AN ASSESSMENT OF ENERGY SAVINGS DERIVED FROM MECHANICAL RECYCLING OF POLYETHYLENE VERSUS NEW FEEDSTOCK

John Vlachopoulos,
Professor Emeritus of Chemical Engineering
McMaster University, Hamilton, ON, Canada L8S 4L7
vlachopj@mcmaster.ca, Tel.+1-905-5923507

A report prepared for
The World Bank

Version 3.2

November 5, 2009

ABSTRACT

In this report a conservative scenario for energy saving from recycling of polyethylene (HDPE and LDPE) is presented supported by documentary evidences.

The only method for commercial production of virgin polyethylene is the energy intensive steam cracking of heavy hydrocarbons into ethylene gas and subsequent polymerization into flakes, which are converted into solid pellets. The steam cracking to produce ethylene gas requires an energy input of 20 MJ/kg, while the polymerization process to produce polyethylene requires 5 MJ/kg for HDPE and 8 MJ/kg for LDPE. Therefore the energy needs for the production of pellets, starting from hydrocarbons, is 25 MJ/kg for HDPE and 28 MJ/kg for LDPE. An upper limit calculations of the energy required for producing pellets from discarded polyethylene is 5 MJ/kg. Therefore, the energy savings with recycling amount to 20 MJ/kg for HDPE and 23 MJ/kg for LDPE.

The estimates presented are conservative and thus lower than the energy requirements and savings in the cited technical reports and scholarly publications.

AN ASSESSMENT OF ENERGY SAVINGS DERIVED FROM MECHANICAL RECYCLING OF POLYETHYLENE VERSUS NEW FEEDSTOCK

J. Vlachopoulos, McMaster University, Hamilton, ON, Canada

1. INTRODUCTION

Globally the production of plastic is about 225 million tons/year (Gielen, 2008) and is growing at about 5-7% annually, especially in developing countries. Europe has the longest experience with plastic waste recycling policies. Nevertheless, the recycling rates remain low but are increasing. According to EIA (2007, page 262), the increase in mechanical recycling has reduced the need for primary plastic production by 2 Million tons over the past ten years, an energy saving of about 125 PJ (125×10^9MJ), which represent 2.5% of the total energy used in the European chemical and petrochemical industry.

1.1 Production of virgin polyethylene

The production of virgin polyethylene (HDPE and LDPE)[1] involves two main steps: cracking and polymerization.

The first step consists on steam cracking of hydrocarbons at very high temperatures for the production of ethylene (monomer, gas). There are two main sources to produce ethylene: naphtha and ethane. Naphtha cracking represents about 45% of world ethylene production capacity while ethane cracking represents 35% of the whole production. The other sources are: LPG 12%, gas oil 5% and others 3% (Gielen et al., 2008). Naphtha is one of the intermediate products of petroleum refining (distillation) and it is a flammable liquid having a boiling point higher than gasoline but lower than kerosene. Ethane is the second (after methane) largest component in natural gas. It is separated from methane usually by a process of liquefaction and subsequent distillation. The energy requirements for the separation processes for the production of naphtha or ethane are relatively small compared to the process of cracking into ethylene and will not be considered in this report.

---

[1] HDPE has linear macromolecular chains, high density and is stiff, LDPE has branched chains, low density and it is soft and flexible.

During the second step, ethylene is subjected to polymerization for the production of long chain molecules (polyethylene, solid). Although the polymerization process is exothermic (i.e., it is accompanied by energy release usually at low temperature) more energy is needed in this step to run compressors and other equipment.

The polymerization of the branched LDPE grades requires very high pressures of the order of 3000 atmospheres and therefore more energy than the linear grades like HDPE, which are produced under low pressure.

Following the polymerization additional steps are required in order to reach the product stage. These steps are described below but are not considered in the energy scenario as they required less energy than the steam cracking and polymerization (as a conservative assessment).

Upon exiting from the polymerization reactor the polymer is in the form of flakes which are difficult to use as feed into the subsequent machinery (usually a rotating screw inside a heated barrel) for melting and shaping into useful plastic products. So, the polymer flakes are subjected to pelletization (production of granules of about 3 mm diameter, usually) and compounding with stabilizers (to prevent deterioration from heat, light or other environmental factors), lubricants (to facilitate processing), colorants, flame retardants, other polymers (to combine the desired properties), fillers (to reduce cost) and sometimes reinforcements (like glass or carbon fibers to increase stiffness).

The compounded products are subsequently processed by extrusion (continuous), injection molding (discontinuous), extrusion blow molding, injection blow molding, thermoforming, rotational molding and other methods for the production of useful products such as packaging film, bottles, car parts, appliance housings, electronic gadgets, pipe, cable coating and more.

1.2 Production of polyethylene from recycled inputs

There are three types of post-consumer plastics recycling:

1. MECHANICAL RECYCLING for the production of plastic regrind/flakes or pellets for subsequent reprocessing into useful plastic products.

2. RECOVERY OF ENERGY by incineration, because the calorific value of plastics is similar to that of crude oil.

3. RECYCLING BACK TO FEEDSTOCK is the re-conversion of waste polymer back to monomer, for subsequent polymerization. Despite several research efforts in the 1990's, this type of recycling did not result in any major applications.

This report is aimed at mechanical recycling, which will be subsequently referred to simply as recycling.

The typical operations for the production of recycled polyethylene are accounted in the energy consumption scenario presented in this report. These steps are the following: washing of recyclables, drying, compaction and granulation (shredding into roughly 1 cm flakes), and pelletization (not necessary, but included in this assessment as a conservative approach).

2. ENERGY REQUIREMENTS FOR PRODUCTION OF POLYETHYLENE FROM VIRGIN INPUTS

There are numerous technical reports and scholarly publications on the subject of plastics production and the impact of polymers in general on the environment. The figure given in EXHIBIT A shows the energy requirements per unit volume for the production of some plastics compared to that for other materials.

From the figure of EXHIBIT A we note that there are two components in the energy used for plastic production: (1) Feedstock energy (energy inherent in the polyethylene, which can be recovered by combustion), and (2) Process energy (fuel used for the conversion of a liquid and/or gas mixture of hydrocarbons into solid polymer granules). This distinction is important in the context of this report.

Energy requirements cited by Danzell (2006), Thiriez (2006) and Thiriez and Gutowski (2006) are summarized in Table 1. Total energy refers to the feedstock energy plus process energy.

There are large discrepancies in the cited values as well as in numerous other literature sources (such as Boustead (1996, 2000), Gerngross (1999), ICCA (2009), Neelis (2005)) for the following reasons:

(a) The term “energy requirements” usually includes both the process energy and embedded energy without specifying the feedstock (naphtha, ethane or other). The term “energy savings” usually includes savings in both process energy and embedded energy in the feedstock, but the data are not always clear.

(b) When the energy requirements of a polymer are reported it is not clear in what form the polymer is produced. As noted earlier first the polymer is in flakes, then pellets, then the pellets are compounded with additives and then further processed into the usual consumer products by extrusion, injection molding etc. For each step there is addition of energy.

(c) The most energy intensive production step is steam cracking and there have been significant improvements in efficiency, up to 50% from 1970 to 2005 according to Bowen (2006), EXHIBIT C. For naphtha cracking, the energy requirement was reduced from about 40 MJ/kg to about 21 MJ/kg. Of course, not all plants are modernized and several sources cited in the literature predate the implementation of the new technologies.[2]

TABLE 1

ENERGY REQUIREMENTS FOR THE PRODUCTION OF VIRGIN POLYETHYLENE

SOURCE	MATERIAL	TOTAL ENERGY MJ/kg	PROCESS ENERGY MJ/kg
Various sources cited by DANZELL (2000)	HDPE	92.5	43.1
	HDPE	87.4 107.76	- -

---

[2] The analysis and energy consumption presented in the report take into account various cited literature including the most conservative considering efficient installation.

	LDPE	98.3 74.44 116.27	46.4 - -
THIRIEZ (2006) and THIRIEZ and GUTOWSKI (2006) (AVERAGES OF NUMEROUS SOURCES)	HDPE	89.8	-
	LDPE	73.1	-

Notes:

- Total energy = Feedstock energy + Process energy.
- Feedstock energy is usually determined from the combustion energy (easily measured).

Only two cited sources above give specific data on process energy: 43.1 MJ/kg of HDPE and 46.4 MJ/kg of LDPE.

Concerning the specific steam cracking process, Gielen et al (2008) reports the process energy to produce ethylene from different feedstocks as provided below:

- Ethane: 15 - 25 MJ/kg.
- Naphtha: 25 - 40 MJ/kg.
- Gas oil: 40 - 50 MJ/kg.

Bowen (2006) reports the following values for the steam cracking process from different feedstocks:

- Ethane: 14 MJ/kg.
- Naphtha: 21 MJ/kg.

Ren et al (2005) reports the following specific energy consumption values for state-of-the-art naphtha steam cracking technologies:

- Technip: 21.6 - 25.2 MJ/kg
- ABB Lummus: 21 MJ/kg
- Linde AG: 21 MJ/kg
- Stone & Webster: 20 - 25 MJ/kg

Based on the above discussion and the fact that Naphtha cracking represents about 45% of world ethylene production capacity while ethane cracking represents 35%, and gas oil 5%, **an energy requirement of 20 MJ/kg is adopted for the steam cracking process**[3].

There are very few sources of data related to energy requirement for the polymerization process. One of the sources found, the International Energy Agency, reports the following values based on weighted EU averages[4]:

- HDPE: 5.43 MJ/kg
- LDPE 8.53 MJ/kg

Although, there are numerous process variations, most of the energy is required for movement of liquids and gases with the help of pumps and compressors by using electricity.

Following the conservative approach of this assessment, **energy requirement values of 5 MJ/kg of HDPE and 8 MJ/kg of LDPE are adopted.**

The adopted values for the steam cracking and polymerization processes give the following **total process energy requirements:**

- **HDPE: 25 MJ/kg**
- **LDPE: 28 MJ/kg**

In this conservative scenario, this is the maximum possible process energy that could be saved by avoiding the production of HDPE or LDPE from virgin inputs.

---

[3] This weighted average was calculated using the following energy values:
  - Naphtha: 22 MJ/kg
  - Ethane: 14.5 MJ/kg
  - Gas oil: 40 M J/kg

[4] IEA, 2007.

As presented in table 1, these values are conservative as they are much lower than the process energy values summarized on table..

3. ENERGY REQUIREMENTS FOR THE RECYCLING OF POLYETHYLENE

The maximum energy required for the recycling process of polyethylene obtained from post-consumer solid waste is provided in this section.

Recycled plastics can be used directly as flakes, whereas virgin polymers must always be converted to pellets. Virgin flakes require considerable amount of de-volatilization and drying and even after that they are too "fluffy" and cannot be fed directly into the usual hoppers of extruders for further processing. Nevertheless, in this conservative assessment we compare pellets from virgin PE to pellets from recycled PE.

The typical operations for the production of recycled polyethylene require washing, drying, compaction and granulation (shredding into roughly 1 cm flakes), and pelletization (not typical, but included in this assessment as stated above).

The following energy requirement estimations for the processing of recycled plastics to pellets are based on conservative factors and conditions.

WASHING: A formula for the washing (using hot water) of polyethylene recovered from post-consumer solid waste is provided below.

$$ED_w = (T_{ww,\ initial} - T_{ww,\ final}) * Eww * WW$$

Where

ED_w = energy demand to clean plastics

$T_{ww,\ initial}$ = initial temperature of wash water, default value @ 20°C

$T_{ww,\ final}$ = final temperature of wash water, default value @100°C

E_{ww} = energy required to heat a kg of water, default value (4,200 J/kg of water/°C)

WW = quantity of wash water used per kg of plastics to be cleaned, default value (5 kg).

Applied to this scenario with the default values, the energy demand for washing is 1.68 MJ/kg. Energy for pumping the water is extremely small and does not merit any calculations. We adopt 2.0MJ/kg to be conservative.

DRYING: Polyethylene is not hydroscopic (does not absorb water). A formula for the drying of polyethylene recovered from post-consumer solid waste is provided below. As a conservative approach we consider that 0.2 kg of water must be removed per kg of plastic.

$$ED_D = HV_w \times WR$$

Where

ED_D = energy demand to dry plastics
HV_W = heat of vaporization of water (default: 2.26 MJ/kg)
WR = amount of water to be removed per kg of plastic (0.2 kg)

Applied to this scenario, the energy demand for drying is 0.452 MJ/kg (say 1 MJ/kg to account for possible inefficiencies). This is almost twice as much as required for a hygroscopic polymer like PET (Pöhler, 2005).

COMPACTION AND GRANULATION: As a conservative approach, we will assume that during granulation enough energy is put into the polymer to raise the temperature of the polymer to its melting point and melt it completely (under standard operating conditions the temperature is raised to 60% of the melting point. Complete melting was used to be conservative.). Such calculations are routinely made in the extrusion industry and an example is given by Vlachopoulos and Wagner (2001), as explained in the next step. These calculations give 0.64 MJ/kg and we will raise it to 1MJ/kg to include the compaction stage.

PELLETIZATION: As a conservative approach, the process energy calculations are based on a small pelletizer consisting of an extruder producing 112 kg/hr as in the example available by Vlachopoulos and Wagner (2001, Appendix 3-11) used also in the previous stage. These calculations yielded 0.64 MJ/kg based on the following equation:

$$ED_P = [\ C_P \times (T_{P,final} - T_{P,initial}) + H_f + \Delta P / \rho] / \eta$$

Where

ED_P = energy demand for pelletization
ρ = molten polymer density, default value 750 kg/m^3
C_P = heat capacity, default value 2500 J/kg^{o}C
$T_{P,final}$ = final temperature of polymer, default value @ 200^{o}C
$T_{P,initial}$ = initial temperature of polymer, default value @ 20^{o}C

H_f = heat of fusion, default value, 130,000 J/kg
ΔP = pressure drop, default value 30MPa
η = extruder efficiency, default value 0.85

TOTAL: The above estimates (for washing, drying, granulation and pelletization) give total energy required for production of pellets from polyethylene recycling as 5 MJ/kg. This level of process energy corresponds with actual case studies, reported by Ebert et al (1996). These authors state that "For treatment to form recycled granulate electricity consumption was found to be: 117 kWh/100 kg [~ 4.2 MJ/kg] of wet input for the bottle process, 56 kWh/100 kg [~ 2 MJ/kg] of wet input for the cable conduit process".

Material of inferior quality (e.g., contaminated, stained or dirty material) is discarded, resulting in material losses. Losses in the range of 10% to 30% are expected in the recycling industry. A publication on solid waste management and GHG emissions by EPA (2006), quotes a ratio of 0.78 tons of product made per ton of recovered material(see Exhibit D). For the sake of the present conservative scenario we will assume that to produce 1 kg of recycled flakes of polyethylene we would need about 1.3 kg of discarded polyethylene products. The loss is expected to occur at the collection or at the washing stage and will not have any significant impact on the energetic requirements for producing the recycled PE pellets

For the pellets produced from the hydrocarbon cracking process and polymerization (virgin) the energy requirements are 25 MJ/kg for HDPE and 28 MJ/kg for LDPE. This gives energy savings by recycling of 20 MJ/kg for HDPE and 23 MJ/kg for LDPE. The production diagrams for virgin and recycled resins are shown in EXHIBIT E. The energy requirements for polymerization are about the same as those for producing the recycled material. The big process energy demand with virgin feedstock production is the steam cracking process.

If an attempt was to be made to convert the energy savings into equivalent kg of CO_2 we would need also to take into account how the energy was generated. We note that the energy for polymerization (5 MJ/kg of HDPE and 8 MJ/kg of LDPE) is mainly needed to run the pumps and compressors for moving the fluids in and out of reactors and separators and several different types exist, depending on patented technologies and catalysts, mostly supplied by electricity. In the case of recycling we have energy requirements (5 MJ/kg) for washing, drying, granulation and pelletization again mostly by electricity. For steam cracking the energy mainly comes from locally available fossil fuels, such as natural gas, different grades of oil, by-products of the cracking and separation processes. Small amounts of electricity are also used in steam cracking. EXHIBITS F, G and H might be of interest in connection with energy savings conversion to tons of CO_2 equivalent.

Table 3 - Energy requirements and sources

	Steam cracking	**Polymerization**	**Recycling**
Energy requirement	20 MJ/kg PE	5 MJ/kg of HDPE 8 MJ/kg of LDPE	5 MJ/kg of recovered PE
Energy source	Mainly fossil fuels (e.g. natural gas, different grades of oil, by-products)	Mostly electricity	Mostly electricity

A frequently cited and quoted study was published by the United States Environmental Protection Agency (EXHIBIT B)[5]. It reports energy savings per ton of recycled material as follows:

- HDPE 51.4 million Btu/ton (54.2 MJ/kg).
- LDPE 56.5 million Btu/ton (59.6 MJ/kg)

This assumes that the materials would otherwise have been landfilled (EXHIBIT B)

4 DISCUSSION AND CONCLUDING REMARKS

This report includes information available in the open literature regarding the energy content of polymers and process energy requirements for the production of virgin polyethylene (PE) granules. For recycled resin, the process energy requirements were calculated. Recycled resins are just different grades of the same commodity among the thousands of grades and can replace virgin polymers. The question of substitution percentage is perhaps an ill-posed one because every kg of recycled PE produced can replace a kg of some grade of virgin polymer (SCHUT (2009), Zahavich (1995, 1998)). A very conservative estimate is that the energy savings will amount to 20 MJ/kg of HDPE and 23 MJ/kg of LDPE.

---

[5] SOLID WASTE MANAGEMENT AND GREENHOUSE GASES - A Life-Cycle Assessment of Emissions and Sinks, 3rd EDITION, September 2006.

It must be noted, also, that virgin polymers are produced in relatively few locations around the world, at/or near petrochemical complexes. According to IEA (2007), there are 256 crackers worldwide. In North America transport is mainly by rail usually from Texas and Alberta to Chicago (which appears to be the central distribution location), and from there to other locations. Internationally, container ships carry resins from Middle East to South America, to Europe and to Far East. Also there are resin shipments from North America to South America. Current production share in various parts of the world is shown in EXHIBIT I. Processing of plastics occurs in numerous small and medium sized companies. There are tens of thousands of processing companies worldwide and recycled plastics are likely to supply the local industry, replacing virgin polymer.

6. REFERENCES

-BOUSTEAD, I. (1996): "Theory and Definitions in Eco-balances" in Brandrup J. et al (eds) RECYCLING AND RECOVERY OF PLASTICS, Hanser Publ.,New York,pp.73-93

-BOUSTEAD, I. (2000):"Eco-profiles of plastics and related Intermediates" Association of Plastics Manufacturers in Europe (APME), Brussels, Belgium.

-BOWEN C.P. (2006): "Olefin Technology Efficiency Today/Tomorrow" Powerpoint Presentation in Paris December 2006, Shaw Stone & Webster, Inc., accessed on 2009.09.24, at www.iea.org.

-DANZELL, J.M. (2000): "Food Industry and the Environment in the European Union" Aspen Publications, Gaithersburg, Maryland, pp.275-278.

-EBERT ,F. et al (1996): "Life-Cycle Analysis of Recycling and Recovery of Households Plastics Waste Packaging Materials" in Bandrup J. et al (Eds) RECYCLING AND RECOVERY OF PLASTICS, Hanser Publ., New York .pp.168-192.

-GERNGROSS, T.U. (1999):"Can Biotechnology Move us toward a Sustainable Society?" Nat. Biotechnol.,17(6), 541-544.

-GIELEN, D. et al (2008) "IEA Petrochemical Scenarios for 2030-2050: Energy Technology Perspectives" International Technology Agency, Paris, France

-ICCA (2009):"Innovations of Greenhouse Gas Reductions" www.icca-chem.org (accessed September 18,2009).

-IEA (2007) "Tracking Industrial Energy Efficiency and CO2 Emissions" OECD/IEA, Paris, France

-NEELIS et al (2005): "Modeling CO2 Emissions from Non-Energy Use with the Non-Energy Use Accounting Tables (NEAT) Model" Resources, Conservation and Recycling, 45,226-250.

-PÖHLER, F. (2006): "Alternatives in Polyester Processing" Kunststoffe, Issue 6, pp.100-104

- REN et al (2005): "Olefins from Conventional and Heavy Feedstocks: Energy in Steam Cracking and Alternative Processes" Energy 31 (4), pp. 425-451.

-SCHUT, J.H. (2009): "Close–Up in Technology: Recycling New Processes for Food Grade Recycled HDPE" Plastics Technology Magazine, March(3) issue.

-THIRIEZ, A. (2006): "An Environmental Analysis of Injection Molding" Masters Thesis, MIT, Cambridge, MA. THIRIEZ, A. and GUTOWSKI, T. (2006), Proceedings of the 2006 IEEE Intern. Symp. On Electronics and the Environment,195-200.

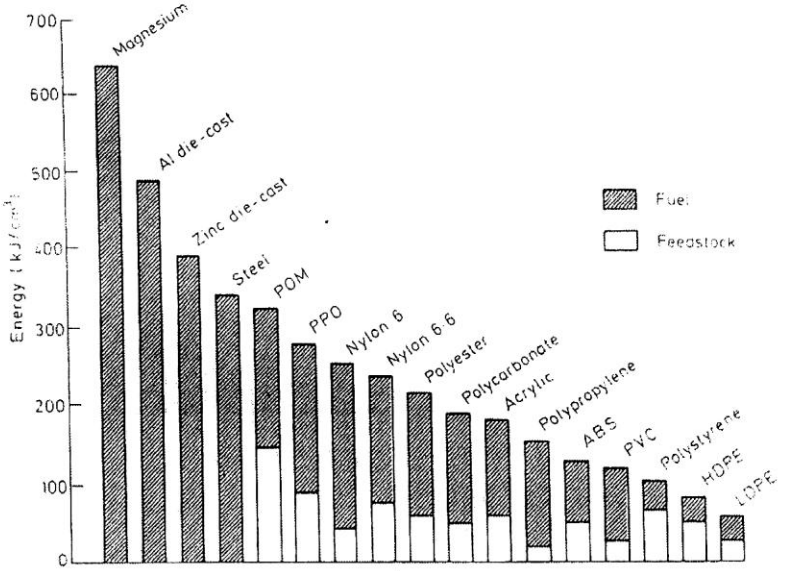
-United States Environmental Protection Agency, SOLID WASTE MANAGEMENT AND GREENHOUSE GASES - A Life-Cycle Assessment of Emissions and Sinks, 3rd EDITION, September 2006.

-VLACHOPOULOS, J. and WAGNER, J.R. Eds. (2001): "The SPE Guide of Extrusion Technology and Troubleshooting" Society of Plastics Engineers, Brookfield, CT.

-ZAHAVICH, A.T.P. (1995):" The Effect of Multiple Extrusion Passes During the Recycling of High Density Polyethylene" PH.D. Thesis, McMaster University, Hamilton, ON, Canada. ZAHAVICH et al (1997), Adv. Polym.Tech.,16(1), 11-24.

-ZAHAVICH, A.T.P. and VLACHOPOULOS, J. (1998): “Reprocessing of Polyolefins” p.271-297 in Akovali, G. et al (Ed.) “Frontiers in the Science and technology of Polymer Recycling”, NATO ASI Series, Kluwer Academic Publishers, Dordrecht (1998).

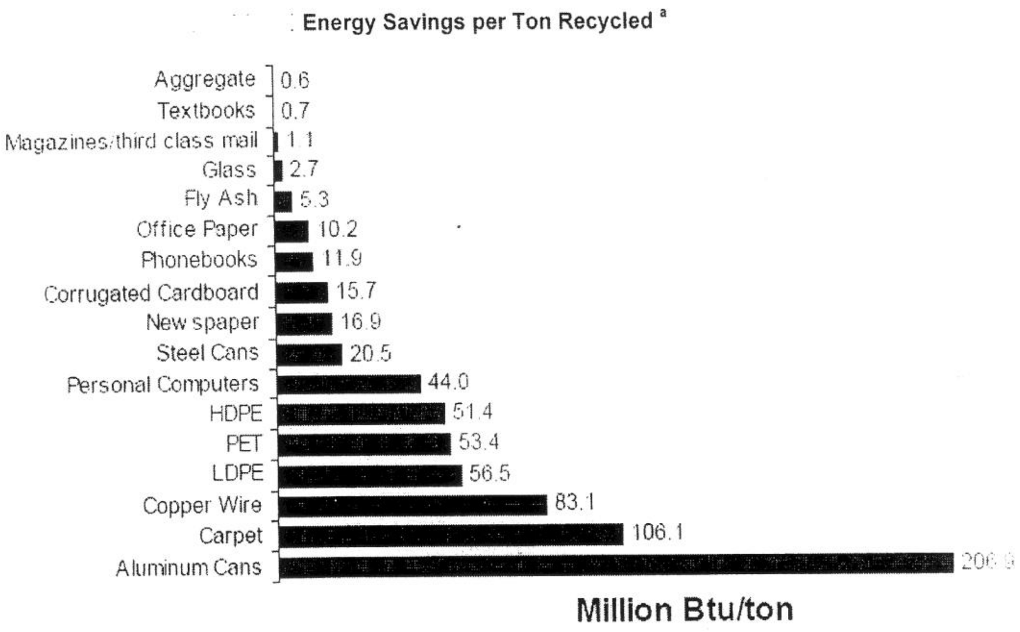
EXHIBIT A



Energy requirements to produce metal alloys and plastics. For plastics the energy required to manufacture the plastic is shown separately from the fuel equivalent of the raw material.

FROM:
N.G. McCrum et al "Principles of Polymer Engineering"
Second Edition,p.12, Oxford University Press, Oxford (1997)

EXHIBIT B



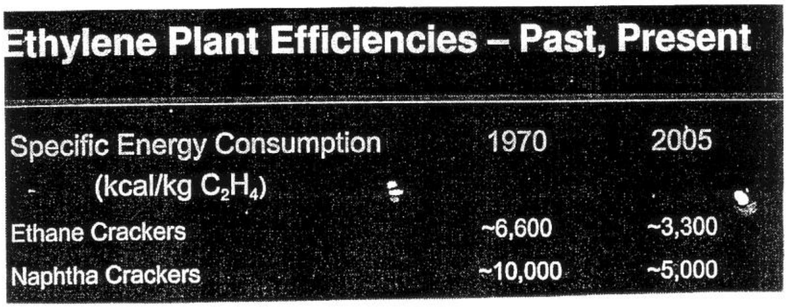
[a] Assumes recycled materials would otherwise have been landfilled. Aggregate refers to concrete recycled as aggregate.

FROM:
US-EPA "Solid Waste Management and Greenhouse Gases"
Third Edition, page 98, EPA, Washington ,D.C. (2006)

NOTE:

51.4 Million Btu/ton
=54.2 MJ/kg
=15 kWh/kg
=15 MWh/ton

EXHIBIT C



Ethylene Plant Efficiencies – Past, Present

Specific Energy Consumption (kcal/kg C_2H_4)	1970	2005
Ethane Crackers	~6,600	~3,300
Naphtha Crackers	~10,000	~5,000

5000 Kcal/kg = 20.94 MJ/kg = 5.8 kWh /kg

C. P. Bowen "Olefin Technology Efficiency Today/Tomorrow" Powerpoint presentation, December 2006, Shaw Stone & Webster, Inc., accessed on 2009.09.24 www.iea.org

EXHIBIT D

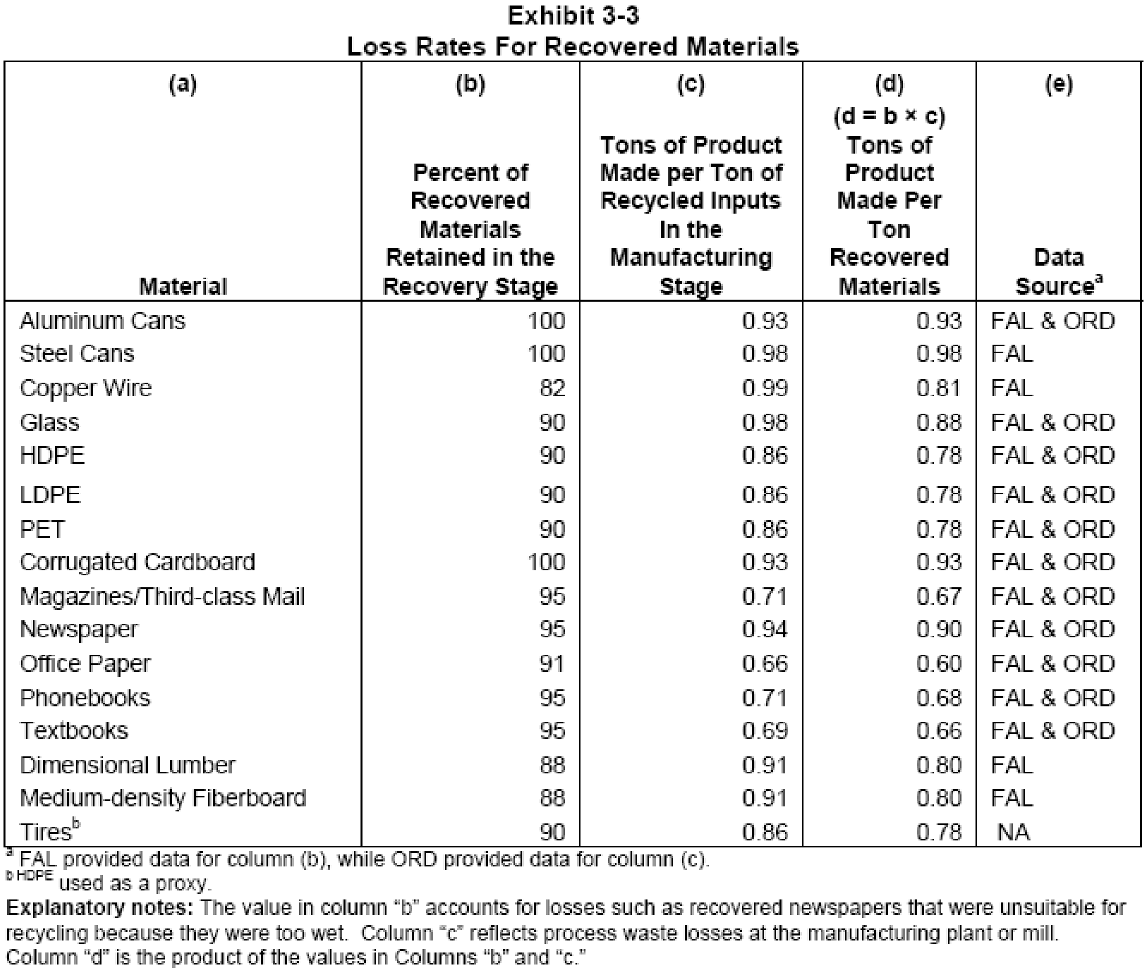


Exhibit 3-3
Loss Rates For Recovered Materials

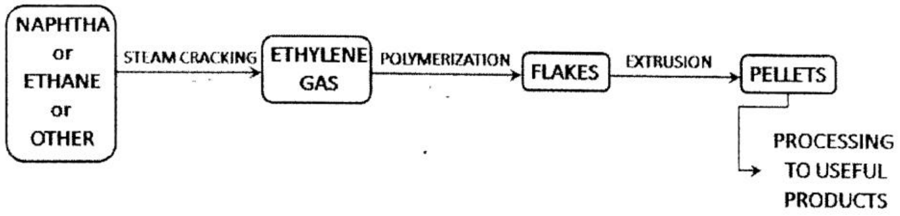
(a) Material	(b) Percent of Recovered Materials Retained in the Recovery Stage	(c) Tons of Product Made per Ton of Recycled Inputs In the Manufacturing Stage	(d) (d = b × c) Tons of Product Made Per Ton Recovered Materials	(e) Data Source[a]
Aluminum Cans	100	0.93	0.93	FAL & ORD
Steel Cans	100	0.98	0.98	FAL
Copper Wire	82	0.99	0.81	FAL
Glass	90	0.98	0.88	FAL & ORD
HDPE	90	0.86	0.78	FAL & ORD
LDPE	90	0.86	0.78	FAL & ORD
PET	90	0.86	0.78	FAL & ORD
Corrugated Cardboard	100	0.93	0.93	FAL & ORD
Magazines/Third-class Mail	95	0.71	0.67	FAL & ORD
Newspaper	95	0.94	0.90	FAL & ORD
Office Paper	91	0.66	0.60	FAL & ORD
Phonebooks	95	0.71	0.68	FAL & ORD
Textbooks	95	0.69	0.66	FAL & ORD
Dimensional Lumber	88	0.91	0.80	FAL
Medium-density Fiberboard	88	0.91	0.80	FAL
Tires[b]	90	0.86	0.78	NA

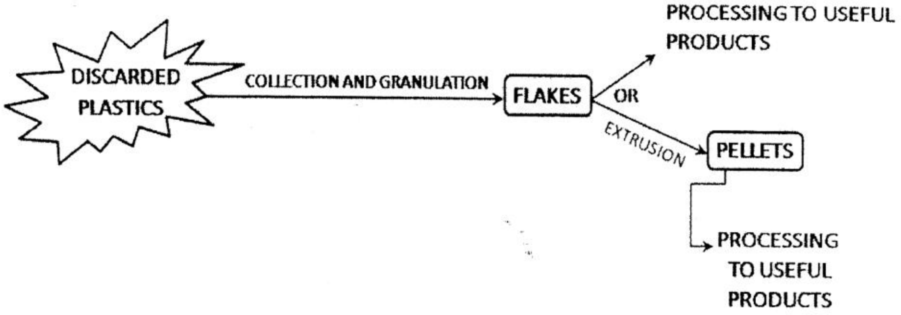
[a] FAL provided data for column (b), while ORD provided data for column (c).
[b] HDPE used as a proxy.

Explanatory notes: The value in column "b" accounts for losses such as recovered newspapers that were unsuitable for recycling because they were too wet. Column "c" reflects process waste losses at the manufacturing plant or mill. Column "d" is the product of the values in Columns "b" and "c."

Source: Solid Waste Management and Greenhouse Gases - A Life-Cycle Assessment of Emissions and Sinks, EPA, 2006.

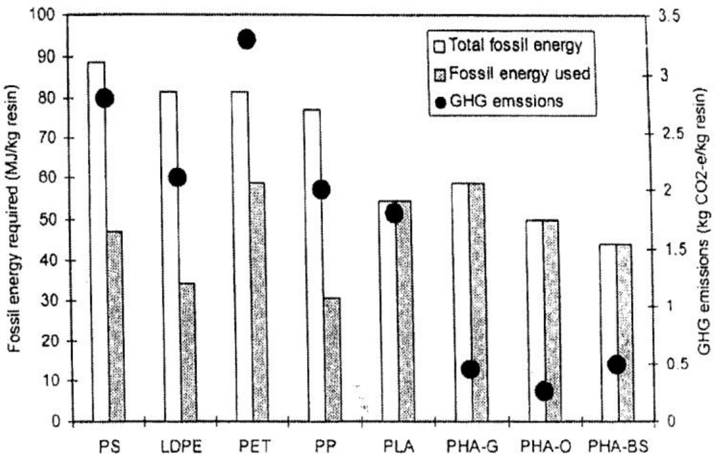
EXHIBIT E





PRODUCTION DIAGRAMS OF POLYETHYLENE FLAKES (AND PELLETS) FROM HYDROCARBON CRACKING AND MECHANICAL RECYCLING

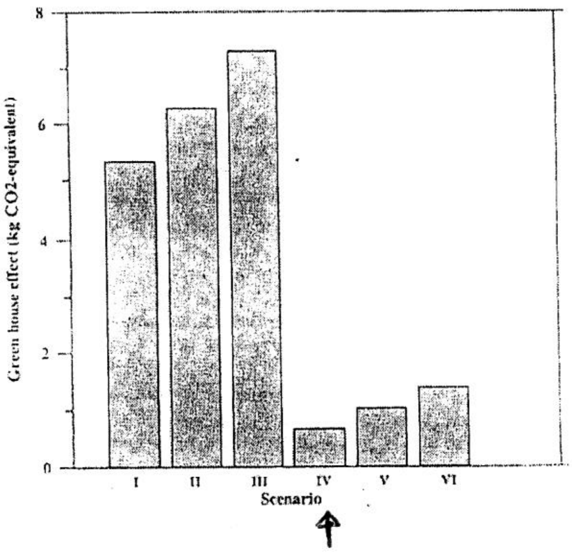
EXHIBIT F



Comparison of GHG emissions and fossil energy requirements of representative petroleum- and biobased polymers based on 1 kg of resin produced. Symbols: polystyrene (PS), low-density polyethylene (LDPE), polyethylene terepthalate (PET), polypropylene (PP), polylactide (PLA), polyhydroxyalkanoates on glucose (PHA-G), PHA on oil (PHA-O), and PHA on black syrup (PHA-BS).

FROM
J. Yu et al " The Greenhouse Gas Emissions and Fossil Energy Requirements of Bioplastics from Cradle to Gate of a Biomass Refinery " Environ. Sci. & Tech., 42 (18), (2008).

EXHIBIT G

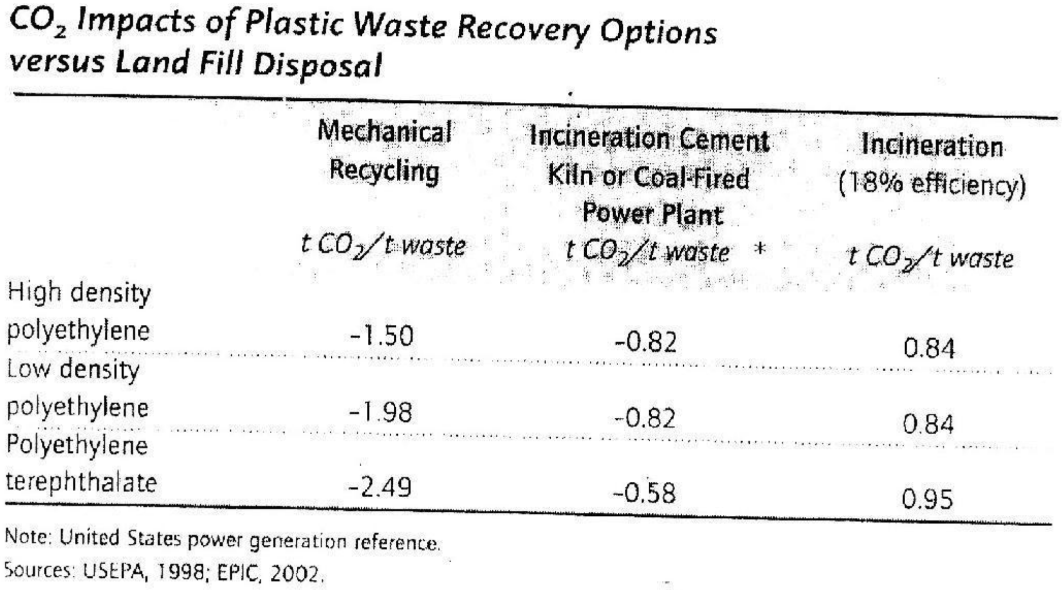


. All the data refer to the production of 1 kg of (recycled or virgin) PET flakes and 0.39 kg of (recycled or virgin) PE flakes

Scenario I	No recycling and landfill disposal of all the collected plastic wastes
Scenario II	No recycling and landfill disposal of 50% of the collected plastic wastes, the remaining being incinerated with energy recovery
Scenario III	No recycling and all the collected plastic wastes sent to incineration with energy recovery
Scenario IV	Mechanical recycling of all the collected plastic wastes and landfill disposal of all the processed wastes
Scenario V	Mechanical recycling of all the collected plastic wastes and landfill disposal of 50% the processed wastes, the remainder being incinerated with energy recovery
Scenario VI	Mechanical recycling of all the collected plastic wastes and all the processed wastes sent to incineration with energy recovery.

U. Arena et al "Life Cycle Assessment of a Plastic Packaging Recycling System" Intern. J LCA, 8(2), 92-98 (2003)

EXHIBIT H



CO_2 Impacts of Plastic Waste Recovery Options versus Land Fill Disposal

	Mechanical Recycling *t CO_2/t waste*	**Incineration Cement Kiln or Coal-Fired Power Plant** *t CO_2/t waste* *	**Incineration** (18% efficiency) *t CO_2/t waste*
High density polyethylene	-1.50	-0.82	0.84
Low density polyethylene	-1.98	-0.82	0.84
Polyethylene terephthalate	-2.49	-0.58	0.95

Note: United States power generation reference.

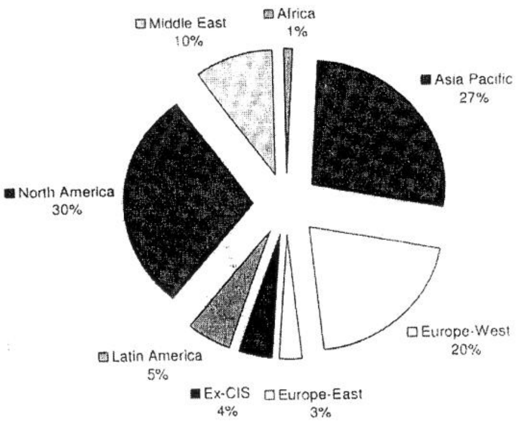
Sources: USEPA, 1998; EPIC, 2002.

IEA (2007): "Tracking Industrial Energy Efficiency and CO2 Emissions" p.261, OECD/ International Energy Agency, Paris, France.

* Incineration in cement kilns is CO_2 equivalent negative, because combustion of PE releases less CO_2 than combustion of coal, which is the conventional fuel in most cement plants.

EXHIBIT I

Steam Crackers Distribution



Source: Oil and Gas Journal, 2006

D. Gielen et al " IEA Petrochemical Scenarios for 2030-2050: Energy Technology Perspectives" International Technology Agency - Paris, France (2008).