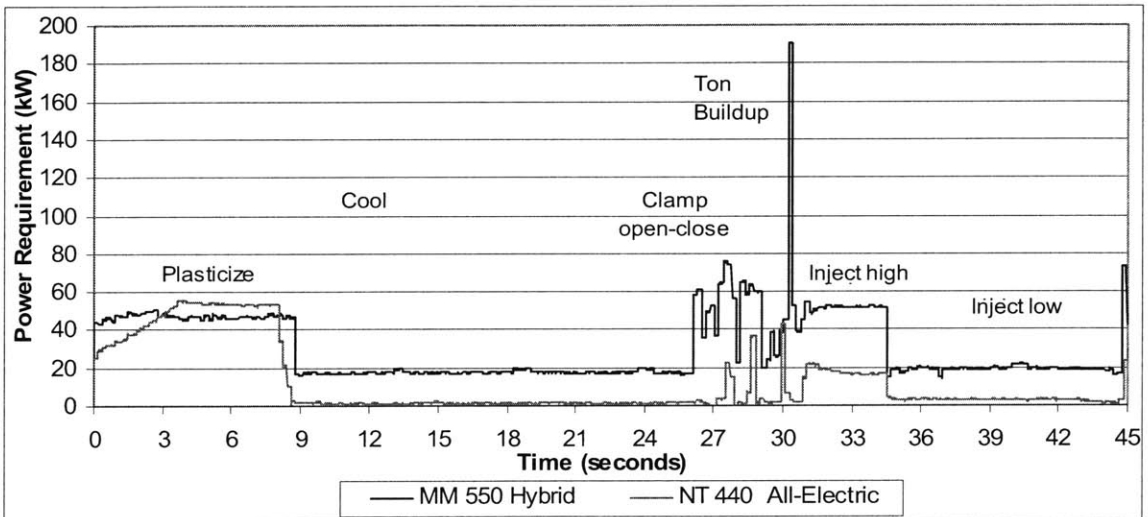
(A) – Cycle Time = 7.6 sec



(B) – Cycle Time = 14 sec

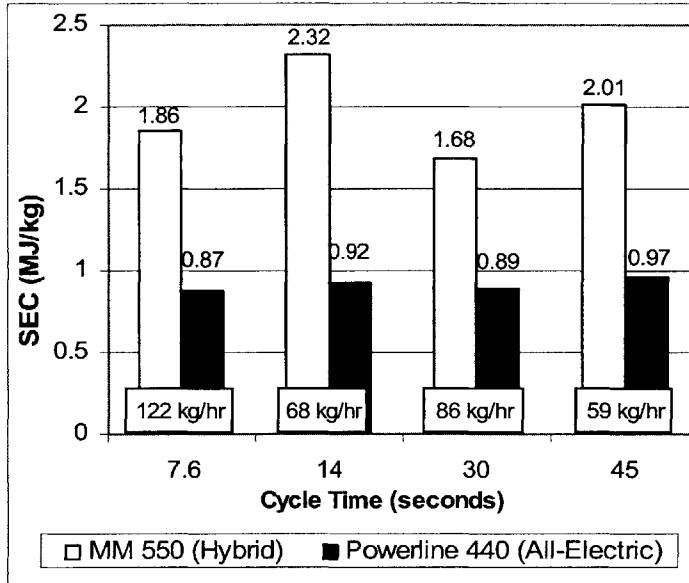


(C) – Cycle Time = 30 sec

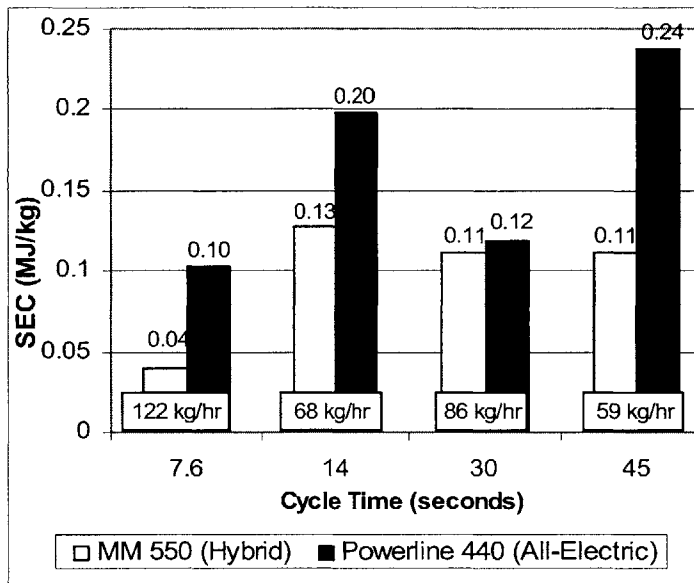


(D) – Cycle Time = 45 sec

Figure 3 A, B, C & D – Energy consumed in the injection molding cycle of a hybrid (electric screw drive) and an all-electric machine. Several cycle times presented (A = 7.6s, B = 14s, C = 30s, D = 45s). Source: [Elsass cm test graphs]



(A) – Energy Consumption including heaters.



(B) – Energy Consumption of the heaters.

Figure 4 – A = Overall energy consumption for the cycles in figure 3. B = Energy consumption of the heaters in the cycle in figure 3. The MM 550 is a hybrid machine. The Powerline 440 is an all-electric machine. These figures do not account for the efficiency of the electric grid. Source: [Elsass cm test graphs].

Figures 3 and 4 provide a cycle specific energy comparison between hybrid and all-electric machines. Before discussing the differences, one should understand the cycle. The cycle starts with the heaters on and the screw rotating {"plasticize"}. The screw rotates shearing the plastic pellets, increasing their temperature to melt temperature. The heaters provide additional heat. Once the polymer melts and is sufficiently mixed the

screw turns off and just the heaters are kept on to maintain the polymer molten. This is portrayed in the above figures as the sharp drop right after plasticizing. The heaters are kept on waiting for the part from the previous cycle to cool. When the part from the previous cycle is ready to be ejected the mold opens and secondary devices such as ejector pins are activated. This requires peaks of power but for a short time. The mold then closes and the tonnage builds up. When the required mold pressure is achieved, the mold is then ready for injection. The screw advances pushing the melt into the mold. This is labeled in the figures as “inject high”. After “inject high”, the melt in the mold solidifies and shrinks. A lower injection pressure, or packing pressure, must be applied in order to compensate for all the volume loss to shrinkage. After the injection stage the parts starts cooling and the screw recedes and starts rotating to melt the next batch.

Having understood the cycle one is ready to analyze the differences between all-electric and hybrid machines. As shown in *figure 4A*, the energy consumption of the all-electric is approximately half of that of the hybrid. It must be mentioned that cycles 7.6 and 14 share a shot size of 0.26 kg, while cycle 30 and 40 share a shot size of 0.72 kg. Increasing cycle time with the same shot size, from 7.6 to 14 seconds and from 30 to 45 seconds, proves to cause an increase in specific energy consumption. Increasing cycle time means either longer injection times, plasticizing times, heater times, clamping times, cooling times, or a combination thereof. Increasing any of these times increases the specific energy consumption of the machine, and since shot size stays constant, the SEC must increase. One case where this is partially untrue is when cooling time is increased, and the plasticizing time is kept constant and delayed in time by the amount cooling time was increased. If the mold has no cooling system, then the energy consumption should not go up by much. It still goes up due to idling inefficiencies. In the case of an all-electric the inefficiencies come from running computers and other auxiliary components that must be on to control the machine. The same is true for a hybrid; although the hybrid has an extra inefficiency since it has an idling pump. *Figure 4B* depicts how the energy consumption of the heaters is minimal when compared to the whole energy consumption of the machine. For the hybrid the heaters represent 2-6% of the total energy consumption. With regards to the all-electric the heaters do play a more significant role consuming 10-20% of the total power.

Close inspection of *figure 3* reveals interesting phenomena. As expected, the biggest drain in terms of energy consumption was plasticizing and heating, clamping, and injection. These functions require a substantial amount of power and last a relatively long time. Other functions either require similar power, but last shorter, such as clamp movements; or require less power but take similar times, such as cooling (just heaters are on keeping the polymer molten). When looking at *figure 3* one must remember that it shows overall consumption and that some functions overlap. For instance, plasticizing occurs while cooling, and clamp force occurs while injecting. It is worth noting the gap between the all-electric and the hybrid curves, signifying the savings of an all electric over a hybrid. It is also interesting how little power the all-electric machine requires, since it is capable of shutting off all motors. The last trend worth mentioning is how, in general, the curves get flatter as cycle time increases. This is a result of machines having

more time to perform a certain function and thus less stress on them. Machines are then capable of functioning at a more optimum pace.

3.1.3 The Debate between Hydraulics and All-electrics

By 2004, 25% of the machines sold in the U.S. were all-electrics [Bregar 2004]³. If all-electrics are so efficient, why is it they are not yet dominant over hydraulics? There is more than energy efficiency concerns to consider in the purchasing of an injection molding machines. In the following paragraphs, tradeoffs of hydraulic and all-electrics will be presented together with opinions from experts in industry. These opinions are extracted from a variety of magazines including *Plastics Machinery & Auxiliaries*, *PlasticNews.com*, *Modern Plastics* and *Medical Device & Diagnostic Industry Magazine*.

Aside from energy efficiency and the flexibility of having a motor for every function, all-electrics provide a wide range of advantages. Having servos for every function not only increases flexibility, but allows the shortening of cycle times by running several functions simultaneously. Beach Mold of Emporia, located in Virginia, mentions that their all-electrics are 10% faster than his comparable hydraulics [Snyder 2002]. They are cleaner than hydraulic machines since they eliminate the need for oil and have a closed-loop liquid cooling systems. Their cleaner environment makes all-electric machines really desirable for clean-room manufacturing [Sakurai 1999]. Inland Technologies, in Fontana California, claims that it uses all-electrics to run precision molded parts in a class 100,000 clean-room. They sell their parts to businesses in the healthcare, electronics and automotive industries [Snyder 2002]. No hydraulic oil also means no spills, no hazardous waste disposal, no oil-related employee falls, no fire hazard, no inventory/storage cost, and no fugitive oil mist. All-electrics also avoid the need for extensive air conditioning. Since less energy is consumed in the process, less waste heat is generated, and thus lower plant air conditioning is needed. It must be noted that motors and controls generate 65-75% less heat load [Energy User News 2001]. All-electrics' noise levels are low (under 70db) [Rosato 2000]. Toshiba and UBE, two electric injection molding machine manufacturers, assert that eliminating the hydraulic pumps leads to a noise reduction of 25% [Sakurai 1999]. All-electrics also have quick start-up and setup and provide high molding quality, high productivity and repeatability, without the operator's attention. The greater simplicity of their power train reduces the number of causes for mold variations present in hydraulic machines. They attain high speeds and can reach an accuracy of ± 0.009 cm in both injection and clamping [Rosato 2000].

All-electric injection molding machinery also raises several concerns. First, they provide mixed economic incentives. With a cost premium of 15% to 20% they are a stronger capital investment than hydraulics [Neilley 2004]. However, with energy savings on the order of 50%, these machines yield a 50% reduction in the variable electric cost. So it

³ In 2001, the Agostino von Hassell of Repton Group New York, said that 29% of the machines sold over the previous three years were all-electric.

becomes an issue of how high the electricity cost is in the region where one is producing. For instance, a hangar maker in Alabama, paying \$0.03/kWh for his power with tolerances of ± 1.25 cm, will not have an incentive to buy a more expensive all-electric [Kirkland 2002b]. On the other hand, in California during the Energy Crisis, all-electrics received a lot of attention. Their energy savings caught the attention of utility companies, which provided injection molders with rebates and other incentives for purchasing all-electrics. For instance, Connecticut Light and Power (CL&P) started an energy rebate program. The company gave rebates to customers who installed energy-saving equipment [Energy User News 2001].

Initially, all-electrics were available in the 50 to 100 ton range. Nowadays, all-electrics are readily available up to the 500 ton range. Beyond this range, their concentration decreases. Some builders, like UBE, make all-electric machines in the 1500 ton range, but there are few [Snyder 2002]. *Figure 5* provides a rough distribution of injection molding machines owned in the U.S. by tonnage. All-electrics would be giving the right tail of the distribution to hydraulic machines. Many believe that in the upper tonnage range, hydraulic clamps are more precise and reliable at controlling pressure than the all-electric toggle clamps [Kirkland 2002a]. Other situations in which hydraulics perform better is in two-shot molding and molding requiring core-pull sequencing [Snyder 2002 & Kirkland 2002b]. People favoring all-electrics claim that they require less maintenance because of the lack of a hydraulic oil circuit [Snyder 2002]. However, the opposite group mentions that their maintenance people are mechanics and not electricians. Thus the necessary infrastructure is not yet in place, but once it is, this shouldn't be an obstacle [Kirkland 2002a]. Introducing all-electrics also entails personnel training costs.

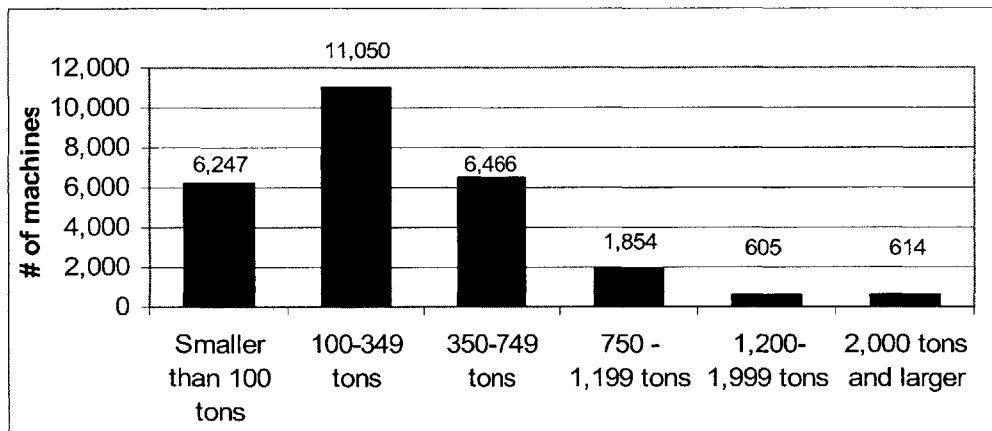


Figure 5 - Number of injection Molding Machines in 2003. Source: [PlasticNews 2003]

The choice between hydraulics and all-electrics seems to be an issue of the cost of electricity, the gap in price between comparable machines and the tonnage range. To fill the needs of those in between, hybrids provide a compromise between energy savings and the usefulness of a hydraulic clamp. In Japan, already 80% of the machines are all-electric [Bregar 2004]. In the U.S., the number of all-electric injection molding machines

has been growing. Since 1994, the growth in all-electric machine sales per year has reached more than 30%, while the sales of other plastics machinery has been relatively flat [Energy User News 2001].

3.2 Trends in Energy Consumption

3.2.1 Thermodynamic Model (Resin Model)

The amount of thermodynamic energy necessary to melt and inject the resin can be represented as:

$$E_{Thermo} = E_{Melt} + E_{Fill} \quad \text{Equation 1}$$

where E_{Thermo} is the total thermodynamic energy required, E_{melt} is the energy to melt the polymer, and E_{Fill} is the energy used to inject it. The energy required to melt the resin depends on whether the resin is crystalline or not, and can be expressed according to the fundamentals of thermodynamics as:

$$\begin{aligned} \text{For non - crystalline polymers : } E_{Melt} &= mc_p(T_2 - T_1) \\ \text{For crystalline polymers : } E_{Melt} &= mc_p(T_2 - T_1) + \lambda mH_F \end{aligned} \quad \text{Equation 2}$$

where m is the mass of the shot, T_1 is the polymer temperature at the hopper, T_2 is the temperature right before injection (nozzle temperature) and c_p is the specific heat capacity of the polymer. The term λmH_F accounts for the heat of fusion that must be provided to convert the polymer from the solid crystalline structure to a disorganized fluidic structure. In this extra term, H_F is the heat of fusion for 100% crystalline polymer and λ is the degree of crystallization. In the present study λ is assumed to be 60%. *Table 5* provides enthalpy values by evaluating *equation 2* for selected polymers. Average processing temperatures are used. This table also includes results from previous literature.

Polymer	Enthalpy (MJ/kg)			
	This Model	Ferromatik Milacron 2001	Todd & Black 1998	
			at 150 °C	at 200 °C
HDPE*	0.67	-----	0.54	0.67
LDPE*	0.67	-----	0.47	0.58
POLYPROPYLENE*	0.62	0.56	0.34	0.54
PVC	0.24	0.16	0.16	0.27
POLYSTYRENE	0.29	-----	0.23	0.36
PET	0.43	-----	-----	-----
POLYCARBONATE	0.37	-----	0.20	0.32
ABS	0.32	-----	-----	-----
LOW	0.24	0.16	0.16	0.27
HIGH	0.67	0.56	0.54	0.67

Table 5 – Enthalpy for selected polymers. * = polymers with 60% crystallinity. The heat of fusion of polyethylene is used as an approximation for all-polyolefins. For this model the following sources were used. For processing conditions: [Brydson 1990]. For specific heats: [MTL 2005]. And for the heats of fusion of 100% crystalline polyethylene: [Sepe 2001].

As can be observed the theoretical energy to melt these polymers ranges from 0.24 to 0.67 MJ/kg. E_{melt} represents the greatest portion of E_{total} and thus is commonly used to estimate the theoretical energy necessary to process the polymer. The E_{melt} values appear low when compared to the actual average energy requirement for injection molding machines: 1.5 MJ/kg for all-electrics to 3 MJ/kg for hydraulics (without accounting for grid's inefficiencies). *Figure 7C* graphically portrays this difference.

Regarding E_{fill} the wide array of mold geometries makes it hard to develop a formula that works for all part shapes and runner systems. Thus, a simplified model is used to illustrate the significance of this term when compared to E_{melt} .

$$E_{Fill} = \int pdV \approx \bar{p}V_{inject} \quad \text{Equation 3}$$

where p is the instantaneous pressure at each volume increment, V is the volume of the mold and runner system occupied by the melt, \bar{p} is the average injection pressure, and V_{mold} is the volume of polymer injected. The ratio of E_{fill} to E_{melt} can be described as follows:

$$\frac{E_{Fill}}{E_{Melt}} = \frac{\bar{p}V_{inject}}{mc_p \Delta T + \lambda m H_F} = \frac{\bar{p} \frac{m}{\rho}}{mc_p \Delta T + \lambda m H_F} \quad \text{Equation 4}$$

$$\frac{E_{Fill}}{E_{Melt}} = \frac{\bar{p}}{\rho c_p \Delta T + \lambda \rho H_F}$$

where ρ is the density of the polymer, ΔT is the difference between T_2 and T_1 of *equation 2*, and λ is the degree of crystallization (0 if non-crystalline and 0.6 if crystalline

according to assumption for *table 5*). The table below tabulates the E_{fill} to E_{melt} ratio for a range of average injection molding pressures.

E _{Fill} / E _{Melt}							
Polymer	Average Pressure During Injection in MPa						
	25	50	75	100	125	150	175
HDPE*	0.039	0.079	0.118	0.157	0.197	0.236	0.276
LDPE*	0.041	0.081	0.122	0.162	0.203	0.244	0.284
POLYPROPYLENE*	0.045	0.090	0.135	0.180	0.225	0.270	0.315
PVC	0.077	0.153	0.230	0.307	0.383	0.460	0.537
POLYSTYRENE	0.081	0.162	0.242	0.323	0.404	0.485	0.565
PET	0.043	0.085	0.128	0.170	0.213	0.255	0.298
POLYCARBONATE	0.056	0.112	0.168	0.224	0.280	0.336	0.392
ABS	0.074	0.148	0.221	0.295	0.369	0.443	0.517

Table 6 - E_{fill} to E_{melt} ratio for a range of injection molding pressures. * = polymers with 60% crystallinity. The heat of fusion of polyethylene is used as an approximation for all polyolefins. For this model the following sources were used. For processing conditions: [Brydson 1990]. For specific heats: [MTL 2005]. For the heat of fusion of 100% crystalline polyethylene: [Sepe 2001].

As expected at higher average injection pressure the ratio increases. On average the ratio has a value of 0.22 indicating that E_{fill} is small but significant when compared to E_{melt} .

Having presented a generic approximation for E_{Fill} , it is worth looking at a specific solution to better understand the effect of process and geometry parameters on the energy consumption. Mattis et al, provide a specific solution for the energy required to fill a flat plate following the work by Tucker [Mattis et al. 1996 & Tucker 1989]. In this derivation they use the power law formula (the second equation below), to account for the viscous flow behavior of molten polymer:

$$E_{Fill} = \frac{2^{\left(\frac{1}{s}+1\right)} 3^{\left(\frac{1}{s}\right)} \eta_0 e^{-\zeta(T-T_0)} Q^{\left(\frac{1}{s}\right)} L^2 W^{\left(1-\frac{1}{s}\right)}}{t^{\left(\frac{2}{s}\right)}}$$

where η_0 belongs to :

Equation 5

$$\eta = \eta_0 \dot{\gamma}^{\frac{1}{s}-1} e^{-\zeta(T-T_0)}$$

where t is the thickness of the plate, W is the width of the plate, L is the length of the plate, Q is the volumetric flow rate, T is the temperature of the polymer, η is the viscosity of the polymer, $\dot{\gamma}$ is the shear rate, s is the power law index ($s > 1$), and ζ is the temperature exponent of viscosity [Mattis et al. 1996]. Increasing thickness and melt temperature leads to lower energy requirements, while increasing flow rate, viscosity, width and length leads to larger energy requirements.

3.2.2 Machine Model (Includes Thermodynamic Model)

The amount of energy an injection molding machine uses is directly proportional to how efficient it is in melting and forming the resin, but also includes some additional energy terms that account for mold movements, clamping, among others.

$$E_{Total} = E_{Melt} + E_{Fill} + E_{Pack} + E_{clamp} + E_{eject} \quad \text{Equation 6}$$

where E_{pack} is the energy required to pack the mold after injection, E_{clamp} is the energy used to hold the mold shut during injection, and E_{eject} is the energy required to eject the part from the mold. E_{pack} , E_{clamp} , and E_{eject} depend on the type and size of machine and on the mold and part characteristics. According to Mattis et al. E_{pack} , E_{clamp} , and E_{eject} account for less than 25% of the process [Mattis et al. 1996].

Injection molding machines use two mechanisms to provide the necessary E_{melt} : screw rotation and barrel heaters. Of these two, the major contributor is the screw rotation which transfers energy into the polymer by means of viscous shearing. The power input into the melt by the screw can be expressed as:

$$P_{screw\ melt} = \frac{\mu\pi^2 N^2 D_b^2 WL}{\sin\bar{\theta}} \left(4 - 3\cos^2\bar{\theta} \frac{Q}{Q_d} \right) \quad \text{Equation 7}$$

where μ is the viscosity of the polymer, N is the screw speed, D_b is the barrel diameter, W is width of channel (screw characteristic), L is the axial distance of one full turn, $\bar{\theta}$ is the helix angle, Q is the delivered volumetric flow rate (flow rate at nozzle), Q_d is the volumetric flow rate that is dragged by the screw [Tadmor & Gogos 1979]. The slack energy left to reach the appropriate E_{melt} is supplied by the heaters by means of conduction and convection.

3.2.3 Observed Trends - SEC⁴ vs Throughput

Having presented the above theoretical models, this analysis will proceed to explore the relationships between energy consumption and processing parameters, such as part shape, polymer type, shot size, throughput and tonnage.

The power requirement of a hydraulic injection molding machine can be represented by the addition of a fix power “cost” and a variable power “cost”. The following function illustrates this:

$$P_{total} = P_f + P_v \quad \text{Equation 8}$$

⁴ SEC = specific energy consumption, or energy consumption per kg of processed polymer.

Where P_{total} represents the total power consumption of the machines, P_f is the fix power requirement, and P_v is the variable power requirement. In other words, P_f is the power necessary to sustain the machine during idle times. This term includes the power to run the computers and controls, the power to maintain the hydraulic pumps running, and any power to maintain heaters idling. This term is constant as long as the machine is on.

$$P_f = fn \left(\begin{array}{l} \text{size of machine, type of machine (Hydraulic, Hybrid, All - Electric), and} \\ \text{added features (hot runner, mold cooling, etc).} \end{array} \right)$$

Equation 9

P_v on the other hand is a function of machine processing parameters. For example, the more tonnage the clamping system delivers the greater P_v is (figure 6).

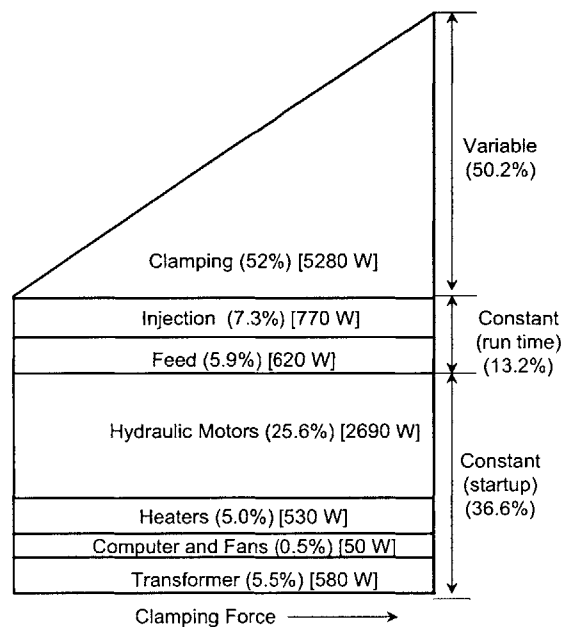


Figure 6 - Diagram of power consumption in an Engle hydraulic machine (30 ton clamp). Source: [Kordonowy 2002].

P_v also increases with increasing shot size, increasing clamping force, more demanding cycles, faster platen movement, among others. All these parameters are somewhat related to the machine throughput. A suggested form for P_v is presented below:

$$P_v = fn(\text{shot size, clamp force, screw speed,})$$

$$P_v \approx p_v \dot{m}$$

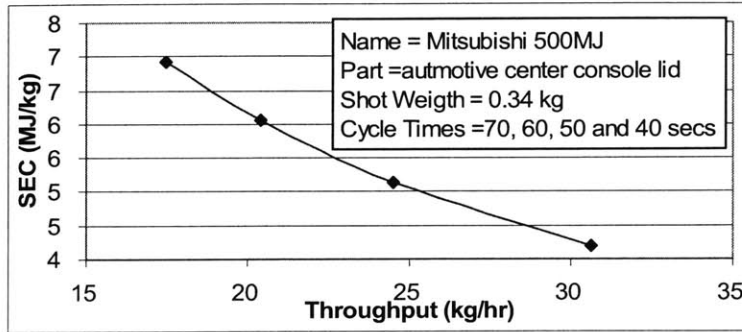
Equation 10

$$\text{where } \dot{m} = \frac{m}{t}$$

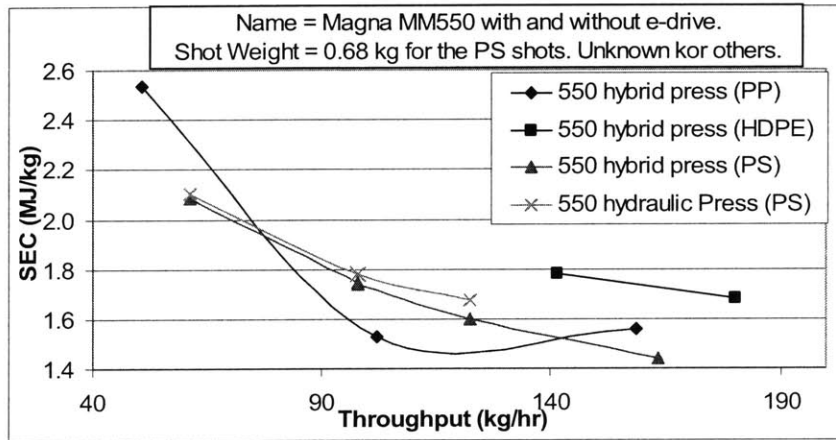
where p_v is the variable energy used per unit mass of injection molded polymer, and \dot{m} is the machine throughput, or shot size m divided by cycle time t . Joining equations 8 and 10 and dividing by throughput yields:

$$\frac{P_{total}}{\dot{m}} = \frac{E_{total}}{m} = SEC = \frac{P_f}{\dot{m}} + p_v \quad \text{Equation 11}$$

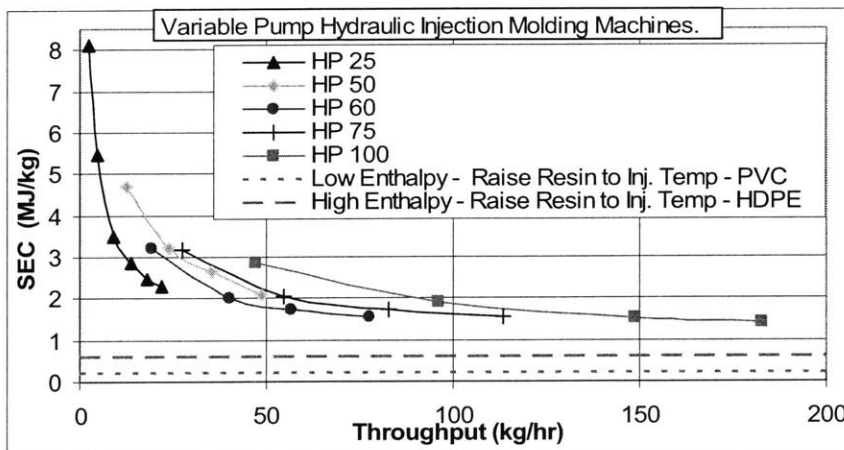
This equation is portrayed in the next several figures.



(A)



(B)



(C)

Figure 7 A,B & C– SEC vs. throughput for several injection molding machines. There is no inclusion of the inefficiencies of the grid. Source for A: [Voisard Energy Cost Comp. File]. Source for B & C: [Ferromatik Milacron Excel].

Figure 7 A, B & C show that SEC decreases hyperbolically as throughput increases approaching a horizontal asymptote determined by p_v . In other words, for small throughputs an increase in throughput causes a great decrease in SEC. For large throughputs, SEC almost appears to be independent of throughput.

Equation 11 is not only applicable to hydraulics but also to hybrids as shown in figure 7B. This is due to the obvious resemblance between the machines. Although a hybrid has an electric unit, it still has a running pump causing idle power losses. The behavior described by this equation is also applicable to a range of data from a mix of machines. Figures 8 and 9 portray this behavior for hydraulic and hybrid machines respectively.

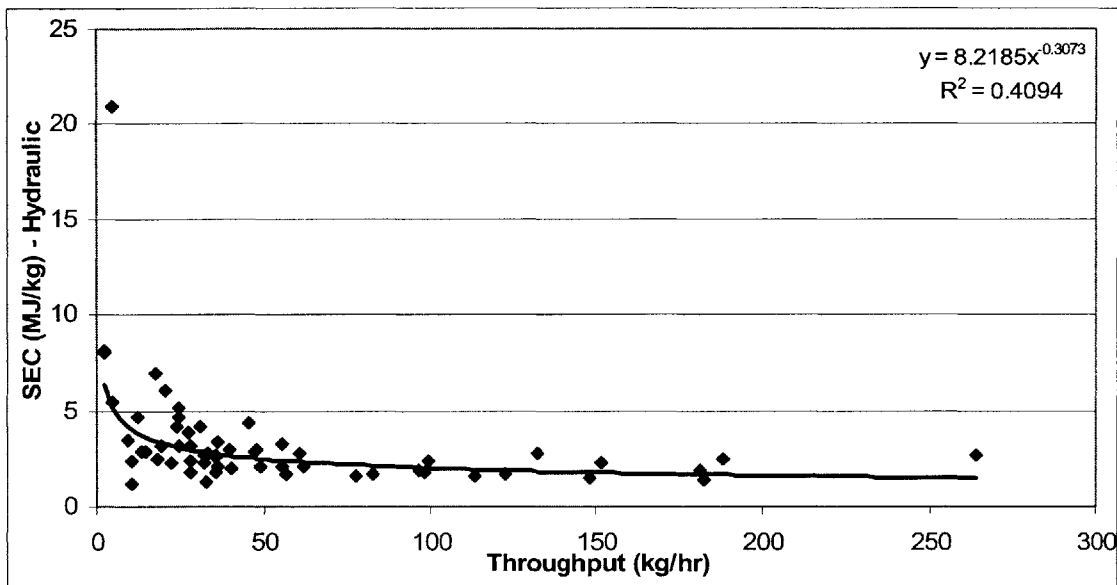


Figure 8 - SEC vs. throughput for all data available on Hydraulic Injection Molding Machines. The efficiency of the electric grid is not taken into account. A trend lines was drawn for visual aid. Low R^2 value is due to the spread in data. Sources: [Mitsubishi All-Electric ME Series], [All-Electric World Milacron], [Nunn & Ackerman 1981], [Voisard Energy Cost Comp. File], [Ferromatik Milacron 2001], and [Ferromatik Milacron Excel].

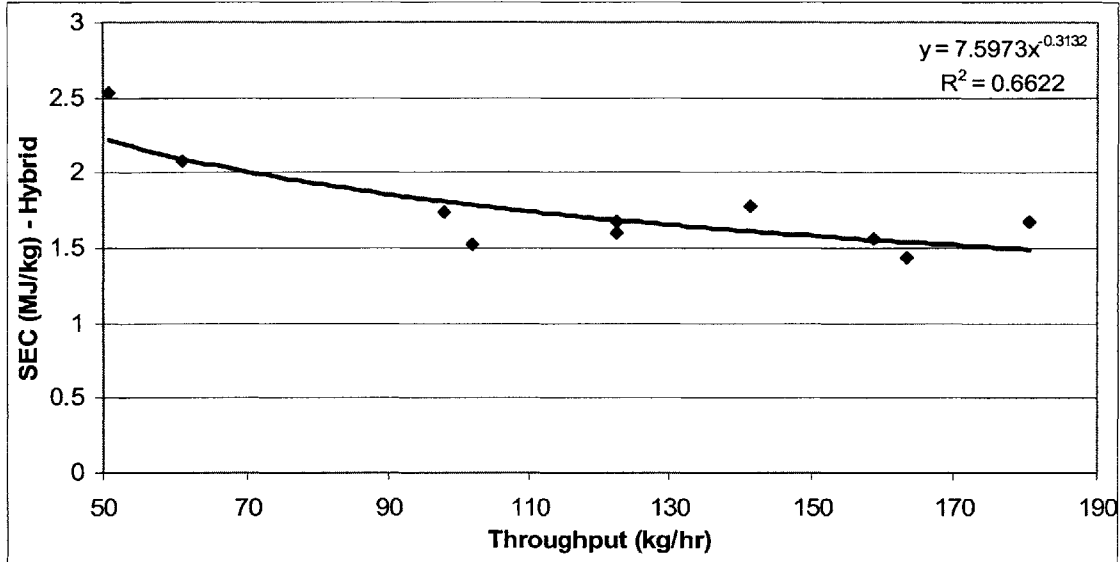


Figure 9 - SEC vs. throughput for all data available on Hybrid Injection Molding Machines. The efficiency of the electric grid is not taken into account. A trend lines was drawn for visual aid. Low R^2 value is due to the spread in data. Sources: [Ferromatik Milacron 2001] and [Ferromatik Milacron Excel].

In all-electrics, the relationship between SEC and throughput is quite different to that in hydraulic machines. Since the main sources of idling are eliminated (the idling pumps), the term P_f goes down so much it can be ignored. So from *equation 11* one is left with:

$$\text{For all-electrics: } SEC \approx p_v \quad \text{Equation 12}$$

Thus holding all other variables constant the SEC curve should be flat. *Figure 10* shows how SEC behaves as throughput increases for a hydraulic and all-electric machine.

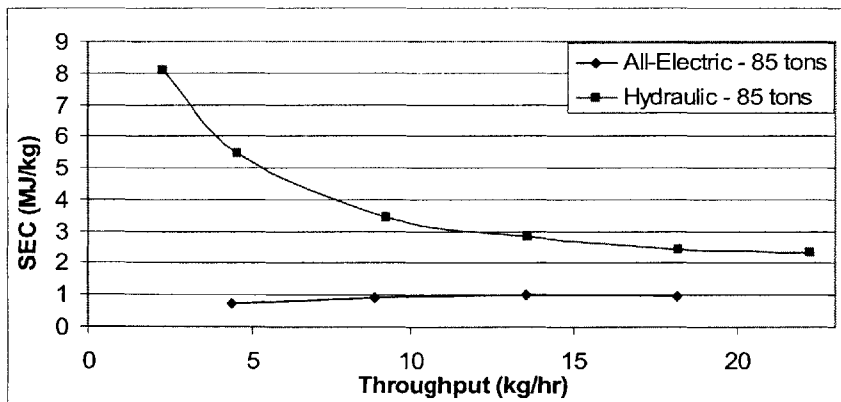


Figure 10 – SEC vs. throughput for an all-electric and a hydraulic machine. No account has been taken for the inefficiencies of the grid. Source: [Ferromatik Milacron 2001].

The hydraulic curve follows the trend predicted *equation 11*. The all-electric portrays *equation 12* with a slight modification. Instead of being completely flat, it increases faintly. Throughput can increase by increasing shot size or decreasing cycle time. Increasing shot size while keeping cycle time constant demands more of the screw and the heaters. If these were running at optimum, then the extra cycle demands lead to more than proportional increase in the energy they spend. Depending on part shape an increase in shot size can lead to a more than proportional increase in clamp pressure. In this case, though, it seems that cycle time was shortened. If cycle time is decreased, the additional clamp cycles required to increase throughput require a more than proportional energy increase [Ferromatik Milacron 2001].

Figure 11, shows *equation 12* holds for a mix of machines with different operational parameters. The deviation of the two highest points is due to the shape of the part injection molded. In this case both points represent the molding of a seal, which has a large projected area relative to its volume. This type of molding is penalized when normalizing by mass, since it is really demanding on clamp force and injection pressure, but has a small mass.

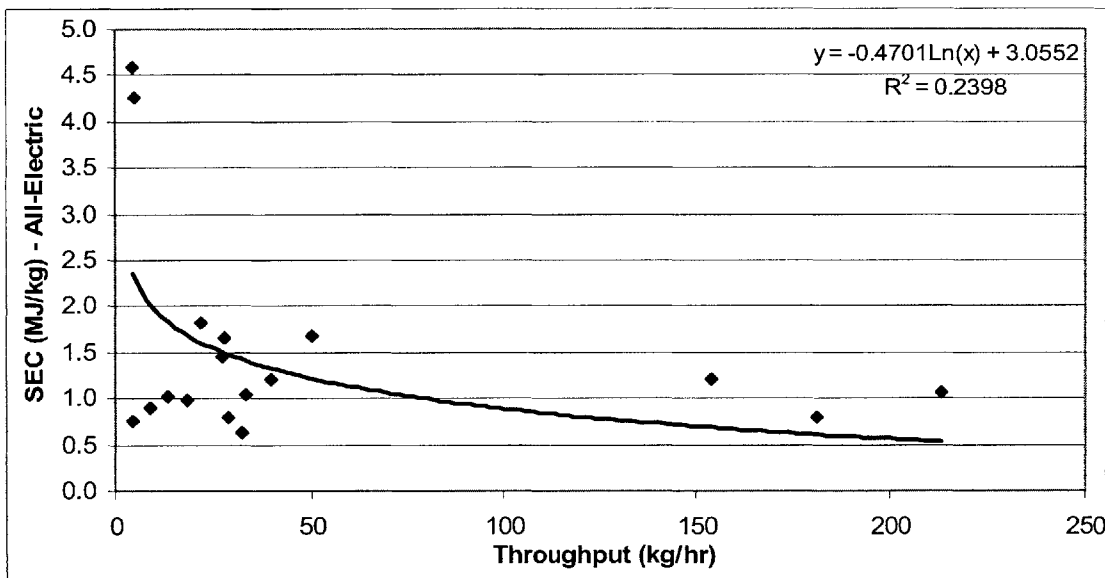


Figure 11 - SEC vs. throughput for all data available on All-electric Injection Molding Machines (not including efficiency of the electric grid). A trend line was drawn for visual aid. Low R^2 values are due to the spread in data. Sources: [Mitsubishi All-Electric ME Series], [All-Electric World Milacron], [Voisard Energy Cost Comp. File], [Ferromatik Milacron 2001], and [Ferromatik Milacron].

3.2.4 SEC vs. Polymer Type

Another factor that affects SEC is polymer type, as shown in *figure 7B* (in the previous sub-section). Each polymer has its own specific heat capacity, thus requiring different amounts of heat to melt. Crystalline polymers have an extra energy requirement to

transform from solid crystal to melt. This energy receives the name of heat of fusion. *Table 5* gives enthalpy values for several polymers. In this case, enthalpy includes all the energy necessary to raise the polymer to the processing temperature. Thus the higher the enthalpy, the higher the expected SEC value. According to these enthalpy values HDPE should be the hardest to melt followed by polypropylene and then by polystyrene. This indicates that the middle point in the polypropylene curve in *figure 7B* exhibits abnormal behavior since it lies under both of the polystyrene curves.

The viscosity and hygroscopia of the polymer also play an important role determining energy consumption. According to *equations 5* and *7* increasing viscosity increases both the energy required to fill the mold and the energy supplied by the screw for viscous work. Hygroscopia refers to whether a polymer needs to be dried or not⁵. When a polymer is dried before injection molding, less energy is necessary to process it since its entering temperature is substantially higher than if it had not been dried. In other words, the ΔT term in *equation 2* is smaller.

3.2.5 SEC vs. Part Shape

The shape of the part injection molded has a great impact on SEC. The projected area of the part in the injection direction determines the clamping force required, which in turns determines the size of the clamping unit, affecting the energy consumption of the machine. At the same time the thickness controls the cooling time, which for large parts will control the cycle time and hence the throughput. Additionally, the thinner the part the greater the injection pressure and the temperature of the melt have to be in order to fill the mold before the melt solidifies. *Equation 5* portrays the relation between the geometric parameters of a flat plate and the energy required to fill the mold. Increasing width and length and decreasing thickness all lead to increased energy consumption. *Figure 12* graphs all those injection molding data points for which the part type was specified.

⁵ This will be explained in greater detail in the “*Drier*” section in the LCI.

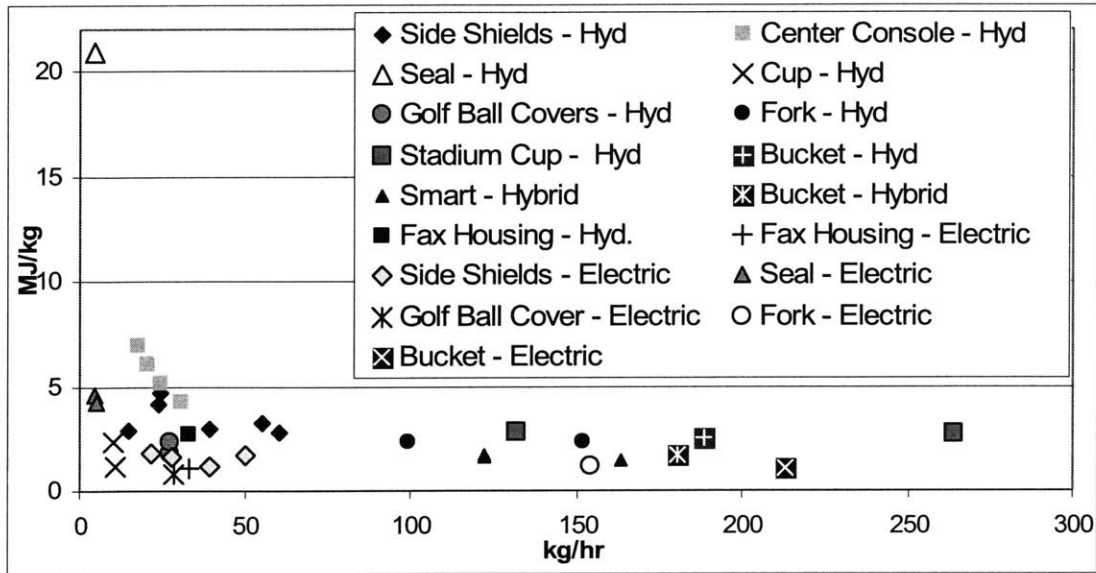


Figure 12 - SEC vs. throughput for cycles with specified part types (not including grid). Sources: [Mitsubishi All-Electric ME Series], [All-Electric World Milacron], [Voisard Energy Cost Comp. File], [Ferromatik Milacron 2001], and [Ferromatik Milacron Excel].

As shown in *figure 12*, seals, center consoles and side shields take the top spot in specific energy consumption. All these parts have large projected areas in comparison to their weight and are relatively thin. Hence, they are penalized when their energy consumption is normalized by mass.

3.3 Other Energy Savings Devices - The Hot Runner System

Aside from the drives powering the machines, there are other ways to reduce energy consumption. Hot Runners, or runnerless molds, provide an alternative to the conventional cold runner. As in the case of conventional runners, hot runners are part of the mold. A hot runner mold has a plate that is thermostatically controlled. This plate is normally made of steel and heated with electric cartridges. Its function is to keep the polymer in the runner system from solidifying and ready for the next cycle [Rubin 1972]. The use of hot runner mold has been increasing amongst injection molders. These molds allow for faster production and improved quality, making the overall production more cost-effective. Recent injection molding technologies such as insert molding, co-injection, and multi-component molding require hot runner molds [Gauler & Blundy 2005].

There are several advantages of hot runner systems that justify their cost premium over cold runner molds. Hot runners can lower cycle time and thus increases throughput. In multi-cavity cold runner molds, it is common for the runner to have the thickest cross-section of all the mold's cavities in order to distribute the melt to all the other cavities.

Thus this section takes the longest to cool. A hot runner eliminates this section, saving on the extra cooling time. During injection some time is wasted to fill the cold runner. This is not the case for a hot runner. The travel of the platens is smaller in the hot runner case, since in the cold runner case enough space needs to be created to dispose the runner system safely. The lack of a runner system simplifies the process of automation. In the case there is no robots, a hot runner saves the time labor would employ in separating the runner from the part and in part trimming. This in turn translates into labor savings. Collectively all these small savings are substantial [White 2005].

A hot runner system also implies energy savings since it requires a smaller shot for a given part. Just at the processor, this implies that the saved material does not need to be dried, process and granulated. The amount of saved material-related energy depends on the size of the cold runner system and the percentage of regrind that is allowed in each shot. Aside from energy savings, the hot runner also consumes some energy during its operation. According to Daniel Ward, Project Engineer at Husky Injection Molding Systems, a middle-of-the-range hot runner requires a power of 5350W, and runs about 50% of the cycle [Ward Interview]. With an average throughput for an injection molding machine of 61 kg/hr⁶, the hot runner SEC comes out to be 0.16 MJ/kg⁷.

Hot Runner - Energy Costs		
	Units	Values
Rated Power	kW	5.35
Used Power (50%)	kW	2.675
Avg. Injection Molding Throughput	kg/hr	61.38
SEC	MJ/kg	0.16

Table 7 - Hot Runner Specific Energy Consumption (SEC). This value does not include the efficiency of the electric grid.

The energy savings of a hot runner system versus a cold runner system can be visualized in the following two models.

3.3.1 Simplified Model

This model compares the energy consumption of the two runner systems as follows:

$$\begin{aligned}
 \text{cold runner : } \text{Energy Used} &= e \times m \\
 \text{hot runner : } \text{Energy Used} &= (e + \Delta e)(m - \Delta m)
 \end{aligned}
 \tag{Equation 13}$$

where e is the SEC of the injection molding system⁸ (compounding plus injection molding), Δe is the additional hot runner energy consumption, m is the shot size and Δm is the runner weight. Dividing both equations by $e \times m$ yields:

⁶ Average using all the throughput measurements from all machines for which data is available.

⁷ This value does not include the efficiency of the electric grid.

⁸ Please refer to the *System Boundary* subsection in the LCI section to understand the scope of e .

$$\begin{aligned}
 \text{cold runner : } \frac{\text{Energy Used}}{e \times m} &= 1 \\
 \text{hot runner : } \frac{\text{Energy Used}}{e \times m} &= \frac{(e + \Delta e)(m - \Delta m)}{e \times m} = 1 + \frac{\Delta e}{e} - \frac{\Delta m}{m} - \frac{\Delta e \Delta m}{em}
 \end{aligned}
 \tag{Equation 14}$$

So the hot runner system saves energy compared to the cold runner system when:

$$\frac{\Delta e}{e} - \frac{\Delta m}{m} - \frac{\Delta e \Delta m}{em} < 0
 \tag{Equation 15}$$

The first term ranges from 0.0213 in the case of a hydraulic machine to 0.0286 in the case of an all-electric machine. Please refer to the LCI section to find average values for e for both types of machines⁹. Regarding the second term, Mattis et al. mention that the runner-gate system is typically less than 25% of the total mold volume [Mattis et al. 1996].

Parameter	Low	High
$\frac{\Delta e}{e}$	0.0213	0.0286
$-\frac{\Delta m}{m}$	Assume low as 0.01	0.25
$-\frac{\Delta e \Delta m}{em}$	0.00009	0.0037

Table 8 – Approximated range in the parameters of equation 15

When the runner to shot weight ratio, or scrap ratio, is greater than 2%-3% then energy savings are observed when changing from a cold runner system to a hot runner one. However, when this ratio is smaller no savings are observed.

3.3.2 Systems Model

Given that:

x = amount of virgin polymer that enter the system.

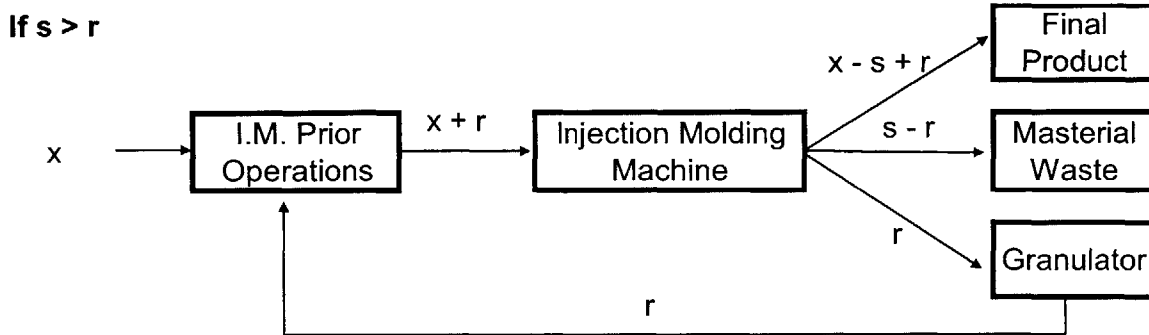
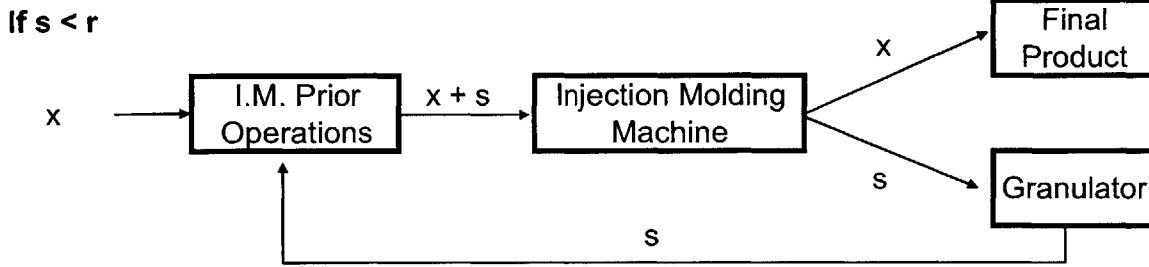
s = scrap rate (ratio between cold runner weight and shot weight).

r = allowed regrind.

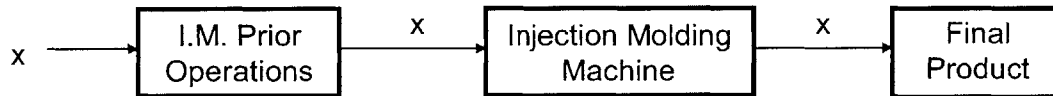
IM Operations = all other operations other than the injection molding machine at the injection molder.

⁹ Beware that the Δe in table 7 does not include the efficiency of the electric grid (30%). Thus the e values from the LCI section must be multiplied by the efficiency of the grid before finding the value of $\Delta e/e$.

From a systematic point of view, in the **cold runner** case two things can happen:



In the **hot runner** case, the system is much simpler:



When the scrap rate is smaller than the allowed regrind ($s < r$), a hot runner saves material (s) from going into the prior injection molding operations, the injection molding machine and the granulator.

In the reverse case ($s > r$), a hot runner also saves the stream of material (r) from going throughout the injection molding system. Additionally, in this case the hot runner system also saves material ($s - r$) from being discarded. The material that is discarded either gets landfilled, incinerated or recycled off-site. In this analysis two scenarios will be considered: the discarded material gets recycled off-site and the discarded material gets landfilled. In the case in which the discarded material gets recycled off-site, this analysis assumes that the recycler takes the credits and the debits from the operation. Thus no additional energy gets credited to the hot runner system from saving the discarded material ($s - r$). In the case in which the discarded material gets landfilled, the hot runner system gets credited for saving the discarded material ($s - r$) from going through the whole LCI.

The energy savings of choosing a hot runner over a cold runner system can be represented as follows:

1. When $(s - r)$ gets Recycled:

$$\text{Specific Net Savings} = sE_{IM} - E_{COST} \quad \text{Equation 16}$$

2. When $(s - r)$ gets Landfilled:

$$\text{Specific Net Savings} = \begin{cases} sE_{IM} - E_{COST} & \text{when } s \leq r \\ (s - r)E_{SYSTEM} + rE_{IM} - E_{COST} & \text{when } s > r \end{cases}$$

Equation 17

where E_{IM} is the specific energy spent at the injection molding facility, E_{SYSTEM} is the specific energy spent in the whole LCI (cradle to factory gate), and E_{COST} is the specific energy consumed by the hot runner system. Using the above equation with the all-electric injection molding values derived in the LCI section yields the following results. The reader must note that the values presented do not include the efficiency of the electric grid. If they did net savings would be about 3 times larger.

Given that:

	Inputs (MJ/kg)
E_{IM}	2.00
E_{SYSTEM}	26.62
E_{COST}	0.16

Table 9 – Energy inputs for the Hot Runner Model (in MJ per kg processed). All-electric values are used since these machines are the most efficient and thus the values obtained in the model are conservative values (lower bound). The values presented do not account for the efficiency of the electric grid. To understand these values please read the LCI section.

Then the hot runner savings are calculated as follows:

Hot Runner Energy Savings (All-Electric Machine) in MJ

Case where (s - r) gets recycled

Runner Weight as % of Shot Weight					
5%	15%	25%	35%	45%	55%
-0.06	0.14	0.34	0.54	0.74	0.95

Case where (s - r) gets landfilled

		Runner Weight as % of Shot Weight							
		5%	10%	15%	20%	25%	30%	35%	40%
Allowed Regrind %	0%	1.17	2.50	3.84	5.17	6.50	7.83	9.16	10.49
	5%	-0.06	1.27	2.61	3.94	5.27	6.60	7.93	9.26
	10%	-0.06	0.04	1.37	2.71	4.04	5.37	6.70	8.03
	15%	-0.06	0.04	0.14	1.47	2.81	4.14	5.47	6.80
	20%	-0.06	0.04	0.14	0.24	1.57	2.91	4.24	5.57
	25%	-0.06	0.04	0.14	0.24	0.34	1.68	3.01	4.34

Table 10 – Hot Runner energy savings (all-electric) as a function of allowed regrind and scrap rate. The values presented do not account for the efficiency of the electric grid. Source: [Ward Interview] and all LCI data (multiple references – see LCI section).

In the case in which the discarded material gets recycled, if the scrap rate exceeds 8% the hot runner system saves energy over the cold runner one. As expected the savings increase with increasing scrap %. In the case in which the discarded material is landfilled, when the scrap rate (s) is smaller or equal to the allowed regrind (r), then the savings from a hot runner system are moderate and increasing with the scrap rate (s), as in the recycled case. When the s is larger than r, the net savings become substantial. This behavior derives from the difference in magnitude between E_{IM} and E_{SYSTEM} .

In order to further realize the energy savings of a hot runner please look at the following example. The calculations were performed with the above model. Precise data for the polymer was used. The piece under study is a basic light cover plate.

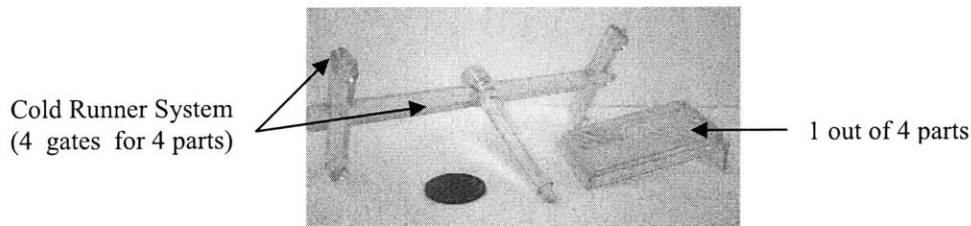


Figure 13 – Photograph of the cold runner system and one of the parts. The material is assumed to be polystyrene.

Case Study - Hot Runner Savings		
Assume 25 % allow regrind	25.00%	
Assume Machine Type	All-Electric	
Material Type	Polystyrene	
Mass of 1 Part	4.7	g
Cold Runner Mass per Part	2.75	g
	58.51%	
Hot Runner Energy Consumption	0.16	MJ/kg
Discared Material gets Recycled		
Approx. Hot Runner Energy Savings	1.01	MJ/kg
Discared Material gets Landfilled		
Approx. Hot Runner Energy Savings	10.53	MJ/kg

Table 11 – Hot Runner energy savings for the Light Cover Plate case study. The values presented do not account for the efficiency of the electric grid.

Other cost savings that can be realized with a hot runner system include mold cost savings and injection molding machine savings. With a faster production, smaller molds can be used and still satisfy the production quota. Hot runner systems allow smaller injection pressures, since the machine does not have to inject into a cold runner. In some cases, this reduction in injection pressure enables running the mold in a machine with a smaller injection unit [White 2005].

Even though hot runner molds are more expensive than cold runner molds, their cost is amortized by their numerous advantages including energy savings, labor savings, materials savings, cost savings and faster production rates.

CHAPTER 4

LIFE CYCLE INVENTORY (LCI)

4.1 System Boundaries

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 *figure 14*.

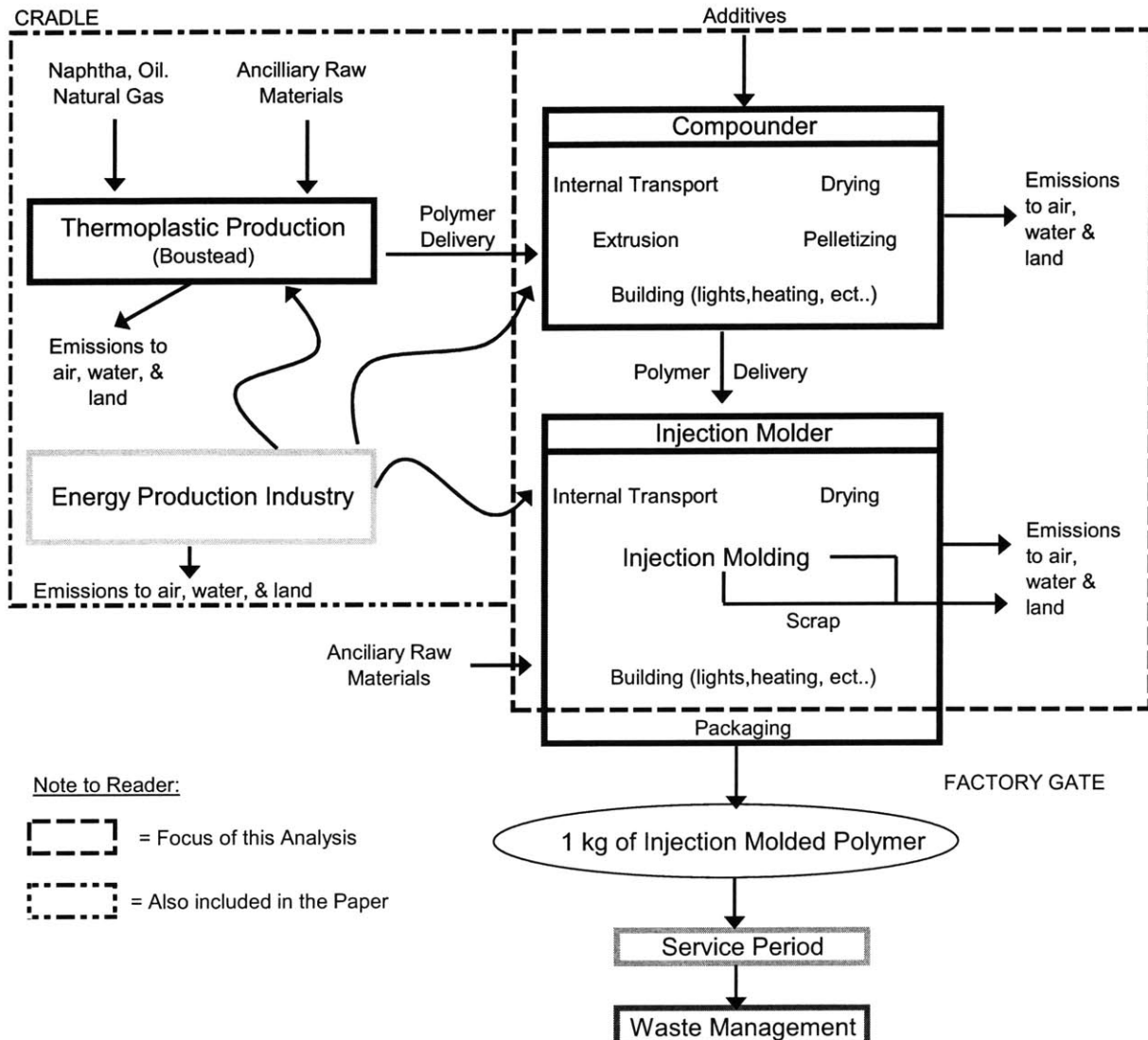


Figure 14 - Injection Molding System Boundaries

In the calculations for this LCI, several factors were omitted since their contribution would be minimal. For instance, energy and emissions associated with the building of tools, machinery and buildings, has been ignored. According to Boustead the contributions of these factors amounts to less than 1% of the total system [Boustead PVC]. The calculation also ignores the energy cost and emissions associated with the workers. The worker is thought of as an industrial machine that takes in food and needs transportation to the factory. According to Boustead, all these factors amount to 0.01% of the total energy cost in the system and thus could be ignored [Boustead PVC].

4.2 Electric Grid

Most of the processes necessary to produce 1 kg of injection molded product require energy as an input. This energy is either obtained from the electric grid or from in-house electric generators that burn coal, oil or derivatives thereof. In order to ascertain data representative of the whole industry, it is assumed that machinery utilized in the injection molding process obtains its energy from the national electric grid. The only exception to this rule are ovens in the polymer production stage, where fuels are used both as supply of energy and as feedstock for producing the polymer resin.

The composition of the electric grid is regional dependent. “The composition” refers to the percentage share that each electricity-producing source contributes to the whole electric supply. Electricity sources include: burning coal (very popular in the U.S.), burning oil, burning natural gas, nuclear energy, hydroelectric energy, and other renewable sources. Each of these sources entails a specific environmental cost. *Table 12* provides the composition of the electric grid for the U.S. and several European countries. For this research, the national composition for the U.S. was used. One could object that each state or county might have different composition. However, to represent the industry in the U.S., the national average must be used. A second general complaint against this kind of assumption is that by locating a plastic processing plant next to a source with a relatively low environmental impact, like hydraulic energy, one could argue that the plant has lower emissions than one located next to a coal burning facility. This complaint is incorrect in that by being located near a low impact electricity source, the plastic processing plant reduces the share that this low impact source contributes to the grid. Thus it has the same impact as it would have had it been connected to the general grid.

	Hydro	Nuclear	Other	Coal	Oil	Gas	Waste/ Renewable	Overall Efficiency
Austria	65	0	0	11.1	3.6	17.2	3.1	43.1
Belgium	1.6	56.9	0	23.9	1.7	14.4	1.5	29.9
Denmark	0	0	2.2	74.2	10.9	10.7	2.1	39.2
Finland	17.2	28.1	0	31.7	1.9	12.3	8.9	45.4
France	13.7	77.5	0.1	6	1.5	0.8	0.4	30.2
Germany	4.8	28.9	0.4	54.6	1.4	8.6	1.3	30.1
Greece	10.6	0	0	69.1	20	0.3	0	26.6
Italy	19.3	0	1.7	10.3	47.9	20.5	0.2	32.2
Netherlands	0.1	5	0.7	31.7	4.6	55.8	2.1	32.5
Norway	99.2	0	0	0.2	0	0.3	0.3	65.4
Portugal	43.2	0	0	36.5	17.4	0	2.9	37.9
Spain	23.5	32.3	0.2	31.4	8	3.9	0.7	32.6
Sweden	36.9	52.5	0.1	3	5.2	0.3	2	40.5
Switzerland	52.4	44.3	0	0	0.5	1	1.7	37.6
United Kingdom	1.4	27.2	0.1	42.2	4	23.5	1.6	29.1
United States	7.1	19.6	0.0	50.7	3.1	16.7	2.2	29.3

Table 12 - Percentage of Gross Electricity generated from different fuels and Overall Efficiency of the Electric Grid (including distribution) in 1993 in different European countries [Boustead PVC] and in 2003 in the U.S. [EIA 2003].

In the table above, the efficiency for the U.S. was calculated by running a regression analysis with data from Europe. Since the data from Europe is from an earlier date there might be some imprecision in this figure due to technological advancements. In order to ascertain the accuracy of this figure, MIT Professor Jeffrey W. Tester was contacted. The efficiency of the electric grid can be represented as follows:

$$\text{Grid's Efficiency} = \text{Power Plant Eff.} \times \text{Distribution Eff.} \times \text{Further Losses Downstream}$$

Equation 18

According to Tester, if one ignores nuclear and hydroelectric plants for their complexity, then the average U.S. power plant efficiency is around 35%. The distribution efficiency in the U.S. is 89%. Thus ignoring the further losses downstream (not significant), the U.S. electric grid's efficiency is approximately 31% [Tester Interview]. In the rest of the report the efficiency of the U.S. grid will be taken as 30%, which lies in between the regression value and Tester's suggested value. Thus for every MJ used in a facility, 3 MJ were consumed creating the necessary electricity.

In the U.S., over 50% of the electricity is obtained by burning coal, which has a substantial negative impact on the environment. Other major sources include nuclear energy and natural gas, contributing 20% and 17% respectively of the U.S.'s electricity needs. In 2003, using 1 MJ of electricity from the U.S. electric grid entailed the following air emissions: 171.94 g of CO₂, 0.76 g of SO₂, 0.31 g of NO_x, 6.24 g of CH₄ and 0.0032 mg of Hg [EIA 2004, EIA 2005a, & EIA 2001]. Other environmentally harmful substances are emitted during electricity production, including arsenic, cadmium, chromium, cobalt, copper, lead, nickel, tin, vanadium, zinc [Klee & Graedel 2004]. According to the Swedish EPA these are the most environmentally harmful of all heavy metals [Swedish EPA 2005]. From these emissions it is worth mentioning cadmium, lead, and mercury, which are extremely toxic for humans and for land and aquatic ecosystems. With regards to human toxicity, one way to measure toxicity is the amount of human body weight that would be exposed to the toxicologically acceptable limit, when in contact with 1 kg of the toxic substance. In the case of cadmium, lead or mercury, 580, 160 and 120 kg of human body weight respectively surpass the acceptable toxicological limit when exposed to 1 kilogram of these substances [UNEP 1996]. Toxicity for ecosystems can be measured as the volume of water (aquatic) or weight land (terrestrial) that is polluted to a critical level when exposed to 1 kg of the substance in question. In the case of aquatic ecosystems, 1 kg of cadmium, lead or mercury pollutes 2×10^8 , 2×10^6 and 5×10^8 m³ of water respectively beyond the critical limit [UNEP 1996]. In the case of terrestrial ecosystems, 1 kg of cadmium, lead or mercury pollutes 1.3×10^7 , 4.3×10^5 and 2.9×10^7 kg of land beyond the critical level [UNEP 1996].

In this LCI the impact from the electric grid is factored in by dividing the energy consumption figures of the several stages by the efficiency of the grid and then adding the CO₂, SO₂, NO_x, CH₄ and Hg emissions for each MJ of energy used.

4.3 Polymer Production

Considering the entire injection molding system, the greatest impact to the environment results from the polymer producing stage. Its main sources of environmental harm include its high energy consumption, the toxicity of some of the substances needed, and the emissions of these substances to air, water and land. Since there are several hundred types of plastics in the market that can be used for injection molding, this analysis is constrained to the six most consumed thermoplastics in the U.S.: high density polyethylene (HDPE), low density polyethylene (LDPE), linear low density polyethylene (LLDPE), polypropylene (PP), polyvinyl chloride (PVC), and polystyrene (PS) [Probe Economics 2000]. The analysis also includes one engineering plastic, polycarbonate (PC), to illustrate a more demanding injection molding plastic and polyethylene terephthalate (PET) for its importance in similar processes, such as blow molding.

In order to give an example of the sort of process involved in the formation of one of these polymers, the production process for PVC is summarized below. PVC is a synthetic polymer material which is produced by creating vinyl chloride monomer which is then polymerized into the chain structure shown below.

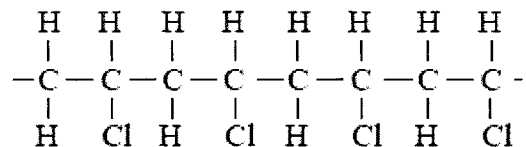


Figure 15 - PVC Structure. Adapted from: [Boustead PVC].

Crude oil, natural gas, and sodium chloride constitute PVC's starting raw materials. Ethylene is obtained from cracking¹⁰ crude oil and natural gas. Chlorine is obtained by electrolyzing sodium chloride in an aqueous solution. Sodium hydroxide and hydrogen are co-products in this reaction. The obtained ethylene and chloride are reacted together to produce Ethylene Dichloride or dichloroethane (EDC), which undergoes cracking to yield vinyl chloride monomer (VCM) and hydrogen chloride (HCL). To efficiently use chlorine, HCl is further reacted with ethylene and oxygen to obtain more EDC, which then leads to more VCM [Boustead 2003]. A diagrammatic explanation of this process is offered below:

¹⁰ Cracking = the application of heat and pressure to break a hydrocarbon into lighter components.

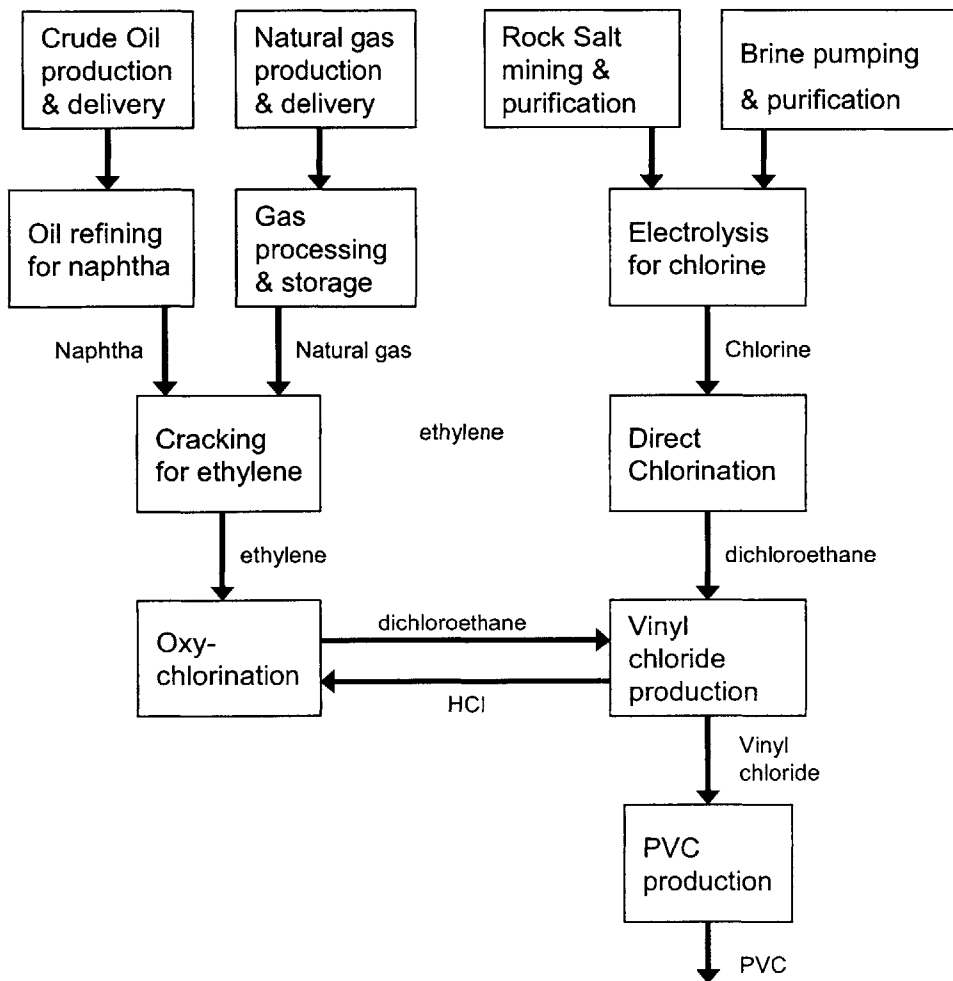


Figure 16 – Diagram of the PVC Production Process. Adapted from: [Boustead PVC].

There are three production polymerization processes for PVC, each using a different technology: suspension, emulsion and bulk. They differ in that the physical properties of the resulting PVC are different. Suspension PVC represents more than 80% of the whole PVC market, while emulsion PVC constitutes about 10% and bulk PVC about 5%. This analysis will use data for Suspension PVC since it is the most abundant.

It is worth noting that in the above example as well as in the production of other polymers, fuels such as oil and natural gas are used both for providing the required energy and as feedstock (raw material). As in the case of producing electricity, producing these fuels is accompanied by an energy cost that needs to be accounted for.

Polymer production has always been a very energy intensive process. The world modeling exercises in 1960's along with the mid 1970's oil crisis emphasized the limited availability of fossil fuels and potential conservation problems. This led the polymer producing industry to take action to improve its plants' efficiency [Boustead 2003].

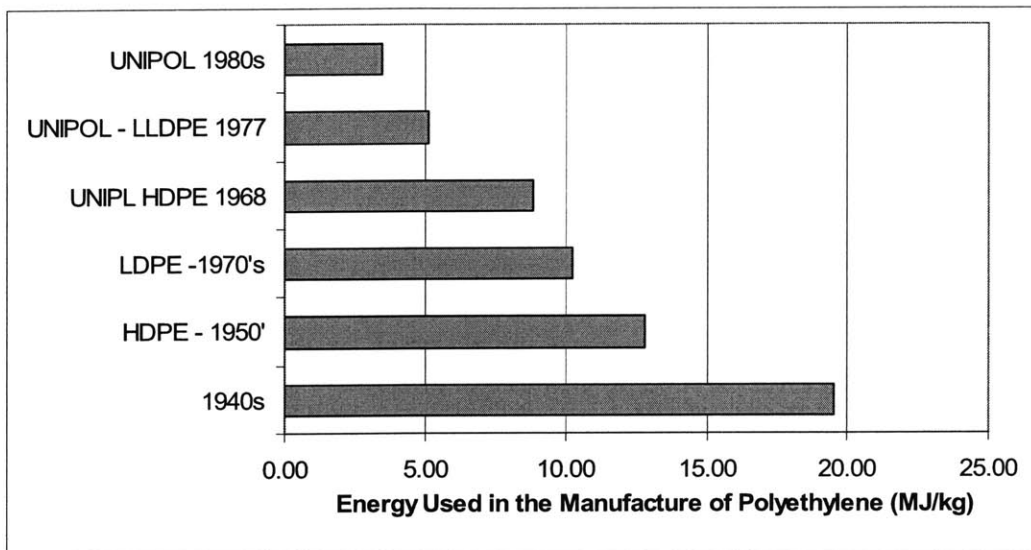


Figure 17 - Improvement in the Energy used in the “manufacture” of polyethylene (at plants). No inclusion of electric grid or material related energy costs. Adapted from: [Joyce 1990].

However the problem not only lies in the plant, but in all the steps leading to the production of polymers. This is where LCA/LCI¹¹ analysis is valuable. It not only provides an environmental balance sheet of input/outputs of the system, but also enables the identification of areas needing improvement. In the 1990’s, the APME (Association of Plastics Manufacturers in Europe) lead an initiative to develop a knowledgeable database of LCI of the main plastics and fuels under the supervision of Ian Boustead [Boustead 2003]. Other LCI’s have also been created by researchers such as M. Patel and organizations such as the U.S. OIT¹² [Patel 1999 & OIT 1997]. The table below extracts from a diverse set of LCI’s the energy required to create 1 kg of each of the polymers studied in this report. While the OIT’s LCI’s refer to the U.S., the other studies are based on European data.

Sources	HDPE	LLDPE	LDPE	PP	PVC	PS	PC	PET
Boustead	76.56	77.79	73.55	72.49	58.41	86.46	115.45	77.14
Ashby	111.50	-----	92.00	111.50	79.50	118.00	-----	-----
Patel	-----	-----	64.60	-----	53.20	70.80	80.30	59.40
Kindler/Nickles [Patel 1999]	-----	-----	71.00	-----	53.00	81.00	107.00	96.00
Worrell et al. [Patel 1999]	-----	-----	67.80	-----	52.40	82.70	78.20	
E ³ Handbook [OIT 1997]	131.65	121.18	136.07	126.07	33.24	-----	-----	-----
Energieweb	80.00	-----	68.00	64.00	57.00	84.00	-----	81.00

Table 13 - Energy Requirement in MJ to produce 1 kg of selected polymers. The sources indicate where the information was obtained. These values include the efficiencies of their respective electric grids.

¹¹ LCA = life cycle analysis. LCI = life cycle inventory

¹² OIT = Office of Industrial Technologies.

As can be observed, the above LCI values exhibit some variation. These variations can be attributed to several factors. One is the differences in geography, which imposes differences in the electric grid, in transportation, and in feedstock. These differences in geography refer not only to countries, but also to regions within countries. Another factor that explains the energy differences has to do with variations on where the system boundary is drawn. Patel does not include ancillary materials used in small quantities in his analysis, while Boustead does. Whether a high heating value or low heating value is used in the calculations can also lead to major differences. For instance, Boustead uses HHV while Patel uses LLV. In accounting for machine maintenance, start-up and shut down can also lead to differences in the measurements as it alters throughput. Patel has rather high operating rates as he assumes 100% continuous production [Patel 1999]. The technology used to produce the polymer together with the time of the study can also account for the differences in data, as illustrated in *figure 17*.

When needed, this study relies on the results provided by Boustead in his eco-profiles.

The following table presents a summary of the main emissions generated in the production of selected thermoplastics.

Emission	g							
	HDPE	PP	LDPE	LLDPE	GPPS	S. PVC	PC	PET
Dust	0.85	0.76	0.92	1.42	1.52	3.22	6.69	5.04
CO	11.58	5.79	2.44	2.25	1.62	1.37	3.61	5.96
CO ₂	1618.00	1687.40	1704.57	1665.92	2560.89	1889.73	4964.48	3130.85
SOX	4.05	3.59	4.96	3.90	9.46	9.65	12.42	23.35
NOX	2.82	2.72	3.41	2.76	11.27	9.69	19.28	16.06
HCl	0.07	0.05	0.07	0.06	-----	-----	-----	0.18
HC	3.46	2.73	2.69	1.78	-----	-----	-----	-----
Organics	0.07	0.07	-----	-----	-----	-----	-----	-----
Hydrocarbons	-----	-----	-----	-----	2.63	2.26	5.08	11.52
HCl	-----	-----	-----	-----	0.03	0.14	0.13	-----
Metals	-----	-----	-----	-----	-----	-----	-----	0.06
Hg	2.53E-05	1.87E-05	4.53E-06	2.25E-06	6.15E-05	4.99E-04	4.99E-04	1.02E-04
CFC/HCFC	-----	0.02	-----	-----	-----	0.03	-----	-----
Organics	-----	-----	0.11	0.24	-----	0.02	0.34	0.19
H ₂	-----	-----	0.02	0.01	0.04	1.58	0.90	0.46
Organo-Cl	-----	-----	-----	-----	-----	0.01	0.33	-----
CH ₄	9.08	7.73	9.20	7.39	8.99	8.88	18.28	10.25
Aromatic HC	0.08	0.09	0.03	0.02	0.21	-----	0.09	0.36
VOC	0.16	0.02	0.49	0.07	-----	-----	-----	1.32
Ammonia (NH ₃)	-----	-----	-----	-----	-----	0.08	-----	-----
DCE	-----	-----	-----	-----	-----	0.08	-----	-----
VCM	-----	-----	-----	-----	-----	0.09	-----	-----
Aldehydes (CHO)	-----	-----	-----	-----	-----	-----	0.06	-----

Table 14 - Air emissions from polymer production, per kg of polymer processed. These emissions come from all the steps leading to the production of the polymer: from mining the oil to producing the polymer. Only those emissions larger than 10mg are presented. Hg violates this previous statement but is presented for its environmental significance. Source: [Boustead PE, PS, PVC, PC & PET]

If interested in emissions to land and water please refer to the Boustead Eco-profiles [Boustead PE, PS, PVC, PC & PET]. A link to an electronic copy of these documents is provided in the “References” section.

4.4 Note on Averaging Data

In the following sections of the LCI, most of the data obtained for each process portrays variation according to the type of polymer processed, machine models, machine rate and source of data. With the exception of variation by polymer type, the data is averaged for all the rest with equal weight.

Data with variation by polymer type was averaged in two ways.

1. If there was data for all the 6 main thermoplastics then the data was averaged and weighted according to the U.S. injection molded amounts of these 6 main plastics (*table 15*).
2. If data did not exist for each of the main thermoplastics then the data was averaged with equal weight. In each subsection when averages are presented, the different polymers related to the data will be specified.

In the case of the polymer production data, in the *Overall Section* two averages are presented: generic by amount consumed and generic by amount injection molded. The “generic by amount consumed” is the weighted average of the six main thermoplastics according their total U.S. consumption. The “generic by amount injection molded” is the weighted average of the six main thermoplastics according their injection molded amount.

	Million kg		%	Data Year
	Consumption	Injection Molded		
HDPE	6108	1023	17%	1997
LDPE	3518	134	4%	1997
LLDPE	3600	268	7%	1997
Polypropylene	4001	1653	41%	1997
Polystyrene	2907	2180	75%	1997
PVC	6395	313	5%	1996+1997 data
Total	26529	5571	21%	

Table 15 – U.S. consumption and injection molded amounts for the 6 main thermoplastics. Source: [Brydson 1999] and [N.C DENR 1998].

From *table 16* one can obtain the weighting factors for both generic polymers:

	Percentage Share of Market	
	Total Market	Injection Molding
HDPE	23.0%	18.4%
LDPE	13.3%	2.4%
LLDPE	13.6%	4.8%
PP	15.1%	29.7%
PS	11.0%	39.1%
PVC	24.1%	5.6%

Table 16 - Percentage share of the "6 Main Thermoplastics' Market". Source: [Brydson 1999] and [N.C DENR 1998].

4.5 Transport

In the model created for this study, the polymer has to be delivered twice. First, the polymer is transported from the polymer producing facilities to the compounder, and later it is delivered from the compounder to the injection molder. This is assuming that compounding is not done "in-home" either at the resin producer or the injection molder. If the compounding were done "in-home," then one must subtract one of the transport values from the model. The model also assumes that each of these manufacturing facilities is 100 km away from each other. Polymer can be delivered either in plastic sacks or in bulk in a tanker, by train or boat, or. Since most of the industry works on economies of scale, it is safe to assume that all transportation is done via tanker. And since the scope of this report is geographically based in the U.S., it can be assumed that the tanker was transported by train. This assumption is backed by the fact that imports of resin in the U.S. represent just 13% of the total U.S. resin production¹³ [Probe Economics 2000]. It also assumed that on the return trip, when the tanker is empty, the train consumes only 70% of the energy utilized when the tanker is full.

Several studies, including Boustead's PVC Conversion Processes, and the BUWAL and Idemat databases, include data on the energy consumption and emissions of such tankers. The table below portrays the results of the above studies under the current set of assumptions.

¹³ In 1999, the U.S. exported around 25% of its resin production (\$11.7 billion dollars). With a resin import value of 5.6 billion dollars, the situation resulted in net exports of value of \$6.1 billion dollars. The value of the total shipments of U.S. produced resins was \$42.5 billion dollars [Probe Economics 2000]. It is assumed that the price of resin imported, exported and nationally traded is the same.

		Source		
		Boustead	BUWAL 250	Idemat 2001
Energy				
	MJ	0.21	0.12	0.24
Air Emissions (selection)				
CO2	g	14.41	4.90	17.68
SOx	g	0.07	0.02	0.04
NOx	g	0.15	0.02	0.04
Particulates	g	0.01	0.01	0.02
Methane	g	----	0.01	0.05
VOCs	g	0.05	0.02	0.00
Water Emissions (selection)				
Suspended Solids	g	0.04	----	----
Chloride	g	----	0.03	0.06
Land Emissions (selection)				
Mineral Waste	g	0.46	----	1.85
Slags& ashes	g	0.03	----	----
Mixed Industrial	g	0.02	----	----

Table 17 - Energy requirements and emissions for the transportation of 1 kg of polymer 100km. Regarding emissions, cut-off value is 0.005 g. Not adjusted for the U.S. grid due to small relevance and to the lack of knowledge of the mix of energies used (Diesel and Electricity).

Although the values above are relatively small compared to the contribution of the other steps in the LCI, it is worth noting that the assumption of 100km as the distance between manufacturing facilities is probably an underestimate, making the figures above lower than they would be in reality. For instance, if in fact there were 500km between facilities, then the energy consumption jumps up to 1 MJ/kg!

4.6 Extruding

In the scope of this injection molding model, extrusion is used during compounding to uniformly mix the resin with its additives. Basically, the polymer, along with its additives, is molten and forced through a die, creating an object of constant cross-section. In fact, the mixing unit of an extrusion machine is really similar to that of an injection molding machine. Although there are fewer machines in extrusion than in injection molding, much more polymer goes through these machines than it does through injection molding ones [Brydson 1990]. Extrusion is not only used in compounding, but is also used to make finished products such as film, piping, ducting, and cable [Brydson 1990].

4.6.1 The Additives

The purpose of compounding is to modify the polymers properties by means of adding additives, fillers, and reinforcements. The combinations of the available compounds to be mixed with the polymer are pretty much infinite. For instance, additives include antioxidants, antistats, anti-blocks, UV stabilizers, heat stabilizers, flame retardants,

nucleating, crosslinking, blowing agents, slip agents, biostabilizers, and colorants¹⁴. In the case of fillers and reinforcements a partial list includes: carbonates, silicates, graphite, mica, talc, glass fibers, and carbon black. All these additives can be added in different sizes and grades. Specific polymer properties require a specific recipe; the ingredients include the polymer and some the compounds listed above [Todd & Black 1998]. Each recipe comes with its own environmental damage and emissions. Since the objective of this study is to give a systematic view of the process, it does not cover just one recipe. Therefore additives are treated as if they were part of the polymer they are being mixed with. This is reasonable since in general additives constitute a minority by weight in the polymer matrix. The table below provides a brief listing of some additives used in term of their annual U.S. consumption.

Additive Type	Millions kg			
	1997	1987	1992	2000
Fillers	1,646	2,539	3,014	3,795
Plasticizers	645	770	834	929
Reinforcements	280	406	518	727
Flame Retardants	174	233	302	439
Colorants	126	199	239	302
Impact Modifiers	26	59	73	91
Lubricants	35	44	52	68
Heat Stabilizers	39	38	41	46
UV Stabilizers	2	3	4	6
Antioxidants	12	19	23	27
Organic Peroxides	15	20	24	32
Chemical Blowing Agents	6	6	7	8
Antimicrobial Agents	3	5	6	8
Antistatic Agents	2	4	4	6
Urethane Catalyst	2	3	3	4
Others	18	47	59	78
Total Additives	3,031	4,395	5,203	6,566
Total Plastics	13,866	22,664	27,727	36,636
% Additives to Plastics	21.86%	19.39%	18.77%	17.92%

Table 18 – Additives consumed annually in the U.S. Source: [Todd & Black 1998].

Several additives are worth mentioning due to their environmental impact and the press attention they have received. One of them is the group of fluorinated blowing agents, heavily used for plastic foams, specially in polyurethane and extruded polystyrene foams. Fluorinated blowing agents, like CFCs and HCFCs, have a tremendous global warming potential¹⁵, ranging from the 600 for HCFC-141b to 3800 for CFC-11 (with an integration time horizon of 100 years) [Barthélemy 1999]. The trend in industry has been to move from CFCs to HCFC and organics due to their lower GWP compared to CFCs. Some, like extruded polystyrene packaging and flexible PU foams, have been able to

¹⁴ Colorants are generally added at the Injection Molding Facility.

¹⁵ Global warming potential is generally measured in CO₂ equivalents, meaning that 1 g of the substance under consideration contributes to global warming as much as X grams of CO₂. CO₂ would thus was a global warming potential of 1.

completely switch away from these blowing agents, but other have not been able for technical and economical reasons. In 1996, 173 million CO₂ equivalent metric tons of fluorinated blowing agents were consumed. This value was 22% of the 1990 value and is expected to decrease to 106 by the end of 2005 [Barthélemy 1999].

Phthalates, a type of plasticizers, are most important due to their large quantity and their strong environmental hazards. PVC by itself consumes about 80% of the phthalates produced [Malin & Wilson 1994]. Common phthalates include: bis-2-ethylhexyl phthalate (DEHP), diisodecyl phthalate (DIDP) and diisononyl phthalate (DINP). Two of these, two phthalates (DINP and DEHP) have potential adverse effects on liver, kidney and testicles. The presence of these two phthalates on children toys (specially those that can be sucked on) is a raising concern in the EU's Scientific Committee on Toxicity, Ecotoxicity and the Environment (CSTEE) [CEC 2000]. According to the U.S. EPA, DEHP is a probable human carcinogenic based on the evidence of carcinogenicity in animals [IRIS 1997].

Another example of hazardous additives is lead, cadmium and organotin stabilizers, which in the case of PVC are used to prevent polymer degradation from heat and light [CEC 2000]. Substitutes for these stabilizers, such as calcium-zinc stabilizers and tin organic stabilizers, are already being used. They are still not completely benign but their hazardous potential is supposed to be lower. Higher costs and technical difficulties have delayed industry's transition to these substitute stabilizers [Malin & Wilson 1994]. It must be noted that some of these substitute compounds are toxic for the human immune system and damage marine wildlife [CEC 2000].

4.6.2 Extrusion Machinery

There is a great variety of extrusion machinery. In compounding, the two most widely used are single-screw extruders and twin-screw extruders [Todd & Black 1998]. There are 3 types of twin extruders: co-rotating, counter-rotating intermeshing and counter-rotating non-intermeshing. The table below gives the output capacity (throughput) and the type of polymers compounded in this type of machines.

Extruder Type	Polymer applications	Polymer Output Capacity (kg/hr)	
		Low	High
Single-Screw	All thermoplastics	45	7275
Twin-screw			
Co-rotating	Nylon, thermoplastic polyester, polypropylene and styrenics	225	32000
Counter-rotating Intermeshing	Styrenics, all polyolefins, vinyls, ionomers, nylons, engineering thermoplastics and elastomers	70	5000
Counter-rotating Non-intermeshing	PVC, polypropylene, styrenics, polycarbonate and nylon.	180	9100

Table 19 – Characteristics of single-screw and twin-screw extruders. Source: [Todd & Black 1998]

As portrayed above, twin-screw corotating and counterrotating non-intermeshing extruders provide on average the highest throughputs. This extruder types are ideal for compounding lines where throughput is of great concern. The table below provides a comparison between a single-screw extruder and a corotating twin extruder. The twin extruder exhibits lower specific energy consumption values for a given screw speed. For both extruders higher screw speed (higher throughput) yields lower specific energy consumption. As throughput increases, fixed energy costs are spread over more kilograms of polymer. The maximum temperature that a polymer can sustain without degrading limits the screw speed at which the machine can run. In order to partially bypass this limitation extrusion machines include cooling systems together with heating systems along the barrel. This allows them to carefully control the temperature profile of the polymer along the barrel and thus optimize for screw speed [Radovich Interview].

Screw Speed	Energy values in MJ/kg (Not including grid)			
	Single Screw w/ enlarged feed zone		Coorotating Twin Screws (67 mm in Diameter)	
	PP flakes	LDPE	PP flakes	LDPE
(r/min)				
50	1.35	1.17	1.28	1.04
150	1.28	1.08	1.17	0.9
300	-	-	1.04	0.72

Table 20 – Specific Energy Consumption for a single-screw extruder and a comparable corotating twin-screw extruder. The values above do not account for the efficiency of the electric grid. Source: [Tenner 1997].

In this report, energy measurements for extrusion machinery are extracted from the works of several researchers including H. Tenner, Ian Boustead, Baitz, and Kinkler and Nickles, from an industry contact, John Christiano at Davis-Standard LLC, and from a study from the Department of Science, Technology and Environment (DOSTE) of Ho Chi Minh City. The following table presents energy measurements adjusted to the U.S. grid (30% efficient). Some of the sources cited below provide several energy measurements for one or multiple types of machines. In those cases, the values were averaged each with equal weight.

Sources/ Data Included	Required Energy (MJ)				Polymer
	Avg	Low	High	# pts	
Tenner 1997 Extrusion Machine	3.68	2.40	4.50	10	PP, LDPE
Christiano 2005 Extrusion Machine	2.59	1.82	3.31	3.00	HDPE
Boustead Conv. PVC & PE Full Extrusion Facility	7.38	7.01	7.75	2	PVC, HDPE
Baitz et al. 2004 Extrusion Machine	4.00	3.00	5.00	2	Unspecified
Kinkler and Nickles [Vinidex 1996] Extrusion Machine	4.00	----	----	1	Unspecified
DOSTE 2002 Full Extrusion Facility	12.84	----	----	1	Unspecified

Table 21 - Energy required for the extrusion of 1 kg of polymer. Additives are treated as the polymer itself. These values include the efficiency of the electric grid (U.S. grid = 30%). The 4th and 5th source could not be adapted to the U.S. electric grid due to lack of information about their respective electric grids. Unspecified means that the polymer type was not specified for the data points.

As can be observed, extrusion contributes substantially to the energy load in the injection molding model. Emissions from the process itself are minimal when compared to the resin production stage [Boustead Conversion PVC]. Emissions from the process will be treated as a separate subsection, covering both extrusion and injection molding. Since the machines are similar, the emissions from an injection molding machine will be considered representative of those of an extrusion machine, and vice versa.

4.7 Size Reduction

Two steps in the injection molding model, involve size reduction. Size reduction refers to the transformation of a polymer of a certain shape to a smaller form by means of shredding and cutting. The first size reduction operation occurs as polymer comes out of the extrusion machine in a constant cross-section shape. In order to be transported and fed into the other plastic processing machinery, the size of the polymer needs to be reduced. A pelletizer is used to fulfill this function. Two calculations are performed with information on two types of pelletizers produced by Conair. The Conair VSP Series pelletizer takes in molten polymer directly, and then drives it through a set of annular die holes where a rotating knife assembly cuts through projecting the pellets onto an outward rotating wall of water. This wall of water captures the pellets and cools them down. The pellets are then conveyed onto a spin drier where the water is separated and re-circulated back into the machine [Conair VSP]. The other type of pelletizer is the Conair T200. This model takes stranded polymer as an input and uses a rotor with several layers of teeth to transform the strands into pellets [Conair T200]. In order to calculate the energy required to pelletize 1 kg of polymer the following formula is applied:

$$\text{Specific Energy (MJ / kg)} = \frac{\text{Power (MW)}}{\text{Throughput (kg / s)}} \quad \text{Equation 19}$$

The formula is used with the assumption that maximum power usage occurs at the rated throughput. It must be mentioned that within each type of pelletizer there are different models according to the throughput desired. Each model has its own power requirements. Throughputs are also dependent on the polymer being processed. However, in order to attain a systematic view, all energy calculations were averaged, representing an average throughput for a generic polymer.

Source	Required Energy (MJ)				Polymer
	Avg	Low	High	# pts	
Conair VSP	0.24	0.16	0.44	50	Main 6
Conair T200	0.08	0.06	0.10	4	Unspecified

Table 22 -- Energy required to pelletize of 1 kg of extruded polymer. All data is relevant to the U.S (includes grid's efficiency = 30%). Unspecified means that the polymer type was not specified for the data points.

The second size reduction occurs at the end of the injection molding process, when scrap is reduced in size and in some cases is fed back into the injection molding machine. This job is done by a granulator, which takes in injection molded products of several shapes and sizes and then cuts them into small granules. Sources of scrap in the injection molding process include start-up operations, cold runner systems, and defective parts. Energy measurements for several granulating operations can be found in the work of T. Tenner 1997. Aside from his data, two calculations are performed based on information from the two Conair granulator types. The first type is the Conair Meter Feed Granulators (CLS series). These models have a low speed rotor for high quality regrind. They are meter fed and beside-the-press granulators. They are designed for robot or conveyor fed sprues, runners, and light duty parts [Conair CLS]. The second type is the Conair Batch Feed Granulators (CHS series). These models have a high speed rotor for tough batch fed jobs. They are designed for batch fed parts and runners, and tougher jobs, such as engineered polymers and bulkier cross-sectional parts. They are ideal for blow molded parts, sheet and film, small pipe, tubing, and profile [Conair CHS]. *Equation 19* is employed to calculate the specific energy requirements. As in the previous case, due to variation in throughputs, power requirements, and materials being granulated, the results are averaged to convey a systematic view.

Source	Required Energy (MJ)				Polymer
	Avg	Low	High	# pts	
Tenner 1997	0.72	0.36	1.20	5	PE, PP, PVC, PS
Conair CLS	0.38	0.31	0.43	4	Unspecified
Conair CHS	0.51	0.43	0.55	4	Unspecified

Table 23A – Energy required to granulate 1 kg of polymer (includes grid’s efficiency = 30%). Unspecified means that the polymer type was not specified for the data points.

In the current injection molding model, 100% of polymer does not get scrapped, as shown in the above table. The scrap percentage depends on the design of the injection molded part and on the type of runner system (hold or cold). Therefore it exhibits great variability across scenarios. Mattis et al. mention that the runner-gate system is typical less than 25% of the mold volume [Mattis et al. 1996]. A hot runner mold would require no polymer to be granulated. In order to find a middle ground, this analysis assumes 10% of the injection molded polymer is scrapped.

Source	Scrap Rate				Polymer
	10%				
	Required Energy (MJ)				
	Avg	Low	High	# pts	
Tenner 1997	0.07	0.36	1.20	5	PE, PP, PVC, PS
Conair CLS	0.04	0.31	0.43	4	Unspecified
Conair CHS	0.05	0.43	0.55	4	Unspecified

Table 23B - Energy expended granulating per kg of injection molded product (includes grid’s efficiency =30%). Unspecified means that the polymer type was not specified for the data points.

As can be seen, the contribution of size reduction operation is quite small when compared to other stages in the LCI. Never the less, on-site emissions arising from pelletizing and granulating are treated in the *Emissions from Polymer Processing* subsection.

4.8 Internal Conveying Systems

Internal conveying refers to all the movement of raw materials and products within a factory. In the scope of this analysis, the movement of finished products to storage and to the loading dock is ignored. This analysis looks at the movement of the raw polymer through the plant. For compounding, this includes transporting the polymer from the tanker to the resin storage container, from this container to each of the extrusion machines, from the pelletizers to storage, and finally from storage to a new tanker. In the case of injection molding the circuit is shorter involving the movement of polymer from the tanker to the resin storage container, and from this container to each of the injection molding machines. This analysis assumes that there are 30 meters between the tanker and the storage container and 30 meters between the storage container and the machines, making the total travel distance 60m for injection molding and 120 for compounding. These turn out to be a low estimates, as most resin conveying machines are rated for distances 3 times as large. The machinery used in this analysis is the Conair VRU series:

a vacuum pump delivery system [Conair VRU]. According to the desired throughput, several pumps are offered within the VRU series, leading to several energy measurements. Throughput also varies with the polymer conveyed due to different densities. For the scope of this model, the data is averaged to represent average machinery and a generic polymer. This analysis does not take into account the particulate emissions from polymer conveying, since when normalized by the weight of polymer processed the contribution of these emissions seems low.

	Required Energy (MJ)				Polymer
	Avg	Low	High	# pts	
Compounding	0.09	0.07	0.11	6	PE, PET
Injection Molding	0.04	0.04	0.05	6	PE, PET

Table 24 - Energy spent conveying 1 kg polymer in a plant (includes grid's efficiency =30%).

4.9 Drying

Drying occurs in two steps in this injection molding model: before extrusion and before injection molding. Drying is a requirement for hygroscopic resins, or resins that adsorb moisture. Hygroscopic resins include Nylon, PET, polysulfone, polyester, polycarbonate, and most of the other engineering plastics [Witzler 2001 & ESC 2005]. Many of the major polymers (PVC, HDPE, and LDPE among others) require drying depending on their additives. For instance, HDPE does not require drying, but HDPE with carbon black does [Newton Interview]. Injection molding hygroscopic resins without proper drying will cause captured water to turn into steam. This results in processing problems, cosmetic defects, or voids that become stress concentration points, all leading to product failure. In other materials the consequences are even more transcendental. For example, heating polycarbonate that absorbed water results in hydrolysis, leading to a breakdown of the molecular structure. Obviously, this entails the irreversible loss of the material's physical properties making the polymer worthless [Muccio 1994]. This last characteristic applies to other hygroscopic polymers made by condensation, such as Nylon.

Dryers are used not only to eliminate imbedded moisture in the polymer, but to evaporate surface moisture. Surface moisture in a polymer may be detrimental for processing and can cause minor surface defects. Thus non-hydroscopic resins, such as polypropylene, PVC, and polyethylene, can benefit from a trip to the drier [Newton Interview].

There are several drier types according to the type of drying mechanism used. "Hot Air Driers" are mainly used to remove surface moisture on non-hydroscopic pellets. A hot air drier takes air from the outside, heats the air, and then sends the heated air through the hopper. Inside the hopper there is a cone that allows for uniform distribution of the hot air [Shreffler Interview]. This analysis uses data from Conair's Hot Air Drier, as a representative of this type of drier [Conair HAD].

A “Desiccant Drier” is mainly used for hygroscopic materials to remove the imbedded and surface moisture. Theoretically this is done by providing an environment of a partial pressure that is at a lower pressure than the vapor pressure of the surface moisture. This allows for the evaporation of the surface moisture, letting a moisture gradient to be established within the granule. In other words, moisture migrates from the inside of the granule to the surface [Muccio 1994]. In practice this can be accomplished with several different machine architectures. This analysis will cover the architecture of Conair’s Carousel Plus Series. A diagram of its main components is provided below:

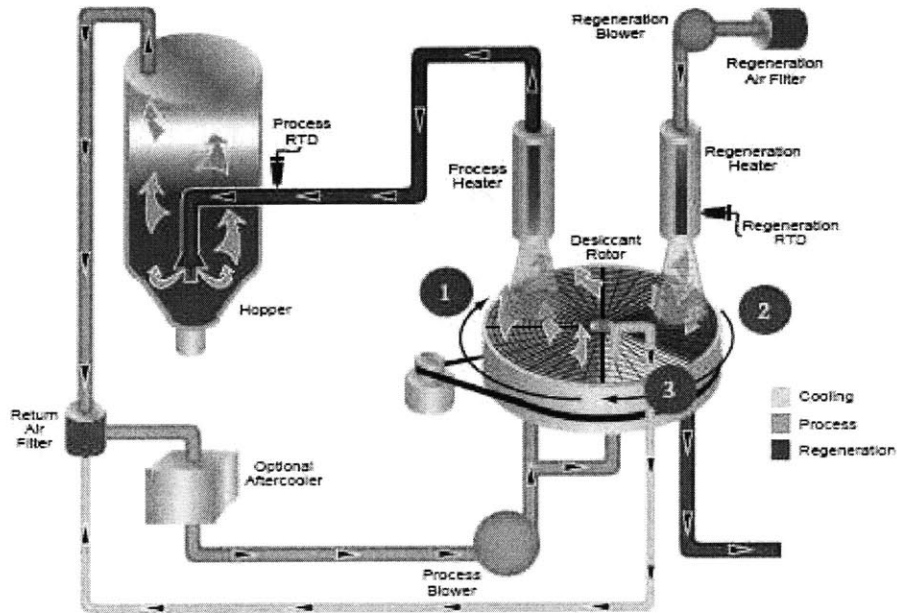


Figure 18 - Conair's Carousel Plus Drier Functional Diagram - Source [Conair CPD]

As displayed in the above diagram, air is first blown through a desiccant tray to remove its moisture (1). Then this air is heated up and blown into the hopper to dry the polymer pellets. The return air loops back and is exposed again to the desiccant. In the mean time the desiccant undergoes a regenerative cycle by which warm air is blown through it in order to evaporate its moisture (2). The desiccant then enters a post regeneration cooling stage, in which close loop air is blown through (3). One must note that if the heating temperature for the drying of the pellets is too high, the process can have an after-cooler to condensate some of the air moisture and provide the necessary cold air for the post regeneration cooling cycle. A pre-cooler can also be used in the intake cycle before the heater box. A breakdown of how energy is spent in a Carousel Plus W-300 drier is presented below.

Carousel Plus Drier W-300	MJ/kg Including Grid's Eff.			
	Process	Regen	Misc	Total
Dewpoint Control & Temp SB	0.68	0.15	0.28	1.11
Dewpoint Control Option	0.71	0.15	0.28	1.14
Temperature Setback option	0.68	0.33	0.28	1.29
Base Model	0.71	0.33	0.28	1.33

Table 25 – Energy breakdown for a Carousel Plus W-300 Drier per kg of dried polymer. Process refers to the energy consumption of the heaters in the drying cycle. Regen accounts for the heaters in the regeneration loop. Misc accounts for all the blowers, motors, and controls. The figures presented above take into account the efficiency in the production of the electricity required.

The heating unit in desiccant driers can be powered either by electricity, as in the Carousel Plus Drier case, or by means of natural gas, which is more energy efficient [Shreffler Interview & Conair CPD]. However, gas powered driers appear to be less widespread than electric desiccant driers due to costumers' perception that gas powered equipment is less mobile and less safe than electrically powered equipment [Muccio 1994].

Desiccant driers can also be used to remove surface moisture from non-hygroscopic pellets. In some cases, like for PVC, the use of a drier is not necessary but it improves the injection molding conditions and lowers the energy requirement of the injection molding machine [Newton Interview]. The latter characteristic can be easily understood if one recalls that when the pellets come out of the drier their temperature is higher than atmospheric. Usually pellets enter the injection molding machine at atmospheric temperature, but if a drier is used, the pellets enter at a higher temperature. The injection molding machine then uses less energy in raising the temperature of the pellets to melting temperature. Data from "Carousel Plus Drier Series" and the "Twin Tower Series" will be used as a representative of desiccant driers. This data was obtained from the published specifications of this machinery and from an energy analysis file provide by Bob Newton, the New England representative of The Conair Group, Inc [Conair CPD & Newton Energy Analysis]

Another type of drier is a "Vacuum Drier", which uses vacuum and heat to absorb moisture from pellets. It is a venturi type device. This analysis obtains some figures from the Maguire "Low Pressure Drier" (LPD) as a representative of this type of drier.

Most airflows in the above mentioned devices are closed-loop. Those machines that have open air flows, like some of the hot air driers, usually include air filters. These filters eliminate any particulates from the polymer left in the exiting air before it is released to the atmosphere. Thus, aside from the energy related emissions, no other emissions are considered due to their low magnitude. The table below presents the results of this analysis. As can be seen, the values fall around 1 MJ/kg, with a vacuum drier being the lower limit with 0.19 MJ/kg, and a desiccant drier representing the higher limit with 2.43 MJ/kg.

Source/Type of Drier	Required Energy (MJ)				Polymer
	Avg	Low	High	# pts	
Conair HAD Hot Air Drier	0.42	0.41	0.43	5	Non-hygroscopic
Conair CPD Desiccant	0.89	0.21	2.45	154	ABS, Acetal, Acrylic, Nylon, PBT, PC, PET, PETG, Polysulfone, Polyurethane, PPO, PPS, SAN (Hygroscopic Polymers)
Newton Energy Anal. CPD Desiccant Drier	1.62	1.11	2.22	8	PC
Newton Energy Anal. TwinTower Desiccant	2.37	1.94	2.80	2	PC
Maguire 2001 Desiccant Drier	0.44	-----	-----	1	Mainly Hygroscopic
Maguire 2001 Low Pressure Drier	0.18	-----	-----	1	Mainly Hygroscopic

Table 26 - Energy required for drying per 1 kg of polymer (includes electric grid's efficiency = 30%). Mainly hydroscopic means that the dryers are intended for hygroscopic polymers, but can also be used for non-hygroscopic polymers.

The amount of water absorbed by a polymer is a function of the polymer base and the amount of additives. Thus different polymers require different drying times, or residence times, and thus different specific power consumption, or power consumption per kg of polymer dried. The figure below portrays the average energy requirement for several hygroscopic polymers and three generic polymers. The "generic-hygroscopic" category is the average of all the hygroscopic values, and would be used for describing a non-tabulated hygroscopic polymer. The "generic-non-hygroscopic" describes those polymers that are not hygroscopic but can benefit from a trip to the drier. Finally, the "generic unspecified" describes all those polymers whose hygroscopia is unknown. This value is the midpoint between the previous two generic values. This LCI analysis uses this value to describe the energy spent drying for the main six thermoplastics, since their hygroscopia can change according to what additives they have.

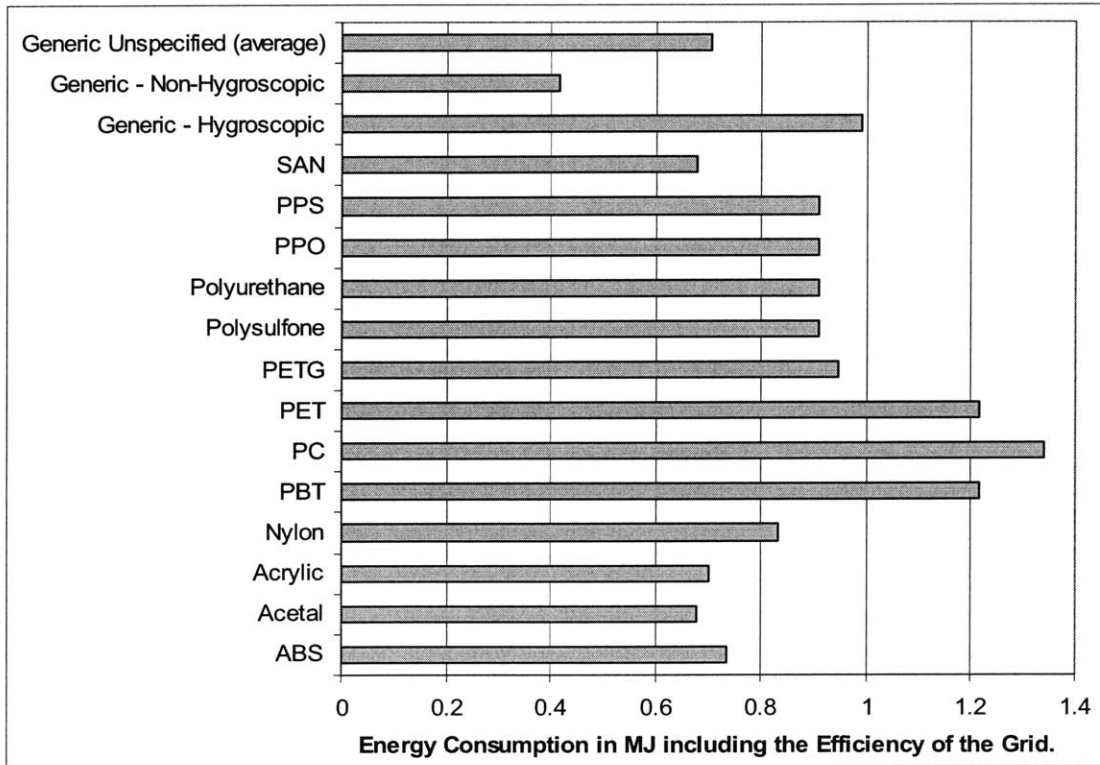


Figure 19 - Drying energy requirements for 1 kg of selected hygroscopic polymers (includes electric grid's efficiency = 30%).

From a specific energy consumption point of view, resin drying also exhibits economies of scale. In other words, as throughput of polymer dried increases (bigger machines), the specific energy consumption decreases, as shown in the following figure. This trend is observed in most of the injection molding auxiliary machinery.

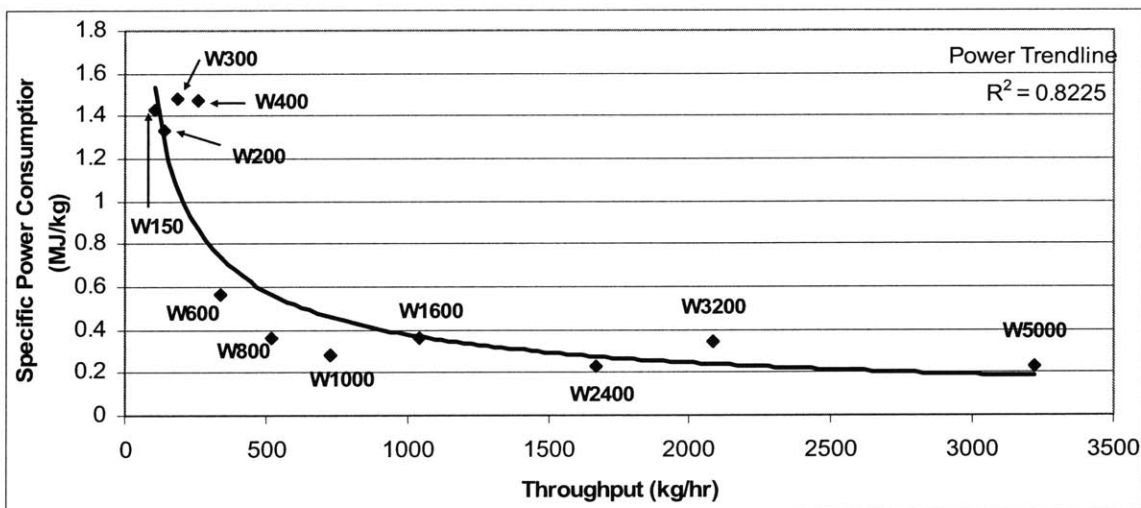


Figure 20 - Specific energy consumption vs. throughput for drying. Source: [Conair CPD]. Driers in the Carousel Plus Series [Conair CPD] are arranged according to their maximum throughput. Thus in the graph above each throughput represents a different machine within the series.

4.10 Injection Molding

This subsection will provide a summary of the results for injection molding, and how these results fit in the whole LCI context.

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. As will be shown, 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 in 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. For further comparison of these three types of machines please refer to the *Injection Molding Machine* section.

Energy consumption for injection molding machinery is dependent on a multitude of factors including part shape, what polymer is molded, shot size, throughput, and machine size. There are infinite combinations of these factors that yield a single energy value. In order to deal with this variability and obtain figures for a generic injection molding machine, substantial energy measurements were obtained from a variety of sources, including previous literature, product brochures, and energy studies supplied by injection molding machine producers, such as Cincinnati Milacron and MHI Injection Molding Machinery. Energy measurements are organized into three groups: hydraulics, hybrids, and all-electrics. The results are presented below.

Hydraulic

Source of Information	SEC (MJ/kg) Including Grid's Efficiency				Polymer
	Avg	Low	High	# pts	
Mitsubishi All-Electric ME Series	9.15	----	----	1	PC
All-Electric World Milacron	9.50	6.22	12.79	2	Unspecified
Nunn & Ackerman 1981	12.57	6.02	26.82	8	HDPE, PS (GPPS & HIPS), ABS
Voisard Energy Cost Comp. File	19.40	9.37	69.79	11	PP, ABS, TTP, TPO
Ferromatik Milacron 2001	7.63	3.99	14.71	12	PP, PS, PET, ABS, Nylon, Surlyn
Ferromatik Milacron Excel	9.82	4.69	26.99	34	HDPE, PP, PS, Unspecified

Hybrid

Source of Information	SEC (MJ/kg) Including Grid's Efficiency				Polymer
	Avg	Low	High	# pts	
Ferromatik Milacron 2001	4.35	3.11	5.60	2	HDPE, PET
Ferromatik Milacron Excel	5.75	4.80	8.45	13	HDPE, PP, PS

All-Electric

Source of Information	SEC (MJ/kg) Including Grid's Efficiency				Polymer
	Avg	Low	High	# pts	
Mitsubishi All-Electric ME Series	3.48	----	----	1	PC
All-Electric World Milacron	3.75	2.65	4.85	2	Unspecified
Voisard Energy Cost Comp. File	8.44	4.00	15.29	6	PP, Unspecified
Ferromatik Milacron 2001	2.83	1.80	4.00	5	HDPE, PP, PET, ABS, Surlyn
Ferromatik Milacron Excel	3.05	2.51	3.42	4	Unspecified

Table 27 – Energy required by different types of injection molding machines, in MJ per kilogram of input polymer (shot weight). These values include the electric grid's efficiency =30%. Unspecified means that the polymer type was not specified for the data points.

As can be seen, hydraulic machinery lies at the top of the energy consumption ladder with an approximate specific energy consumption of 11 MJ/kg of polymer processed

(shot weight). All electric machinery show the lowest specific energy consumption with around 4 MJ/kg, while hybrids lie somewhere in between hydraulics and all-electrics with around 5 MJ/kg. As in the extrusion subsection, emissions from the injection molding process itself are minimal when compared to the resin production stage [Boustead Conversion PVC]. These emissions will be treated as a separate subsection that covers emissions for both extrusion and injection molding.

4.11 Building

Building energy consumption and related emissions are commonly disregarded as they are not directly related to production. However, buildings can actually represent 17% of the total energy costs for a plastic processor [Kent 2001]. Researchers, such as Robin Kent, have extensively analyzed consumption trends of production facilities in several industries, and devised recommendations to improve their energy efficiency [Kent 2001]. *Table 28A* provides the results of the ECG018 “Energy Efficiency in Industrial Buildings and Sites” conducted all across the UK. This table presents the power consumed per meter squared on an annual basis. The first column assumes working days of 18.4 hours, while the second column assumes working days of 8 hours [Kent 2001]. *Table 28B* presents the results of an energy calculation for an injection molding facility. In order to perform the calculation, two simplifying assumption are made, namely: the average throughput is 61.4 kg/hr¹⁶, and the space occupied by an average machine plus its share of auxiliary devices and storage space is 100 meters squared.

	Per Year Values Based on Machine Running x hours/day		
	18.4 hrs	8 hrs	% of total
	kWh/m ²	kWh/m ²	
Process	532	231	61
Buildings	340	148	39
Within building Consumption:			
Space Heating	288	125	33

(A)

	Required Energy (MJ/kg)
	Avg
Building	0.99
Heating	0.84

(B)

Table 28 – A –Results of “Energy Efficiency in Industrial Buildings and Sites” Survey. B - Building related energy required per kilogram of injection molded polymer (unspecified). Source: [Kent 2001].

¹⁶ Average of all the injection molding data analyzed for this report.

The values presented above are a rough approximation. Energy consumption depends on a multitude of factors: the factory's geographic location, how much share of the building does each machine take, what are the throughputs of the machine, and is a clean room required among others. The values in *table 28B* represent the building related energy consumption to run an average machine at a throughput of 60 kg/hr in similar weather to that of the U.K. Warmer weathers decrease heating energy consumption in the winter but increase air conditioning consumption in the summer. If a clean room is required much higher values would be expected.

The EEBPP, or Energy Efficient Best Practice Programme, recommends several easy tips for reducing one's building energy consumption [Kent 2001]. These include:

1. Prevent any heat loss by making building as air-tight as possible.
2. Avoid high ceilings since they increase the heating requirement. Otherwise, use false ceilings or fans to blow the air from the ceiling area to the workers.
3. Do not heat areas with open windows to the outside.
4. Insulate supply pipes to radiators.
5. If possible divide building into separate zones, each with its own heating system. This saves heat where it is not needed and makes heat leaks easier to spot.
6. Have a heat management system (programmable thermostat or a plan of action) to turn off the heat when its not need.
7. Use efficient bulbs that provide correct lighting.
8. Use natural sunlight whenever possible.

4.12 Emissions from Polymer Processing

Although the emissions from processing are small, their importance is underestimated. Plastic processors need to either estimate or measure their emissions to make sure they are under their zone's emission levels in order to meet EPA regulation. Emissions from polymer processing come from a range of sources and depend strongly on the composition of the resin being processed and the temperature at which it is processed. The primary sources of emissions in a plastic processing plant are handling equipment, raw materials, and the production of the final product. Secondary sources include storage tanks, equipment leaks, and cleaning and surface coating operations [EIIIP 1998]. In the case of an extrusion or injection molding, this analysis narrows its attention to the main source of emissions, namely the injection molding or extrusion machine. This analysis will also touch briefly on emissions from size reduction operations and mold lubrication. Emissions from drying, polymer conveying, and from building operations are not covered due to previously stated assumptions. The table below portrays the main sources of emissions in an injection molding facility according to this analysis.

IM Machine	Air Emissions					Solid Waste		
	Particulates		Volatiles		Decomposition Products	Polymer	Plasticizer	Additives
	Polymer	Additives	Monomer	Additives				
Hopper	X	X						
Heating/Injection			X	X	X			
Mold			X	X	X			
Granulator	X	X				X	X	X

Table 29 - Main sources of emissions in an injection molding facility. Adapted from: [Pun 2003]. Similar sources would apply to an extrusion facility.

As can be observed, particulates are generated in the feeding and mixing of polymer in the hopper, and in granulating post injection molded products. Volatile emissions emanate from vents in the injection cylinder and the mold. These emissions include traces of monomers, additives, and decomposition products. The latter emissions occur when the processing temperature reaches or exceeds the decomposition temperature of polymer [Pun 2003]. The table below portrays a selection of polymers whose processing temperature might exceed their decomposition temperature. With regards to solid waste, excess scrap that is not recycled must be disposed. In facilities where scrap is granulated and re-used on site, such as a PVC pipe fitting facilities, the polymer solid waste can amount to 0.7% of the processed polymer [Boustead PVC Conversion]. Other facilities with stringent quality requirements, such as safety or medical products, allow no recycled scrap to be used. Even though the disposal rate in these facilities is much higher, the scrap can be recycled off-site and re-used in less stringent applications.

Polymer	Highest Processing Temperature (°C)	Decomposition Temperature (°C)	Decomposition Products
Fluoroplastics	330	300	HF
Polyester (thermoplastic)	300	300	Acetaldehyde
LDPE	240	100	Ketone carbonyl group appear as a result of oxidation
HDPE	300	100	
EVA	280	100	
PVC	210	100	HCL

Table 30 – Selection of polymers whose processing temperature can reach or exceed decomposition temperature. Adapted from: [Pun 2003]

In some injection molding applications, lubrication agents are applied to the mold in order to prevent plastic from adhering to it. These mold releasing agents are sprayed on the inner cavity surface of the mold, forming a thin layer that facilitates the removal of the solidified part from the mold. These lubricating agents contain carrier solvents that evaporate on application. These solvents are mainly petroleum or hydrocarbon by-products (parafinic oil, propane, and isobutene). The emissions of some of these solvents are classified as hazardous air pollutants, or HAP. Other sprays using these carrier solvents that are applied to injection molding machinery include mold protector agents, degreasers, and cleaning agents. The amount of emissions of these chemicals can be substantial if the amount of chemical sprays and training of the workers is not controlled [EIIP 1998 & Pun 2003].

In 1990, the Clean Air Act Amendments enforced the reduction of several air pollutants released to the atmosphere. This regulation forced companies to inventory their emissions with emphasis on chemicals that produce volatile organic compounds (VOCs) and any of the 189 hazardous air pollutants (HAPs) listed by the U.S. Environmental Protection Agency (EPA). With their emissions inventoried, companies could then apply for a state operating permit. In order to help companies create their emission inventories, the SPI (Society of Plastic Industrials), together with partner companies, developed studies revealing emissions factors for the processing of selected polymers including polyethylene, polypropylene, polycarbonate, nylon, EVA, and ABS. Of these studies, the results of the polypropylene study will be presented as a representative of the 6 major thermoplastics [Adams et al. 1999]; and the results of the polycarbonate study will be presented as a representative of engineering plastics [Rhodes et al. 2002]. These studies both use a 15-hp power extruder with a 1.5 in single screw. Both the hopper and the area after extrusion have collecting chambers to measure emissions. However, emissions from the hopper are not presented since their contribution is insignificant [Adams et al. 1999]. Since the type of polymer processed has a strong impact on the emissions observed, several polymer recipes within polypropylene and polycarbonate are explored. Temperature dependency is also explored. Other variables that can affect emissions, but are not included in this analysis, include extruder size and type, air exposure of the extrudate, and cooling rate of the extrudate [Adams et al. 1999]. It must be mentioned that due to the similarity between extrusion and injection molding equipment, the emission data presented in *tables 31* and *32* is considered representative of both processes.

Examining *table 31* carefully yields some interesting behavior. As observed in runs 1, 2, 3, 5, and 6, increasing temperature has a significant impact in increasing emissions. Runs 2, 4, 5, 7 and 8 show that at approximately the same temperature (260 °C), controlled rheology homopolymer generates the highest concentration of particulates and VOCs of all the resins tested. *Table 32* does not allow for direct comparisons since the processing conditions were different from resin to resin. It is interesting to mention though that the PC/ABS blend produced the highest emissions.

A fast glance at *tables 31* and *32* reveals that the emissions from processing are small when compared to the polymer production stage. The largest emissions are 0.813 g of total hydrocarbons per kg of processed polymer for polypropylene, and 0.19g of total suspended VOCs per kg of processed polymer for polycarbonate. Even though these figures seem small, studies like these allow processors to estimate how much plastic they can process without exceeding the emissions limits set by the EPA for their zone. One must note that even though the emissions per kg are small, the overall amount of polymer processed is rather large, making the absolute processing emissions substantial.

Test Run No	1	2	3	4	5	6	7	8
Test Characteristics	Polypropylene Resin Type							
	Controlled rheology homopolymer	Controlled rheology homopolymer	Controlled rheology homopolymer	Controlled rheology homopolymer with antistat	Reactor grade homopolymer	Reactor grade homopolymer	Reactor impact copolymer (15-20 wt% EPR)	Random copolymer (3-6 wt % ET)
Avg. Melt Temp. (°C)	204	266	318	254	254	299	263	266
Average Additive Concentration (ppm)	Antioxidant = 1,700. PA ^c = 1,000			Antioxi.=1,700. PA ^c =2,500 AS ^d =3,400	Antioxidant = 1,700. PA ^c = 900		Antioxi.=2,500. PA ^c =1,500	Antioxi.=2,000. PA ^c =2,200 Slip/AB=3,000
Emissions (mg/kg of processed polymer)								
Particulate Matter	30.3	68.4	653	150	17.3	218	34.5	27.9
VOCs	184.59	355.63	1425.91	296.98	58.22	331.66	145.5	89.59
THC ^a	104	177	819	191	33.4	202	80.3	59.4
Heavy/Light Hydrocarbons	79.1	175	587	104	24.6	127	65.1	29.8
Ethane	0.90	1.39	4.65	0.78	0.07	0.37	0.02	0.08
Ethylene	0.38	1.44	1.36	0.50	0.03	0.05	0.02	0.05
Propylene	0.21	0.80	13.90	0.70	0.12	2.24	0.06	0.26
Aldehydes	2.15	3.23	45.84	6.71	0.4	14.99	1.43	0.26
Formaldehyde ^b	0.74	1.38	19.1	1.3	0.17	7.05	0.18	0.09
Acrolein ^b	<0.01	0.05	0.81	0.14	<0.01	0.1	<0.01	<0.01
Acetaldehyde ^b	0.46	0.54	15.8	0.53	0.09	5.63	0.2	0.08
Propionaldehyde ^b	0.05	0.07	1.6	3.31	0.02	0.97	0.95	0.02
Butyraldehyde	0.78	1.05	3.32	0.92	0.04	0.36	0.08	0.01
Benzaldehyde	0.12	0.14	5.21	0.51	0.08	0.88	0.02	0.06
Ketones	9.85	12.84	36.52	9.62	0.22	8.05	0.35	0.22
Acetone	9.66	12.6	26.9	9.36	0.15	2.82	0.31	0.18
Methyl Ethyl Ketone ^b	0.19	0.24	9.62	0.26	0.07	5.23	0.04	0.04
Organic Acids	1.79	2.68	10.58	10.88	0	3.83	0.25	0.83
Formic Acid	0.69	1.43	3.98	5.98	<0.2	1.19	<0.2	0.31
Acetic Acid	1.1	1.25	6.6	4.9	<0.2	2.64	0.25	0.52
Acrylic Acid	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08
Notes: a. THC = Total Hydrocarbons (excluding methane). b. Hazardous Air Pollutants (HAPs). c. Process aid additive. d. Antistat. The above emission values are averaged from duplicate runs. Variation in the values between runs are smaller than ±15%.								

Table 31 – Emissions from polypropylene processing in mg/kg of polymer processed. Source: [Adams et al. 1999]

Composition	Polycarbonate Resin Type/Application																	
	Composite (50%-50%)						Single											
	Food Contact	Compact Discs	UV Stabilized	Radiation stabilized	Impact Modified	Ignition Resistant	Radiation stabilized	Branched	PC/ABS blend									
Bayer MAKROLON	3108	MAS140 &	3103	RX-2530	T-7855	6485												
Dow CALIBRE	201	XU 73109.OIL	302				2081	603-3	Pulse 830									
Emissions (mg/kg of processed polymer)																		
Particulate Matter	8.48	9.04	13.07	12.8	28.99	30.85	8.02	5.94	20.83	17.83	9.30	9.66	22.77	22.66	31.12	32.85	138.6	138.5
Total VOCs	38.57	36.88	21.36	23.43	37.93	40.17	70.64	62.05	116.30	108.90	18.80	20.47	14.45	14.54	11.05	11.12	118.5	115.2
Suspended VOCs (total)	31.83	38.20	23.40	24.33	46.16	53.18	88.19	85.43	147.90	139.90	7.61	9.58	6.95	7.42	1.39	1.75	190.3	165.3
Methyl-methacrylate	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	75.27	74.19	0.03	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Monochlorobenzene	29.59	31.29	21.98	23.35	42.23	47.36	56.75	56.87	36.92	38.53	6.09	8.68	0.06	0.02	0.08	0.06	<0.01	<0.01
Carbon Tetrachloride	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.22	0.19	<0.01	<0.01
Methylene-Chloride	<0.01	<0.01	<0.01	<0.01	0.34	0.36	<0.01	0.16	<0.01	<0.01	0.16	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
<i>p, m</i> - Xylene	0.02	0.02	<0.01	<0.01	0.09	0.09	<0.01	<0.01	0.03	<0.01	<0.01	<0.01	<0.01	<0.01	0.1	0.11	68.71	60.23
Styrene	0.02	0.03	0.02	0.02	0.02	0.03	<0.01	0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	66.96	55.05
<i>o</i> - Xylene	<0.01	<0.01	<0.01	<0.01	0.03	0.03	<0.01	0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.02	0.03	0.43	0.36
Toulene	0.04	0.04	<0.01	<0.01	0.03	0.04	<0.01	<0.01	0.03	0.02	0.03	<0.01	<0.01	0.02	0.02	0.02	1.74	1.58
Target SVOCs	2.62	3.02	1.02	0.78	3.07	4.29	5.34	6.06	8.18	8.78	2.62	2.60	3.70	2.27	1.22	0.78	2.28	1.94
Diphenyl-carbonate	1.28	1.59	0.53	0.40	2.23	2.74	3.90	4.68	6.04	6.36	1.81	1.84	2.88	1.38	0.68	0.21	0.35	0.19
Bis-phenol A	0.39	0.36	0.30	0.22	0.33	0.33	0.26	0.19	0.30	0.38	0.12	0.11	0.41	0.35	0.29	0.26	0.65	0.61
Phenol	0.95	1.07	0.19	0.16	0.51	1.22	1.18	1.19	1.84	2.04	0.69	0.65	0.41	0.54	0.25	0.31	1.28	1.14
<i>p</i> -Cumyl Phenol	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

Table 32 - Emissions from polycarbonate processing in mg/kg of polymer processed. Source: [Rhodes et al. 2002]

Note: Please take care when using the above values. In general, extrusion emissions are larger than injection molding ones, since in extrusion the hot polymer has more contact with air. Approximating injection molding processing emissions with the emissions from extrusion provides a slight upper limit of the real value.

4.13 Overall System

So far the report has covered each step pertinent to the current LCI. In order to sum all this data into a coherent format, several assumptions must be made. The result of this analysis outputs values normalized by the amount of polymer injection molded (shot size). In the case of a hot runner system the amount of polymer injection molded is equal to the amount of injection molded product. In any other situation these two values differ according to the relationship between the scrap ratio and the allowed regrind percentage.

Due to the variability of solutions, the current analysis normalizes the energy values by the amount of polymer injection molded and assumes 10% of this polymer is scrap and thus must be granulated. The analysis also assumes that no regrind is allowed and ignores what happens to the scrap material. If the reader desires to normalize the values by the amount of injection molded product, then by following the argument in the *Hot Runner* section, the data could be easily converted. For example, if the allowed regrind is 0% and the scrap rate is 10%, then dividing the injection molding values by 1 minus the scrap rate yields energy values normalized by injection molded product weight.

Packaging after the injection molding stage is ignored in this model. Its inclusion may significantly increase the values. Since packaging is completely dependent on the application, its inclusion is left for those interested in particular applications.

The results of the analysis are presented as follows:

ENERGY CONSUMPTION BY STAGE in MJ/kg of shot

Thermoplastic Production										
	HDPE	LLDPE	LDPE	PP	PVC	PS	Generic by Amount		Extras	
							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

TOTAL w/ Generic Inj. Molded Polymer		Hydraulic	Hybrid	All-Electric
	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' hygroscopicity. In other 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 scrap rate of 10 % is assumed

Figure 21 - Overall System Diagram. The values above account for the efficiency of the electric grid = 30%.

Regarding LCI emissions, this section will not repeat or sum up the polymer production emissions and the processing emissions. Instead, energy-related air emissions are presented for the compounder and the injection molder stages.

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 33 – Energy-related air emissions for the “compounder” stage and the “injection molder” stage.

CHAPTER 5

ENVIRONMENTAL SIGNIFICANCE

When compared to other manufacturing processes, injection molding appears to be a relatively benign process. Other manufacturing processes, such as sand and die casting, have similar energy requirements (11-15 MJ/kg) [Dalquist & Gutowski 2004a and Dalquist & Gutowski 2004b]. However when compared to processes used in the semiconductor industry, such as chemical vapor deposition and atomic layer deposition, the impact of injection 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 is its use 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. In 1970's, injection molding used around 30%, or 1,930 million kg, of the major thermoplastics produced in the U.S [Rubin 1972]. The use of injection molding has heavily increased since then as portrayed in *tables 34 and 35*.

	Total Plastic Consumption - Million kg/year			Amount Injection Molded		
	U.S. Only	Source	Global	Source	%	Source
HDPE+LDPE+LLDPE+PP+PVC+PS	26,529	1997/98 [Brydson 1999]	113,800	1999 [Probe Economics 2000]	21%	[Brydson 1999] + [Probe Economics 2000]
All Plastics	41,686	1999 [Probe Economics 2000]	135,000	1998 [Brydson 1999]	29%	[Rubin 1972]

Table 34 - U.S. and global consumption values for the 6 main thermoplastics and for all plastics on a yearly basis. The % of injection molded polymer is derived from U.S. estimates and assumed to be same for the global case. The U.S. consumption figure for all plastics is estimated with the U.S. production figure for all plastics. In order words, for that value, exports are considered equal to imports.

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

Table 35 – Amount of polymer injection molded in the US and globally. Includes the main 6 thermoplastics and all plastics. These values are derived from the previous table.

From these estimates together with the results of the LCI, one can estimate the total energy spent in injection molding in the U.S. and globally. In order to get an overall value for injection molding, a distribution of the different machine types has to be assumed. According to Snyder, in 2002 29% of the machines sold in the U.S. were electric based rather than hydraulic [Snyder 2002]. With this information I assume that 70% of the injection molding machines are hydraulic, 15% are hybrids and 15% are all-electric. *Table 36* shows the results of the U.S. and global energy estimate.

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

Just Injection Molder	U.S.	Global
	GJ/year	GJ/year
6 Main Thermoplastics	6.14E+07	2.63E+08
All Plastics	1.36E+08	4.39E+08

Table 36 – U.S. and global estimates for the amount of energy spend at the injection molder and at the injection molder + the compounder on a yearly basis. These estimates exclude the polymer production stage. The efficiency of the grid is accounted for.

In order to understand the magnitude of these values one must look at comparable processes. According to Dalquist & Gutowski, sand casting consumes 1.62×10^8 - 2.28×10^8 GJ in the U.S. on a yearly basis [Dalquist & Gutowski 2004a]. Die casting consumes 3.07×10^7 GJ [Dalquist & Gutowski 2004a]. As can be observed, the injection molding energy values for the U.S. lie in between these values. In the case in which compounding is included in the injection molding accounting, injection molding can be even more significant than sand casting! For the reader to comprehend the scale of the U.S. injection molding energy consumption, *table 37* provides values of the entire electricity production of several countries. Without accounting for the electric grid, the overall injection molding energy consumption (injection molder plus compounder) in the U.S. amounts to 6.19×10^7 GJ/year¹⁷. This value can be compared with the values in *table 37*.

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 37 – Selected countries with smaller or similar order of magnitude electricity production to the amount of electricity spent injection molding (compounder + injection molder) in the U.S. Source: [EIA 2002].

In the U.S. alone, there are at least 31,090 injection molding machines [PlasticNews 2003]. Estimates for this figure range from 25,725 [American Machinist 1989] to 58,000 [Rubin 1972]. The picture becomes even larger when growing production economies,

¹⁷ Equivalent to electricity consumption.

like the China, are included. By the 2005, the Southeast Asian market is already larger than that of Europe and the U.S. [IMM 2005].

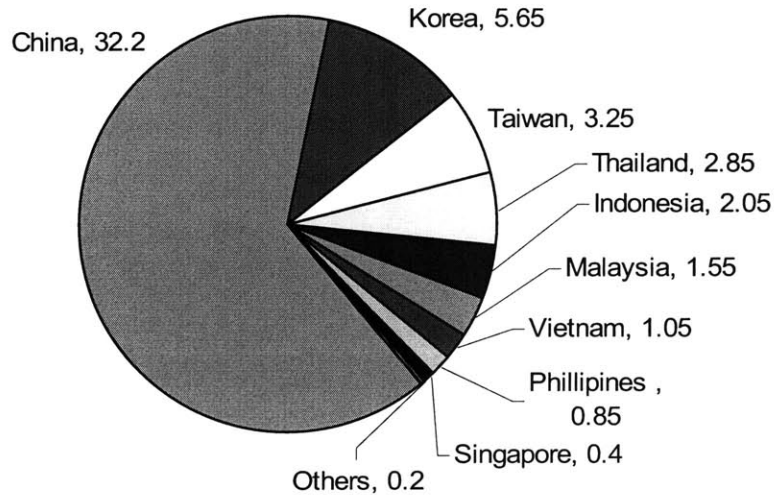


Figure 22 - Plastic Demand in Southeast Asia. Unit: billion kg. Source: [IMM 2005].

In a world of such scale, a saving of 0.01 MJ/kg in the whole injection molding LCI can lead to immense savings in terms of energy and energy-related emissions. It thus seems imperative for the injection molding industry to keep improving its energy efficiency. This thesis hopes to have provided a systems overview and thus exposed the areas where improvements will have the largest impact on the overall energy consumption.

CONCLUSION

This environmental analysis of injection molding highlights a few important points. With regards to the injection molding machine, 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 analyzed are 11.3, 5.6 and 4.9 MJ/kg respectively. 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. The polymer processed also has an impact on SEC values. As viscosity and specific heat capacity increase so does SEC. Finally, SEC varies greatly with part shape. The thinner and the greater the projected area of the part the greater the SEC. As an additional section, the energy savings of hot runner systems were analyzed. Potential savings were observed to be dependant on the scrap percentage, allowed regrind percentage and the fate of the discarded polymer in the cold runner scenario.

With regards, to the LCI 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 portray an SEC of 19.0, 13.2 and 12.6 MJ/kg respectively. These values take into account the energy burden associated with producing the electricity to power the manufacturing processes. 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. *Figure 21* provides a diagram of the LCI together with SEC values for each stage.

The overall injection molding energy consumption in the U.S. in a yearly basis amounts to 2.06×10^8 GJ. This value is of similar magnitude to the overall energy consumption for casting. When transformed into the electricity equivalent, 6.19×10^7 GJ/year, it can be compared with the whole electric production for some developed countries, as seen in *table 37*. It seems imperative for industry to keep improving the efficiency of the process, since small savings anywhere in the LCI lead to tremendous energy savings on a national scale. This seems an intelligent move in a time of rising energy prices.

The work presented in this thesis provides an easy way of estimating the energy cost and emissions in all the life cycle stages surrounding injection molding. Further work in this topic should refine the analysis and provide more theoretical models to predict energy consumption trends.

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