

5. An international comparison of polymers and their alternatives

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Energy analysis is now developed to the point at which we can make useful comparisons among the patterns of energy use in different nations. The first aim of this article is to start making these comparisons. The authors' attention has been focussed on polymers, especially the packaging materials, both to help fill out the overall perspective being developed in this series on Energy Budgets and because the polymer industry, with all its technological diversity, displays a rich spectrum of patterns of energy use, from which one can draw some useful object lessons.

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Iron, steel and aluminium

Metals – especially iron and steel and aluminium – compete with polymers in certain applications. A comparison of data on iron and steel making in the UK,^{1,2} the Netherlands³ and the USA,^{4,5} and for aluminium production for the same three countries^{4,10} reveals that in the UK and the USA, the total energy requirements of hot-rolled steel are about 47 gigajoules/metric tonne (GJ/t) – ie, 47×10^9 joules/metric tonne or 11 900 kWh/short ton – and that the energy requirements for aluminium production are about 250 GJ/t (63 kWh/short ton) in the UK, the USA and The Netherlands. The similarities of the energy requirements among these nations were reassuring, and gave an extra cachet of validity to the calculations. Then the Dutch figure³ for producing iron and steel appeared: 32 GJ/t, which is 15 GJ/t below the UK-US figures. This of course stimulated a closer look at the apparently similar figures. We concluded that similarities of energy cost figures for the same product made in different countries are liable to be deceptive. Aggregated energy requirements may be very nearly equal and yet be the sums of quite different sets of disaggregated contributions. The illusion of similar totals must not keep us from looking at energy requirements step by step.

Let us illustrate this point by examining aluminium production. The figures are given in Table 1, disaggregated into the three stages of ore extraction, conversion of ore to aluminium oxide, and production of aluminium metal from the oxide by electrolysis in the Hall-Héroult process.¹¹ The similar values of the sums at the bottom come from two cancelling effects. The energy requirements to convert bauxite ore to alumina vary markedly, with the USA value by far the lowest. In contrast, the figures for electrolysis differ in the opposite direction. The value of 242 GJ/t for the USA represents the national average figure; the values for the UK and The Netherlands are those for the best available technology. If one used the average value of the efficiency of British electrolytic cells, the UK figure for smelting would be 226 GJ/t, and the total for the UK would then be 287 GJ/t. If one used the best available technology for the USA, the new ALCOA process,¹² the US smelting figure would be 170 GJ/t and the total,

¹ P.F. Chapman, *Energy Policy*, Vol 2, No 3, September 1974, pp 231-243.

² P.F. Chapman, *Metals and Materials* (February 1974).

³ J.A. Over (ed), *Energy Conservation: Ways and Means*, (Stichting Toekomstbeeld der Techniek, The Hague, The Netherlands (1974).

⁴ R.S. Berry and M.F. Fels, 'The Production and Consumption of Automobiles,' A Report to the Illinois Institute for Environmental Quality, July, 1972.

⁵ R.S. Berry and M.F. Fels, *Science and Public Affairs – Bulletin of the Atomic Scientists*, October 1973, p 11.

⁶ R.S. Berry and H. Makino, *Technology Review*, Vol 76, No 4, 1974, p 32.

only 186 GJ/t. Still another difference in the practices of producing aluminium is in the fraction of scrap in the input. About 20% of the US and The Netherlands' productions comes from scrap; in the UK, the fraction is closer to 33%.

Elasticity of demand

It is important to note a relationship between the elasticity of demand for energy and the energy requirements, based on average and most efficient equipment. The output elasticity of demand is the fractional change in output per fractional change in input – in this case, of energy. Thus, if Q is the amount of product, $\Delta Q/Q$ is its fractional change, $\Delta E/E$ is the corresponding fractional change in energy requirement and the elasticity is

$$\left(\frac{\Delta Q}{Q}\right) \left(\frac{E}{\Delta E}\right) = \left(\frac{\Delta Q}{\Delta E}\right) / \left(\frac{Q}{E}\right)$$

$$\frac{\text{marginal productivity of energy}}{\text{average productivity of energy}} = \frac{\text{average energy requirement}}{\text{marginal energy requirement}}$$

Average and marginal productivities of energy are the inverses of the average and marginal energy requirements.

The marginal energy requirement for producing an additional unit of output is essentially the same as the average energy requirement for the most modern and efficient equipment in use. With this approximation, the elasticity of demand for *increasing* production, which we can call ϵ_{up} , is given by

$$\epsilon_{up} = \frac{\text{average unit energy requirements over all the industry}}{\text{average unit energy requirements with 'best' equipment}}$$

This is not the same as the elasticity of demand for *decreasing* production, which we can call ϵ_{down} , because decreases are generally absorbed in the least efficient (and often oldest) equipment. Rather,

$$\epsilon_{down} = \frac{\text{average unit energy requirement over all the industry}}{\text{average unit energy requirement with 'worst' equipment}}$$

No data are yet available from which we can estimate ϵ_{down} , and we have very little information thus far to find values for ϵ_{up} 's. However, we do, for the first time, have enough to estimate the ϵ_{up} elasticity of demand for energy in aluminium production in the UK and the USA. For the UK, where the new ALCOA process is presumably not yet realistically available, $\epsilon_{up}(E)$ is 287/253 or 1.13.

⁷ H. Makino and R.S. Berry, 'Consumer Goods, A Thermodynamic Evaluation of Packaging, Transport and Storage,' A Report to the Illinois Institute for Environmental Quality, June, 1973.

⁸ P.F. Chapman, 'The Energy Cost of Producing Copper and Aluminium from Primary Ore,' Report ERG001, Open University, 1973; *Energy Policy*, Vol 3, No 1, March 1975, pp 47-57.

⁹ J.C. Bravard, H.B. Flora and C. Portal, 'Energy Expenditures Associated with the Production and Recycling of Metals,' Oak Ridge National Laboratory Report ORNL-NSF-EP-24, 1972.

¹⁰ P.R. Atkins, *Engineering and Mining Journal*, Vol 1974, No 5, 1973, p 69.

¹¹ A conversion efficiency for electricity of 32% was assumed for UK and The Netherlands and 33% for the USA²⁻⁵

¹² News release from ALCOA, January 11, 1972.

Table 1. Energy costs of primary aluminium production (Transportation energy is neglected)

Process	UK ⁸	The Netherlands ³	USA ⁴
Ore extraction	5 (GJ/t)	5 (GJ/t)	3 (GJ/t)
Alumina production from ore	56	31	13
Aluminium production from alumina	192	196	242
Total	253	232	258

For the USA, we estimate $\epsilon_{up}(E)$ as 258/186 or 1.39, based on the new ALCOA process. Because the historical trend has been toward greater efficiency in the use of energy, we expect to find that, in general, $\epsilon_{up}(E) > \epsilon_{down}(E)$ when we confine ourselves to a narrow technological range of processes. However, wherever we have made substitutions of large energy inputs for large capital or labour inputs, we must watch for situations where ϵ_{up} is actually smaller than ϵ_{down} , due to increases in energy intensity outpacing technological improvements in efficiency.

The aggregate figures for energy used in steel production, likewise, deserve scrutiny. Part of the discrepancy between the low figure for The Netherlands and the UK and US figures given above, occurs because almost all the Dutch steel furnaces are basic oxygen furnaces. If all US production were carried out this way, the energy requirements would drop from 47 GJ/t to 43 GJ/t; another 2 GJ/t of the difference can be assigned to the difference between the coke-oil-gas mixture put into Dutch blast furnaces, as compared to coke alone in the USA. The data available in the open literature appear to be insufficient to account for the remaining discrepancy of 9 GJ/t.

Thus we see that, even for the most easily-analysed, well-documented processes, international comparisons can illustrate quite large differences among practices, and, by implication, indicate useful ways to reduce energy demand.

Polymeric materials

Energy requirements of producing some principal commercial polymeric materials in the USA, the UK, and The Netherlands vary dramatically. We have explored the technological differences underlying these variations to the extent that proprietary interests permit. Energy requirements for fabrication of a few common consumer items are also presented, as well as the costs of paper and paperboard, which are the principal competitors for plastics in the packaging industry.

As Chapman pointed out,¹ there are diverse procedures which one may adopt in energy analysis. Here we are limited by the data for polymer production that is available for the UK¹³ and The Netherlands^{3, 14} to evaluations based on the energy input into the productive system. A more detailed investigation of energy requirements for polymeric materials used by the consumer goods packaging industry in the USA^{6,7} calculates both the energy requirements and the free energy requirements.

When we calculate the energy requirements for making an item, we add the inputs of energy from each fuel; the total is a payment required to operate the process. Many fuels contain greater capacities to do work than they furnish by combustion to generate heat. The maximum heat we obtain from a fuel is the parameter known as its heat of combustion. The total potential to do useful work includes the part associated with purity and structure, as well as the part associated with the energy contained in chemical bonds. This total is called the *free energy* ('free' in the sense of useful, *not* in the sense of 'without price'). Thus the free energy is an opportunity cost.¹⁵ It tells us exactly the minimum amount of *energy* that would be required to reconstitute the materials used as fuels in production so that they contained not only their original heat content, but also had the same

¹³ Imperial Chemical Industries, Ltd. (private communication).

¹⁴ Private communications.

¹⁵ This point is discussed in more detail by R.S. Berry and T.V. Long, 'The Use of Energy', (submitted for publication).

physical and chemical structure as the original fuel. The free energy cost of a gallon of oil, for instance, is the minimum energy payment that our descendants would have to make to resynthesise the oil from the products of combustion. This could happen if petroleum grew truly scarce and hydrocarbons were desired for their unique, un-substitutable chemical properties. The actual energy cost of synthesis would always be greater than the free energy; the difference depends on the inefficiencies of the technology used, but the free energy content is the lower bound.

In calculating the amount of primary fuel required for generating, transmitting, and distributing electricity, we have assumed the efficiencies given above for the USA and The Netherlands. A value of 30% has been used for the UK,¹³ although a recent study indicates this may be too high.¹⁶ Primary energy costs for producing steam in the USA and The Netherlands are evaluated directly, so that the efficiency of conversion does not enter the calculation. A conversion efficiency of 75-80% was used in the UK study.¹³ The US figures for steam correspond to about 82% efficiency, and represent an estimate slightly weighted toward the optimistic side. This corresponds to a fuel input of about 0.474 kWh/lb or 3.75 GJ/tonne of steam. If, as is sometimes done,^{6,7} one uses the electrical output potential of the steam as the measure of its energy equivalents, the conversion factor has been estimated to be about 1.1-1.9 kWh/lb or 8.7-15.0 GJ/tonne, corresponding to an efficiency of about 27-35%.

The manufacture of polymers falls into three large steps – acquisition of feedstocks; manufacture of the monomeric material and other inputs to polymerisation; and polymerisation itself. To these, we have to add the energy required to fabricate the final articles. The principal primary resources for polymers are petroleum and, in the USA, natural gas. Petroleum acquisition (US figures) requires about 0.3-0.4 GJ/t. We have assumed, for lack of more data, that this figure is approximately correct for petroleum going to the UK and The Netherlands. It does not reflect any shift to North Sea oil or other energy-costly oil. Natural gas is three times more costly to acquire – over 0.9 GJ/t. Table 2 shows how these totals arise from inputs of electricity, fuel oil, gasoline and natural gas; the data are taken from the US Census data for 1967.^{17, 18}

¹⁶ P.F. Chapman, 'The Energy Costs of Delivered Energy, UK 1968.' Report ERG-003, Open University, November 1973.

¹⁷ *Census of Mineral Industries 1963 and 1967*, Bureau of the Census, US Dept. of Commerce, Washington, D.C. (1967 and 1971).

¹⁸ W.E. Franklin and R.G. Hunt, 'Environmental Impacts of Polystyrene Foam and Molded Pulp Meat Trays,' MRI Projects 3554-D, Midwest Research Institute, Kansas City, Mo, 25 April 1972.

Table 2. Fuel inputs to acquire crude petroleum and natural gas¹⁸ (Units are megajoules – 10⁶J – per tonne of petroleum)

Input	Crude petroleum (per tonne)		Natural gas (per tonne)	
	Amount	Energy input (MJ/tonne petroleum)	Amount	Energy input (MJ/tonne natural gas)
Primary energy to generate electricity (33% effi- ciency)	14.0 kWh (from primary source)	55.0	8.4 kWh	33.1
Fuel oil	0.80 gal	132.0	0.62 gal	103.4
Gasoline	0.18 gal	25.3	0.18 gal	26.4
Natural gas	88 cu ft	105.6	363 cu ft	868.0
Total		318		1030

Note:

The energy supplied by crude petroleum falls in the range 42.7 GJ/tonne of crude (based on international values) to 44.6 GJ/tonne of crude (based on US Census). The energy supplied by natural gas is approximately 54.7 GJ/tonne of gas. Hence the data of ref. 18 implies that the ratio of energy available from combustion (enthalpy of combustion)/PER is 134-140 for crude oil and 53.1 for natural gas.

The processing of petroleum to petrochemicals starts with cleaning the petroleum of water-solubles. The water is then removed electrostatically, and the oil is fractionally distilled. The useful fractions are desulphurised, and then sent through catalytic conversion and other chemical transformations to become the useful hydrocarbons for polymer production – ethylene, vinyl chloride, styrene, for example. Outside the USA, the naphtha fraction is used to make ethylene and propylene. The general practice in the USA is to obtain ethylene and propylene by low-temperature distillation of ethane and propane, followed by dehydrogenation.

The manufacture of monomers and polymers is accomplished by highly varied, interwoven and individualised processes. Much of the information is proprietary. Table 3 gives a sample of the total output and the unit energy requirements in the USA for the production stage of most of the important inputs to polymer production. The energy requirements to acquire the feedstocks are not included, so the figures in this table are *not* the total energy requirements. The petrochemicals span a range of about a factor of five, if we omit the alcohols, between about 12 and 60 GJ/t. The greatest total amounts of energy are spent in making olefins, vinyl chloride, acrylate and methacrylate, and styrene, among the monomeric materials. Moreover the *total* energy requirements, which are often given with feedstock fuel values included, can be considerably higher than the figures in Table 3.

Polymerisation is a rather energy-consuming process, despite the fact that many polymerisation reactions actually release heat. A flow diagram for the manufacture of polyethylene is given in Figure 1. Several different processes are used for production of each polymer. They may differ according to catalyst, as in the case of polyethylene and polypropylene formation, or according to the form in which the monomeric material goes into the polymerising process, eg, in

Table 3. Quantities and unit process energy requirements for inputs to polymer manufacture^a

Material	Quantity (10 ³ tonne)	Process energy (GJ/t)
Ethylene	931	16.7
Butadiene	84	16.7
Other olefins	1479	16.7
Acetic anhydride	31.4	28.9
Acrylates and methacrylates	199	56.6
Acrylonitrile	57.2	42.8
Alcohols (except ethanol)	31.7	125.0
Cellulose acetate	54.7	75.5
Urea	93.5	14.0
Vinyl acetate	125	35.6
Vinyl chloride	666	20.1
Formaldehyde	389	10.2
Plasticisers	103	64.8
Phenol	159	14.7
Phthalic anhydride	75.2	19.9
Styrene	707	12.5
Sulphuric acid	309	8.1
Hydrochloric acid	9.4	8.0
Sodium hydroxide	172	5.9
Woodpulp	246	1.5

^aUS figures taken from the US Census of Manufactures for 1967; transportation and feedstock energies are not included

suspension, in an emulsion or in bulk in the formation of poly(vinyl chloride) PVC; or in bulk (without solvent), in solution, in suspension or emulsion for polyethylene. These variations sometimes cause large variations in the requirements for process energy, but not always. The Ziegler (transition metal halide) catalyst method and the metal oxide catalyst method for making polyethylene differ by over a factor of two in their energy requirements, because the metal oxide catalyst method calls for more process steam.⁷ Moreover energy requirements can depend on process temperatures – eg, polystyrene formation in bulk is carried out at 230–250°C but only at 20–45°C in solution. In the manufacture of PVC, the emulsion process has high energy requirements because it involves a stage of heat drying.

The production of most polymeric materials is increasing. Outputs for the USA for four recent years are given in Table 4, with the flow diagram for the principal materials in Figure 2. Production figures for a broader spectrum of polymers are given in Table 5 for the USA and UK.

Table 4. USA production (10^6 metric tonnes)

Year	Polyethylene	Polystyrene	PVC	Polypropylene
1962	0.916	0.579	0.712	0.066
1967	1.73	1.08	0.974	0.301
1970	2.65	1.61	1.71	0.469
1972	3.47	2.09	1.95	0.787

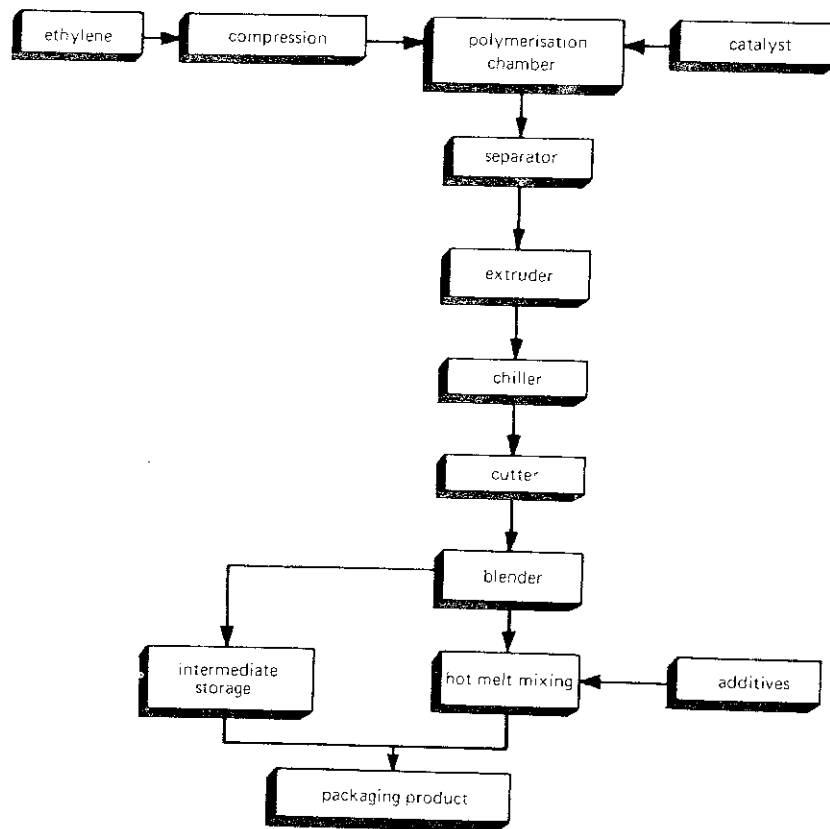


Figure 1. Production of polyethylene for packaging

Table 5. Production levels of major polymeric materials in the UK and the USA (10⁵ tonnes)

	UK	USA (1968)
Plastics, total	12.8	50.2
Regenerated cellulose	0.11	3.2
Low-density polyethylene resins	} all poly-olefins 4.95	13.3
High-density polyethylene resins		7.8
Polypropylene resins		3.3
Polystyrene		1.44
ABS ^a	n.a.	1.9
Poly(vinyl chloride)	5.06	14.2
Poly(vinyl acetate)	0.37	1.9

Note:

^a Acrylonitrile-butadiene-styrene

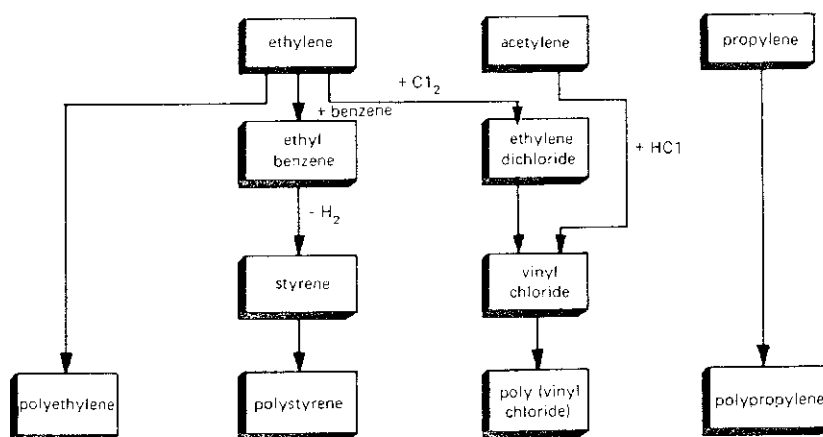


Figure 2. Major plastics in the USA

Polyethylene

Table 6 contains the total process energy to make polyethylene from crude oil or natural gas, disaggregated into steps of acquisition, monomer production, polymerisation and typical product fabrication (film, in this example), for the USA, the UK and The Netherlands. The differences among the three nations' practices are quite striking. The largest relative difference is in the distillation of naphtha from crude oil. The energy differences between using naphtha and natural gas as the ethylene source are large, a factor of 2.5 to 3 between the USA and UK – Netherlands. The largest absolute differences occur in the polymerisation, particularly when UK and Netherlands figures are compared with the metal oxide catalyst method. We have found that most of this difference is associated with the energy used for process steam – partly because almost three times as much process steam is used per unit of output in the USA. (We have used a figure of 0.474 GJ per pound of steam for the USA based on stream flows and process casts. This corresponds to an efficiency of about 0.82, effectively the same as the value of 0.8 used to determine the UK figures.) Some UK and Netherlands chemical plants generate their own electricity and use the by-product steam from the home generating station as process steam. The Dutch operations were designed, it appears, to optimise the use of heat at every possible

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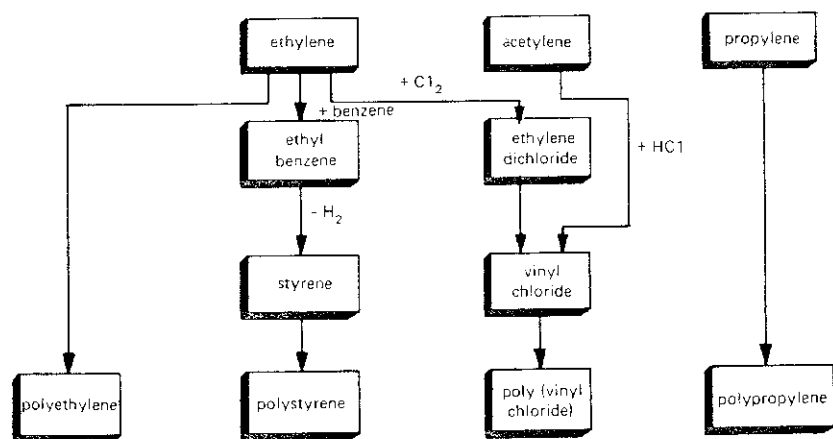


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a G. Haller, in 'Resource Utilization and Environmental Impact of Alternative Beverage Containers,' presented at the Symposium on Environmental Impact of Nitrile Barrier Containers, July, 1973, from a study carried out for the Monsanto Company. Haller arrives at a figure equivalent to only about 22 GJ/tonne. Of the 40 GJ/t difference, we can account for 10 by differences in prorating among multiple-output processes. With Haller's figure for production of ethylene, the US energy requirement is 120 GJ/t, differing from the European figures entirely because of the energy requirements claimed for the polymerisation step.

b Figures are for low-density polyethylene, in The Netherlands and the UK. For high-density polyethylene, add about 1.8 GJ/t.

c Calculated for the Ziegler catalyst method; if the metal oxide catalyst method is used, the US energy requirements for polymerisation becomes 92.1 GJ/t, and the total, 169 GJ/t, because of the very high steam requirements in solvent recovery and polymerisation.

Table 6. Energy use in the production of polyethylene (GJ/tonne ethylene)

	The Netherlands	UK ^{1,3}	USA ^{6,7}
Production of crude oil or nat. gas	0.3	0.3	0.4
Crude oil → naphtha	1.4	5.7	—
Naphtha → ethylene	25.8	20.5	—
Natural gas → ethylene ^a	—	—	62.2
Ethylene → polyethylene ^b	18.3	18.2	43 ^c
<i>Subtotal, for polymer production</i>	<i>45.8</i>	<i>44.7</i>	<i>105.6</i>
Polyethylene → film	3.4 ³	13.7	10.9
Total	49.2	58.4	116.5

stage. Hence some of the difference between the UK and The Netherlands in polymer manufacture may be due to technology, particularly that of heat conduction and insulation.

The total figures are a dramatic illustration of differences in the use of energy to achieve a common end product. The process energy cost of polyethylene film in the USA is almost 2 times that of the UK, and almost 2.4 times that of The Netherlands. If the US manufacturers were to use Dutch practices instead of their own, the manufacture of polyethylene would consume 0.22% of the US energy budget instead of 0.45%, neglecting feedstock energies.

Polypropylene, PVC and polystyrene

Polypropylene follows a pattern qualitatively like that of polyethylene, but with less striking differences. Comparative figures for polypropylene manufacture are given in Table 7.

PVC, whose energy requirements are in Table 8, shows significant international differences, again less than those for polyethylene. We have already seen the differences due to the use of naphtha in The Netherlands and the UK, and of natural gas in the USA. Large absolute and relative differences in PVC manufacture come in the generation of chlorine. A wide range of energy requirements appear in

Table 7. Energy use in the production of polypropylene (GJ/tonne propylene)

	UK	USA
Production of crude oil or nat. gas	0.3	0.4
Crude oil → propylene	33.5	—
Natural gas → propylene	—	56.3
Propylene → polypropylene	28.4	44 approx.
<i>Subtotal</i>	<i>62.2</i>	<i>101 approx.</i>
Polypropylene → film	62.7 (oriented film) or: 17.4 (molded crate)	10.1 (unoriented film)
Total	125.0 (oriented film) or: 79.7 (molded crate)	111 (unoriented film)

a The two major processes using ethylene, based on oxychlorination and on hydrogen chloride oxidation, require 10GJ/t and 20GJ/t, respectively. Two other processes utilise acetylene rather than ethylene; the high-pressure process requires about 10 GJ/t of vinyl chloride, while the low-pressure process *generates* about 6 GJ/t in the form of a fuel gas.

b By suspension process, with 80% steam efficiency; 19.8 at 32% steam efficiency. If the emulsion process is used, and steam efficiency is 80%, polymerisation requires 14.1 GJ/t (or 16.0, at 33% steam efficiency); the bulk process requires 8.6 GJ/t (or 16.1 at 33% steam efficiency). The emulsion process requires very little energy for steam, but has large fuel requirements for drying, and some energy requirement for refrigeration. The bulk process, by contrast, uses nearly 80% of its energy requirement for polymerisation in the generation of process steam. Ratios of materials assumed are exact chemical equivalents: C₂H₄: Cl₂: Vinyl chloride = 0.5:0.65:1.0.

c Upper figures: total chloralkali process energy assigned to Cl₂, with no regard to simultaneous production of NaOH; Lower figures (parenthesised): 47% of chloralkali process direct energy attributed to chlorine production, 53% to NaOH production.

Table 8. Energy use in the production of PVC (GJ/tonne PVC)

	The Netherlands	UK	USA
Production of crude oil or nat. gas	0.15	0.15	~ 0.2
Crude oil → naphtha	0.7	5.2	—
Naphtha → ethylene	12.9	9.7	—
Natural gas → ethylene	—	—	31.1
NaCl → Cl ₂	33.8 (26.2)	22.6 (17.4)	9.8 (7.6)
Ethylene + Cl ₂ → vinyl chloride	13.1	18.6	10.20 ^a
Vinyl chloride → PVC	9.1	9.7	9.7 ^b
Total	69.8 (62.2)	66.0 (60.8)	60.8-70.8 (58.6-68.6)

the making of vinyl chloride itself, because there are four methods used for this process. Two are based on the addition of hydrochloric acid to acetylene, and two are based on chlorination of ethylene followed by dehydrochlorination of the ethylene so generated.

Polystyrene, as shown in Table 9, exhibits smaller differences among nations than do polyolefins or PVC. The greater energy used in the USA for polymerisation is compensated for, in part, by the larger energy requirements of the British procedure for obtaining benzene from crude petroleum. Overall, polystyrene requires about half the *average* overall energy for plastic resin manufacture in the USA, about 150 GJ/t.

A variety of other aggregated average values of polymers and plastics have been derived, in the neighbourhood of 100 to 150 GJ/tonne. This is clearly the correct order of magnitude for these products. However, as we have seen, the component steps can vary considerably.

Summary

The figures just presented are all *process energy requirements* (PER).

Table 9. Energy use in the production of polystyrene (GJ/tonne polystyrene,^a excluding transportation)

	The Netherlands	UK ^b	USA ^{6,7}
Production of crude oil or nat. gas	0.3	0.3	0.4
Crude → benzene	31 approx.	26.3	12.0 (or 26.2 ^c)
Crude → isopentane	0.3	0.3	0.3
Natural gas → ethylene	—	—	20.9
Crude → naphtha	0.3	3.7	—
Naphtha → ethylene	7.1	7.1	—
Ethylene + benzene → polystyrene	47.9	12.3 ^b	44.1 (or 58.3 ^c)
Total	86.9	50.0	77.7 (or 106.1^c)

a We assume 1 tonne of polystyrene requires 0.85 tonne benzene, 0.96 tonne crude oil, 0.08 tonne isopentane, 0.31 tonne natural gas and 0.30 tonne of ethylene; ie, the chemically equivalent amounts.

b Data presented by H. Smith, 'The Cumulative Energy Requirements of some Final Products of the Chemical Industry,' presented at the World Power Conference, Moscow, August, 1968. The figure of 12.30 GJ/t for preparation of styrene and its polymerisation is an old figure that may be questioned. An independent recent *total* for the UK is 51.6 GJ/t.

c The higher values are based on the energy requirements for production of benzene, as obtained by Haller; see note c, Table 6.

They do not include the energy (strictly, the gross enthalpy of combustion) of the feedstock sequestered in the polymer. The *gross energy requirement* (GER) is the process energy requirement plus the gross enthalpy of combustion of the feedstock. For polyethylene, polypropylene and polystyrene, the feedstocks required for the processes contain about 46 GJ/tonne of product; for PVC the required feedstocks contain about 22 GJ/tonne of product. There is some difference between the GER for olefin feedstocks produced from crude and from natural gas, due to the differences in their heats of combustion and to the PERs for their acquisition. For olefins from crude oil, the GER is greater than the PER by 44.7–47.6 GJ/tonne ($46.2 + 1.5$), depending on the type of crude and the process losses; for olefins from natural gas, the GER is greater by about 57.4 GJ/tonne. These figures include the best estimates of process losses that were available to us, but would be well worth closer scrutiny.

The information presented here, particularly data released before 1973-74, may be subject to strong bias errors because of inaccessibility of information. The chemical industry, more than any other with which we have dealt, traditionally considered much of its process information to be proprietary. This situation has improved in the past year. Hence older figures are often based on the data from those firms willing to release data, and on census sources which are particularly inadequate in the chemicals field – again, partly because of proprietary reasons, but also partly because of the complexity and diversity of the input-output flow patterns.

The analyses presented here have been validated by comparisons between manufacturers whenever it was possible. Where discrepancies within a single country were large, we have tried to present the differing energy requirements and to explain the origins of the differences, where we could. There are rather wide variations from plant to plant and process to process in the polymer industry, that are considerably greater than our estimate of the uncertainty in the calculations of about 20% in the overall average energy requirements. Because of this variation, we can foresee very large differences between the upward and downward output elasticities, which will only be exposed by a careful and far more detailed analysis of this very complex industry.

Paper and paperboard

The full analysis of paper and paperboard manufacture has already been done for the United States,^{6, 7} and we shall not undertake to present it here. However, it is useful to compare energy costs of paper and paperboard in the three countries, The Netherlands, the UK and the USA, and see how these materials compete with their most likely alternative, polyethylene, on the basis of their energy requirements.

We illustrate the process of making a typical paperboard product, the folding paperboard box, in Figure 3. The conventions for this figure, as introduced previously,^{4, 5} follow the recommendations of the International Federation of Institutes for Advanced Study (IFIAS) Workshop *Energy Analysis*, August, 1974. This displays most of the basic quantities and material flows. The energy costs for comparison among nations are given in Table 10. We are inclined to question the figure for The Netherlands taken from reference 3; we suspect that the energy cost is more likely to be in the range of 50

Figure 3. Energy flow in the production of 1 tonne of folding paperboard boxes

The total is 51.8 GJ/tonne of folding boxes.

Rectangles indicate processes; ovals, amounts in metric tonnes; triangles, amounts of process energy in megajoules (10^6 joules or 10^{-3} gigajoules), and carts, the transportation energy.

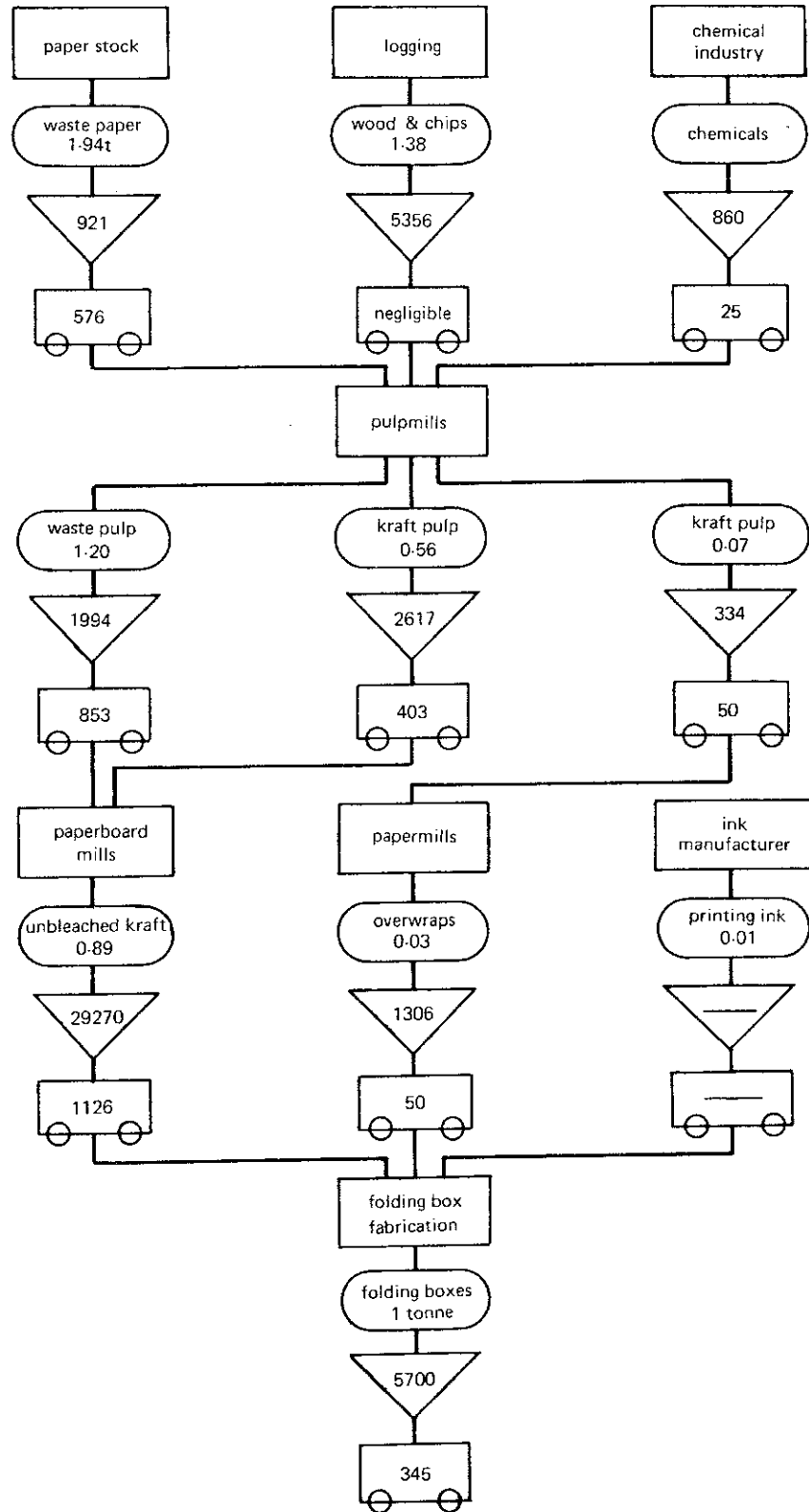


Table 10. Energy consumption in the production of paper and paperboard (GJ/metric tonne)

	The Netherlands	UK	USA
Paper (Kraft)			46.6
Corrugated cardboard	18.8	60.0	40.8
Boxboard			39.0

GJ/t. This point deserves further study.

We can put these figures together into a mundane example, the comparison of the energy input for a paper sack *versus* the energy for a polyethylene sack of the same size and strength. The US figures show the energy cost of a polyethylene sack to be about 1.2 times that of an equivalent paper sack. (This value is lower than the figure of 1.7 given previously^{2, 6} because the older figure was based on the electrical equivalent efficiency, rather than the direct fuel input, for steam.) The British figures put this ratio at about 0.83, and the Dutch figures, if we accept the low value for the energy cost of paper, give a value of 0.76 because of the extremely low energy requirements for polyethylene production in The Netherlands. Given present practices, polyethylene is a more energy-thrifty material than paper in Europe, but is more costly than paper in the USA. All these figures are based on the same polyethylene-to-paper weight ratio of 2/3, for equivalent containers and on the process energy requirements (PERs) not GERs.

Our analysis suggests that if we are looking for points of significant elasticity of demand in energy within the present context, it is in the US manufacture of polymers and their inputs that we shall find the largest elasticity, certainly not in the Dutch plastics industry, and probably not to the same absolute extent in the paper and paperboard industry. The analysis has also illustrated the importance of making international comparisons, especially on a disaggregated basis, if we are looking for technological optima. International comparisons suggest that energy savings can be analysed and made in specific industries in which the economics are well determined and the risks minimised. In framing both public and private policy, we may turn with considerable confidence to such analyses for guidelines toward readjustment, when confronted with resource constraints.

Previous articles in this series:

1. 'Energy costs: a review of methods'. P.F. Chapman, Vol 2, No 2, June 1974, pp 91-103.
2. 'The energy cost of fuels', P.F. Chapman, G. Leach and M. Slesser, Vol 2, No 3, September 1974, pp 231-243.
3. 'Goods and services: an input-output analysis', David J. Wright, Vol 2, No 4, December 1974, pp 307-315.
4. 'The energy costs of materials', P.F. Chapman, Vol 3, No 2, March 1975, pp 47-57.