THE PATTERNS OF ENERGY USE IN THE CHEMICAL INDUSTRY

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SUMMARY

SUMMARY – OVERVIEW

This paper was sculpted from a report commissioned by the Department of Energy to assess the impact of proposed energy taxes on energy use by the US chemical industry. The discussion of energy taxes is eliminated here, however the broader discussion of the impact of energy prices on energy use is retained.

The US chemical industry is currently the world leader by many important measures, such as technology contributions and employment. This leadership traces to a slate of advantages: science base, low cost energy, large market and economic/political stability.

The focus of this paper is on the patterns of energy use:

* There is an optimum economic trade of capital against energy. Industry optimizes this trade to lower its costs. For the large volume chemicals which dominate energy use, this tradeable capital cost exceeds energy cost by a factor of 1.5.
* The capital/energy trade follows clearly defined rules. The basic rules are rooted in thermodynamics.
* An increase in energy prices would result in a drop in process energy use:

  a doubling of process energy prices would cut process energy use by approximately 1/3

  but

  the capital cost would be in excess of $100 billion if driven into a short time span, such as 5 years.

  This is because of the long useful lifetime of capital facilities.

* Process energy is about half the total energy use, with feedstock being the balance. Feedstock use is much less sensitive to price. Restated, the doubling of energy price will result in roughly a 1/6 reduction in total energy use.

* *Technological progress* will also reduce energy use. This reduction is distinct from the impact of energy price. *Technological progress will be at least as important in reducing energy use as will energy pricing, for the foreseeable future.*
* *Technological progress* can be sorted into two themes:
  - *Learning curve* improvements, which are almost inherent in the production process and the nature of competition.
  - *Breakthroughs* that happen in a less predictable way. The speculated causes of breakthroughs are:
    - a widely held perception of a major barrier and need for a breakthrough
    - progress in underlying science.

"THE FIRST RANK" [a] (the largest chemicals in terms of US energy usage)

	-------BTU/yr 10^{15}-------			lb/yr	-------------------$/lb-------------------				---plant scale[f]---	
	total	process	feed-stock	10^9	price	total energy[b]	process energy[b]	capital related[c]	$\$10^6$	lb/yr 10^9
ethylene	1.41	0.40	1.01	40.4	0.19	0.070	0.020	0.097	314	1.10
ammonia	0.75	0.29	0.46	36.0	0.06	0.042	0.016	0.083[d]	300	1.20
propylene	0.70	0.16	0.54	22.3	0.13	0.063	0.014	0.100[d]	42	0.14
benzene	0.43	0.01	0.42	12.0	0.15	0.051	0.002	0.043	25	0.20
sodium hydroxide[e]	0.38	0.38	0.0	24.0	0.12	0.032	0.032	0.057	60	0.36
methyl t-Butyl ether	0.30	0.06	0.24	10.9	0.12	0.055	0.011	0.087[d]	65	0.25
chlorine[e]	0.23	0.23	0.0	22.6	0.10	0.020	0.020	0.060	60	0.33
p-xylene	0.20	0.05	0.14	5.7	0.21	0.070	0.019	0.083	35	0.20
phosphoric acid	0.20	0.15	0.05	25.4	0.30	0.016	0.012	0.083	125	0.50
carbon black	0.16	0.04	0.12	3.0	0.27	0.100	0.024	0.047	27	0.20
	4.78									

All values are from Battelle (1994) except for the conversion of energy and capital usage to \$/lb. The bases for these conversions are noted in footnotes (a) and (b). The Battelle report provides a uniquely valuable set of numbers because it combines in one place the effects of energy intensity, capital intensity and market scale. In a conversation, the prime author, Lipinsky, pointed out that in some cases the Battelle values were "judgment calls", but most were corroborated by industry sources.

(a) This list has been designated as the "First Rank" chemicals to distinguish it from the original Battelle list. The "First Rank" chemicals are unique. They are not made from one another. The original Battelle list included substantial double counting because of listing of chemicals which are made from the "First Rank" chemicals. An example of double counting would be ethylbenzene which is made from ethylene and benzene or styrene which is produced from ethylbenzene.

(b) Computed based on $\$2/10^6$ BTU which is reasonable for direct "process" uses such as natural gas for fuel, as well as for the fuel embedded in "process" use of electricity. Since the subsequent discussion keys against "process" energy use, this single value for energy price introduces no major error. However the use of this value is too low for most feedstocks.

(c) Computed based on [\$ capital/lb]/3. This says that the costs associated with maintenance, depreciation, profit and taxes on an annualized basis will be 1/3 the total capital costs. Restated "...simple capital payback period is 3 years...". This is characteristic of what industry would want for a project with modest risks.

(d) In the cases noted, the capital cost values are inconsistent with the "selling prices" taken from Battelle (1994). For some chemicals like NH_3 this is because the "selling price" listed is well below what a producer would need to justify a new plant.

(e) Sodium hydroxide and chlorine are truly coproducts.

(f) There is a limit on the size of individual components that can be shop manufactured and shipped to a construction site. For example bridge clearances typically limit components to around 14 feet in diameter. As more parallel trains are required, the advantage of building to a larger process unit plant scale disappears. The component size limit explains why there is a characteristic plant scale that typifies the largest units. This maximum economic size is called "world scale".

A few things to note about the "First Rank":

- Energy use for these 10 chemicals sums to greater than 80 % of the chemical industry use shown earlier. This appears to err on the high side.
- The "First Rank" chemicals are dominated by the simple molecules.

[1] THE CHEMICAL INDUSTRY

The chemical industry lies at the front end of the raw material processing cycle. Most of its products flow to other producers rather than to the consuming public. The chemical industry spans an enormous range and is really a multitude of smaller industries. C&EN (June 24. 1996) lists 50 compounds with USA output greater than 1.6 billion pounds per year; and these are only the low-cost, high volume materials. CMA (1996) refers to "...more than 70,000 products".

1.1 General Health in the USA,

The US chemical employment is stable and twice as large as our closest *global* competitor, Germany. Financial measures such as R&D expenditures, capital expenditures and profit also point to good health.

CMA (1996) estimates for the US chemical industry in 1995:

- total employment 1,045,000
    - including 582,000 production workers
    - 92,000 scientists and engineers
- R&D funding $18.1 billion
- capital investment $30.9 billion
- income (after taxes) $11.2 billion
- trade surplus $20.4 billion *the imported energy embedded in the net exports means that the net is ~ $18 billion*

Swift of CMA, (1995) estimated US chemical industry value added at	~ $126 billion
and total energy for "process" and feedstock at	~ $26 billion

The values are net to the overall chemical industry. There is much internal trading within the industry (not counted above), that tends to exaggerate the value of industry shipments.

For the overall US industry, the energy use is about equal for "process" and feedstock. Feedstock energy use is a larger fraction for the major energy using chemicals. Generally the feedstocks are more expensive on a BTU basis than fuels because the feedstocks have purification costs embedded in their production.

1.2 USA as Part of a Global Chemical Industry

It is a sophisticated industry, with an increasing tendency to see competition on a *global* basis rather than as a fight for ranking against other national companies. Most large companies have flexibility to shift production between countries. More importantly, most large companies have shown a willingness to place their new investments anywhere in the world where economics dictate. The most important elements in dictating location economics are:

- regional cost of capital construction
- market size and growth rate
- raw material (feedstock) prices and energy prices
- political/economic stability.

The stability factor (risk of losing capital) seems to be less decisive than it once was, as evidenced by the competition to site facilities in China.

The most direct measure of health is employment. The US employment has dropped slightly but it appears to have maintained its position relative to its global competitors. Note that employment in the US industry (CMA,1996) exceeds the combined total of its largest global competitors, Germany and Japan.

TOTAL CHEMICAL INDUSTRY EMPLOYMENT (in thousands)								
	1980	*1985*	*1990*	*1991*	*1992*	*1993*	*1994*	*1995*
USA	**1107**	**1044**	**1086**	**1076**	**1084**	**1081**	**1061**	**1045**
Germany	568[a]	557[a]			585	557	570	538
France	297	272	266	263	260	248	250	248
U. K.	420	339	326	309	310	303	282	281
Japan	409	396	401	406	415	413	399	390

(a) Data for 1980 and 1985 is for West Germany only

1.3 "Information" and Patterns of Chemical Trade

The chemical industry lives in the science of chemistry. The relationship is symbiotic. Economic competitiveness depends on choosing the right catalyst, temperature and pressure for the reaction step as well as the right (efficient) process for product recovery and {waste/environmental discharge} avoidance. This is the technical part of the chemical industry *"information"*. Technical *"information"* is part of the reason why Germany and Japan are major players in chemical trade despite the disadvantage of energy prices. Technical *"information"* is important to the USA and most measures suggest health.

COUNTRY OF ORIGIN FOR CHEMICAL LITERATURE			
	1984	*1990*	*1994*
USA	**27%**	**28%**	**29%**
Germany	7%	7%	7%
France	4%	4%	4%
U.K.	6%	6%	6%
Japan	10%	12%	13%

Based on address of author, from C&EN (August 28, 1995)

CHEMICAL PATENTS GRANTED IN THE US BY COUNTRY			
	1984	*1990*	*1994*
USA	**11525**	**13124**	**15508**
Germany	2139	2704	2703
France	665	917	1012
U.K.	847	953	911
Japan	3258	5469	6257

Based on address of inventor, from C&EN (August 28, 1995)

One of the hidden roles of technical *"information"* is the ability of educational systems (including the availability of funding for research) to remain a magnet for the world's brightest, most innovative young people. It is not an accident that startup firms that have a chemical base such as micro-circuitry and biotechnology have arisen in the US. It is also not an accident that these firms are often led by individuals not born in the US.

However much of the *"information"* that drives chemical plant location decisions is softer, for example:

- will energy prices be competitive five years from now?
- can a market be dominated from the geographic region in which the technology/market leader feels most comfortable?

Given the need for a billion dollar scale to compete in world markets, *"information"* on political stability provides a key input to the decision process of the global chemical industry. This *information* tends to be mixed with the technology *"information"* and the net is a tendency to site facilities in the developed world. Export/import patterns follow geographical investment patterns.

While the industry is nominally global, with manufacture going to the areas of the world with greatest markets and lowest production costs, the *"information"* of the industry remains based in national origins.

The main labs of a German company will be in Germany and German nationals will be the preferred expatriates for overseas assignments from their parent companies.

THE WORLD'S LARGEST CHEMICAL COMPANIES
(excluding those that are primarily pharmaceutical)

		--$B in 1995--	
		Sales[a]	*Profits*[b]
BASF	*Germany*	22.0	2.5
Hoehst	*Germany*	21.7	1.9
DOW	USA	19.2	4.3
Bayer	*Germany*	18.8	1.5
DuPont	USA	18.4	3.5
Shell	UK/Nether.	15.4	1.7
ICI	UK	13.0	1.4
Exxon	USA	11.7	2.7
Elf Aquitaine	France	11.1	1.0
Formosa Plastics	Taiwan	10.8	1.3

From C&EN (July 22, 1996)

(a) These are chemical sales only. In some cases like Dupont, Shell and Exxon, chemical sales represent less than half total sales.
(b) The profit basis may be defined differently for various countries. The intent was to only report profits from chemical operations.

One explanation for patterns in world trade is energy cost. Another is technical "*information*", and still another is the "*information*" content of the capital decision process.

CHEMICAL INDUSTRY FOREIGN TRADE IN 1995
(exports from)/(imports to) by categories values in $ billions

	organic chemicals	inorganic chemicals	plastics	pharmaceuticals
USA	16.1/12.5	4.5/4.8	4.3/2.7	6.4/5.1
Germany	14.4/6.5	3.8/2.2	6.2/3.7	9.5/6.3
France	5.8/6.1	2.2/2.3	1.5/3.0	6.9/4.8
U. K.	7.8/5.6	1.9/1.4	2.0/2.3	7.7/4.1
Japan	11.1/7.2	1.7/2.7	2.5/0.6	1.8/4.0

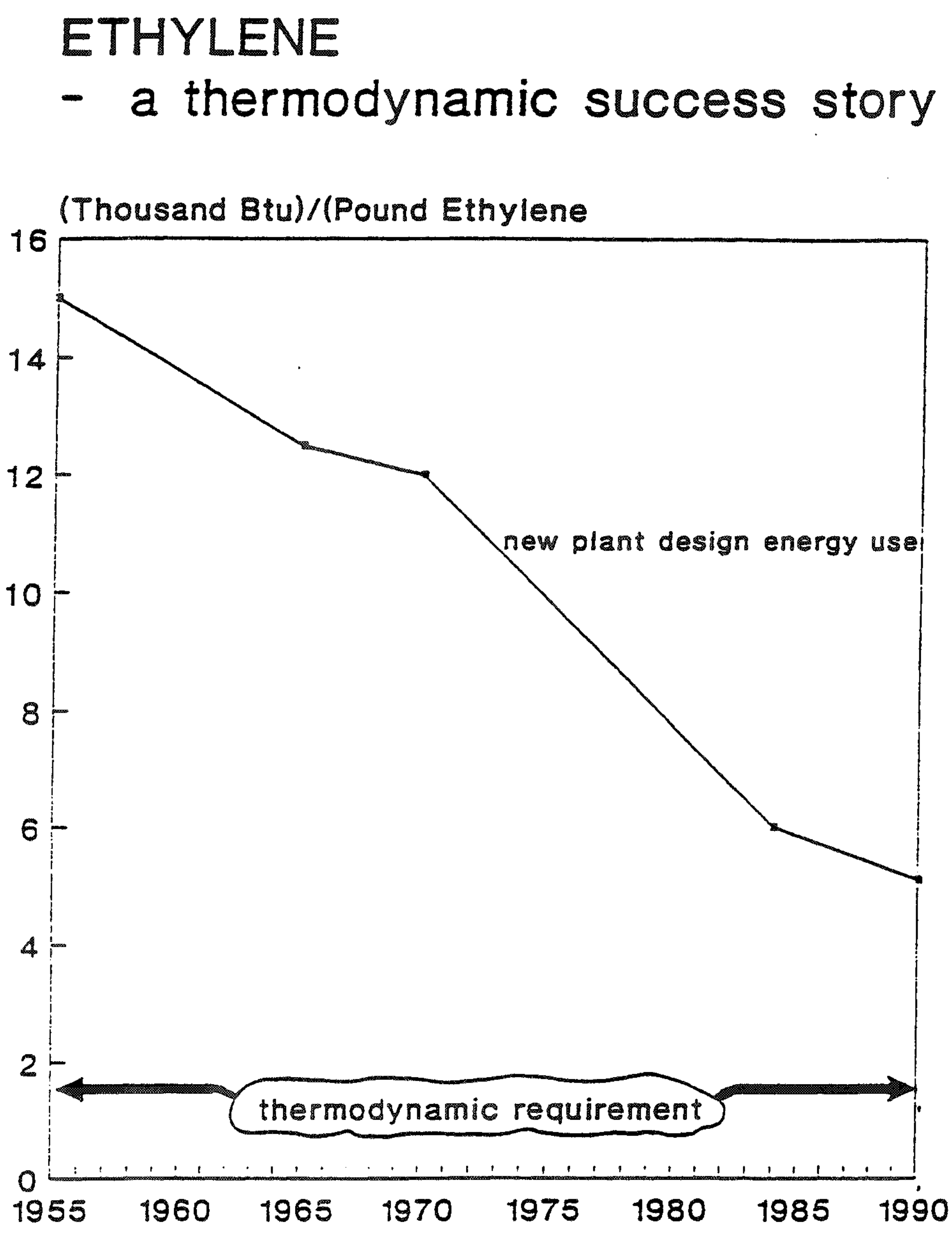
From (CMA, 1996.)

[2] CHEMICAL INDUSTRY ENERGY USE: HOW MUCH AND WHAT TYPE

The largest energy using portions of the chemical industry are relatively young. This means that they are fairly high on the learning curve and are still generating significant energy efficiency gains. The energy use per pound of product has historically fallen an average of ~ 2% per year. This is due to broad technological progress as discussed in Section 5.

As shown by Figure 1, efficiency increased at a steeper rate during periods of rising energy price
--but--
it also increased during periods when energy price was stable or falling.

FIGURE 1


ETHYLENE
- a thermodynamic success story
(Thousand Btu)/(Pound Ethylene
16
14
12
10
8
6
4
2
0
new plant design energy use
thermodynamic requirement
1955
1960
1965
1970
1975
1980
1985
1990

2.1 *The Gross Numbers in the USA*

Over the last 15 years, energy use by the chemical industry shows a slight increase (CMA, 1996):

		1980	*1990*	*1994*	*1995*
Process energy	BTU 10^{15}	2.72	2.70	2.89	2.94
Feedstock	BTU 10^{15}	2.56	2.48	2.88	2.89

When feedstock is included, the chemical industry consumes ~ 25 % of industrial energy use (DOE, 1994) and ~ 8 % of the total energy use in the USA. These totals includes the energy used in generation of the electricity that the chemical industry buys.

2.2 *Types of Energy*

The 1995 hydrocarbon energy use by the US chemical industry breaks down as follows (CMA, 1996):

HYDROCARBON USAGE

	----BTU 10^{15}----	
	fuel	feedstock
natural gas	1.9	0.6
coal/coke	0.3	< 0.1
LPG	< 0.1	1.0
oil	< 0.1	1.3

Note the dominance of natural gas for fuel. This is because of price. The industry has migrated to parts of the USA which produce low cost natural gas in order to reduce its costs. This explains why the prices it pays are below the industry average. DOE (1994) reported that the chemical industry paid ~ 80% of the average price paid by all industry for natural gas.

On a cost basis (DOE, 1994) the 1991 breakdown was:

natural gas	\$3.8 billion
LPG	\$5.5 billion
other fuel	\$2.1 billion
electricity	\$4.5 billion

Electricity use by the chemical industry was estimated (DOE, 1994) as

machine drives	73%	*mostly for pumps and compressors to overcome friction*
electro chemical	14 %	
process heating	4 %	
non-process	9 %	

The high portion of energy costs for overcoming friction in piping systems, is important in explaining the high ratio of {capital cost/energy cost} since:

- piping is a major part of the capital cost
- in piping systems, when the optimum trade is made between capital and energy, capital costs dominate energy costs by a factor of ~10.

2.3 *Which Chemicals Dominate US Energy Use*

It is instructive to sort the chemical industry by energy use.

- Of the "First Rank" chemicals, the only one that primarily goes to final customers is NH3 which is used as a fertilizer.

The chemical industry initially appears to be so complex and multi-dimensional that an attempt at understanding the energy use appears impossible, but a closer look shows consistent patterns such as the ratio of {process energy costs/capital costs}. This is because a large part of the capital cost for the major energy using chemicals is driven by energy costs. ***Energy efficiency is gained through the trade of capital for energy.***

The pattern of energy use is clearer if we deal with an example. Picking ethylene, the largest user of energy:

- Capital costs for making ethylene are 1.3 times total feedstock and process energy use.
- Energy use for feedstock is 2.5 times process energy use. The high energy use for feedstock is because the hydrocarbon framework of the feedstock forms the basis from which the ethylene molecule is shaped. For example, the most common feedstock is ethane which is chemically very similar to the product ethylene:

  ethane ($\mathbf{C_2H_6}$) $\Longrightarrow$ ethylene ($\mathbf{C_2H_4}$) + $\mathbf{H_2}$

  Since the hydrocarbon framework energy is retained, ethylene is only fractionally higher in energy than the ethane feedstock from which it is made. The difference in energy arises because of the *work* of pulling a hydrogen (H_2) molecule out of the framework.
- Because the framework of the feedstock is retained, the total energy input is relatively low. For perspective, to make a pound of ethylene takes only 1/3 the energy that a pound of aluminum requires.

The chemical industry is a high energy user because of the large pound per year totals. not because of the usage per pound. If aluminum were classed as a chemical, the pounds per year would not qualify it for the list of top 20 USA chemicals.

2.4 Polymers, where 1/2 of the Energy Flows out of the Chemical Industry

A high fraction of the "First Rank" chemicals are further transformed to plastics and fibers which move one step closer to end use.

THE MAJOR US POLYMERS (in terms of contained energy)

"THE SECOND RANK" (from Battelle, 1995)

	BTU/yr 10^{15} total including input of chemicals from "First Rank"	lb/yr 10^9	$/lb price
polyethylene	1.02	25.7	0.45
polyvinylchloride	0.41	11.1	0.47
polypropylene	0.36	9.8	0.44
polyesters	0.32	7.0	0.70
polystyrene	0.25	5.9	0.54
phenolics	0.14	3.2	0.76
polyurethanes	0.13	3.8	1.00
polyesters (unsaturated)	0.13	2.9	0.61
Nylon 6,6	0.10	2.0	1.33
acrylo/butadien/styrene	0.10	1.5	0.92
	2.92	72.9	

Note:

- The energy to produce these 10 polymers sums to 50 percent of the chemical industry total use.
- The prices are 2 to 4 times as high as those of the "First Rank" chemicals.
- The Battelle study gave a revenue for these 10 polymers of $41 billion which yields a value over feedstock/energy input of ~ $35 billion. This compares to the total value added of ~ $126 billion estimated for the chemical industry as a whole.

[3] CHEMICAL INDUSTRY -- WHY IT *"USES"* PROCESS ENERGY

3.1 Transformation

A common theme of the chemical industry and its energy use is "transforming" raw materials into discrete, nearly pure molecules like ethylene and ammonia.

Transformation is driven by the *work* potential in fuel and electricity. A major portion of this *work* potential is used in separating the species. A major portion is also used in shifting process reaction conditions so that the desired chemical is present in high concentration as it exits a reactor -- to minimize the *work* of separation, to minimize the input of raw materials and to minimize the energy used (and $ cost) of treating byproducts.

An example of the *work* of separation is the separation of air into nitrogen and oxygen. Nitrogen and oxygen fail to make the "First Rank" list of energy using chemicals because of the absence of feedstock energy. However, if the list were based only on "process" energy, the combined total for nitrogen/oxygen would put it at #7 on the list.

3.2 Thermodynamic Limits

energy and work, what's the difference, what do we measure

One reason engineers and scientists focus on energy is that energy use and efficiency are easy to measure and calculate. The rules are given by thermodynamics. There are two sets.

- Almost all the official counts by governments, trade groups and economists measure ***energy in.*** This measure is accurate, but not helpful in setting expectations. What we value in *energy* is its ability to do *work.* In fact we couldn't truly "use" energy even if we wanted to.

  The first law of thermodynamics guarantees that the "energy in" is identical to the "energy out".

- For setting expectations, a more instructive approach is to measure the ***difference in the ability to do work of the energy inputs and outputs.***

  The second law of thermodynamics can be interpreted to say "when we speak of using energy what we really mean is using the embedded work potential."

  The second law of thermodynamics is often hidden behind abstract terms, but a simple, functional definition of the second law is:

  "It takes work to change things."

  and a practical corollary is:

  "Transformation work underlies cost of production."

A typical production process uses the *work* potential embedded in chemical fuels or electricity to transform a raw material into the desired product. Examples are separating air into oxygen and nitrogen and reacting ethane to ethylene. In the related primary metals industries, examples are the transformation of iron oxide into steel, and aluminum oxide into aluminum.

Part of this *work p*otential is retained in the product -- oxygen/nitrogen, ethylene, steel or aluminum. Steel and aluminum are much higher above the *work* level of the oxide ores from which they are made than ethylene is above ethane. One of the results is that steel and aluminum take more *work* than ethylene to manufacture. As a consequence they cost more money to produce.

mother nature's efficiency

For every process like these, we can compute a theoretical *work* requirement. The ratio

(*work* requirement)/(actual *work* potential consumed)

is what mother nature sees as efficiency. Often it is called the "second law" efficiency. Use of this measure tells us that even for the best chemical processes, the thermodynamic efficiency is remarkably low. The "second law" efficiency calculated in this way for industrial production of oxygen by separating it from air is 20 to 30 percent, and the efficiency of producing ethylene from ethane, is also in this range. See

Figure 1. These low efficiencies provide the margin from which efficiency and economic gains are carved.

3.3 Driving Forces for Flows, Reactions and Moving Energy

Why don't we operate our chemical processes at higher technical efficiency and use less process energy? The explanation (Steinmeyer, Kirk-Othmer, 1996) comes in a sequence of concepts:

- *Driving forces are needed to move energy and materials through our processes, and driving forces cost loss of work potential.*
- *Higher driving forces permit lower capital.*
- *There is an optimum economic balance between energy and capital costs.*
- *In optimized designs, the costs of energy and tradeable capital for components such as piping or insulation, are in a fixed cost ratio.*

This is explained and illustrated in Section 4. *Again, the fixed ratio is a cost ratio not a physical ratio.*

[4] CAPITAL/ENERGY

4.1 Capital/Energy Costs for the "First Rank" Big Users

	-------$/lb------		capital / process energy
	process energy	capital related	
ethylene	0.020	0.097	5
ammonia	0.042	0.016	5
propylene	0.014	0.100	7
benzene	0.002	0.043	22
sodium hydroxide	0.032	0.057	2
methyl t-Butyl Ether	0.011	0.087	8
chlorine	0.020	0.060	3
p-xylene	0.019	0.083	4
phosphoric acid	0.012	0.083	7
carbon black	0.024	0.047	2

The capital and energy contributions to costs in the "First Rank" have a relatively consistent pattern. This seems like an *odd coincidence* and leads to the suspicion that something fundamental is at play. The following discussion explains why the *odd coincidence* occurs, and what it means for the trade of capital against energy.

Despite the central role of energy in making these molecules, capital costs dominate energy use. In the petrochemical industry which dominates this table, the ratio of capital costs to process energy costs typically runs ~ 5/1. The technical data on costs are not accurate enough to make an exact call, but it appears that the fraction of capital available for trade against energy is somewhere in the range of 20% to 40% of the plant's total capital. Thus when we see a capital/energy cost ratio of 5/1 we are looking at a (tradeable capital)/energy ratio somewhere in the range of 1 to 2.

Subsequent discussion focuses on the optimum value of the inverse of this ratio, {energy/ (tradeable capital)} which is designated as ***k***. This ratio turns out to have a technical base. ***k*** also turns out to define the economic rules for the trade of energy against capital, for example the impact of energy prices on optimum energy use, ie what economists call "price elasticity".

4.2 The Rules for Trading Energy for Capital

The process industries have always traded energy cost against capital costs. This is in pursuit of the lowest cost of production. A similar trade occurs against labor costs but the trade against labor turns out to be less important. In a large continuous operation like a chemical plant, there is a minimum staffing level required for safe and reliable operation.

4.21 the technical components of capital facilities -- general

In most areas of equipment design there is a balance made between capital and process energy costs (Steinmeyer, 1982) that arises because capital cost depends on energy use:

$$\$_{total} = \$_{capital} + \$_{energy}$$
$$\$_{total} = [K_1/(\text{energy})^k][\$_{\text{per unit of capital}}] + K_2\,[\text{energy}][\$_{\text{per unit energy}}]$$

The optimum energy use E_{opt} varies with the ratios P and k.

$$E_{opt\ new}/E_{opt\ old} = \{P_{old}/P_{new}\}^{(1/(1+k))}$$

where

P is the ratio of capital to energy price, or ($\$_{\text{per unit capital}}/\$_{\text{per unit energy}}$).

k is the ratio of (energy costs)/(tradeable capital costs) at the economic optimum.

$\{-1/(1+k)\}$ is the "price elasticity of energy use", used in economics discussions.

The general relationship for the costs at the economic optimum is:

$$\$_{\text{new total for process energy and tradeable capital}} = (\$_{\text{old total for process energy and tradeable capital}}) * \{P_{new}/P_{old}\}^{k/(1+k)}$$

4.22 insulation

A simple example of the tie between mother nature and economics is the trade of insulation against heat loss. Heat (energy flow to ambient) loss through insulation drops directly with the thickness of the insulation. And incremental cost for insulation goes up directly with the thickness. As a result, a statement can be made about total combined costs of insulation and energy loss:

$$\$_{total} = \$_{insulation} + \$_{\text{energy loss}}$$

This can be restated in terms of energy lost:

$$\$_{total} = [K_1/(\text{energy lost})^1][\$_{\text{per unit of insulation}}] + K_2\,[\text{energy lost}][\$_{\text{per unit energy}}]$$

Since both terms depend on insulation thickness, we take the derivative and set to 0 to find the optimum thickness. When we compare terms at this optimum thickness we find that

$$\$_{insulation} = \$_{\text{energy loss}}$$

"...the lifetime incremental cost for insulation equals the lifetime cost for heat loss..."

The slightly surprising aspect of this is that *the total cost ratio does not depend on the price of either energy or insulation.* If something causes energy price to rise relative to capital, we reduce energy usage by adding insulation until the dollars spent for the two are again equal.

For insulation, k is 1 and this gives the result that E_{opt} varies with $[1/P]^{1/2}$. Thus if P went up by a factor of 4, we would double insulation thickness, and heat loss would drop in half.

If the initial combined cost ($\$_{insulation} + \$_{\text{energy loss}}$) is \$10 million, with \$5 million for each, the new optimum would be

$\$_{\text{energy loss}}$	= 4*(1/2)*\$5 M	= \$10 M
$\$_{insulation}$	= 2*\$5 M	= \$10 M
$\$_{total}$	=	= \$20 M

Or even though energy use was cut in half, total costs ($\$_{total}$) double. The reason is the increased cost of the capital employed to achieve the energy savings.

4.23 heat exchangers

Heat exchangers are a larger contributor to capital costs. Their cost is dominated by surface added to recover heat and reduce the fuel bill. Heat is driven from one side of the unit to the other by temperature difference. The heat that is not recovered is directly related to this same temperature difference and directly translates to the "fuel bill". The mathematics get a little more complicated in balancing this "fuel bill" against incremental heat exchanger costs (Steinmeyer, Chemical Engr. Progress, 1996), but for the most important class of heat exchangers, ***k*** is 1.5 and at the optimum :

> *"...the lifetime incremental costs for the fuel bill for a heat exchanger is approximately 1.5 times the incremental capital cost of the heat exchanger...."*

In order to minimize the incremental heat exchanger costs, the designer also runs a second energy bill. This is for the pumping costs (power) to move the fluids through the heat exchanger. The area and pumping power costs are linked because the high turbulence due to high power usage increases the effectiveness of the heat transfer area. It has been shown that within a fairly broad region an optimum exists with ***k*** equal to 1/3:

> *"...the lifetime bill for pumping fluids through the heat exchanger approximates 1/3 the lifetime capital cost for the incremental capital cost of the heat exchanger ...."*

The fuel and power costs are endured only because they reduce the capital cost of the heat exchanger.

4.24 piping

The largest contributor to capital costs is typically piping. The very low ***k*** value for piping is due to the fact that frictional losses vary with

$(1/[\text{pipe diameter}])^{5.2}$

This gives a relationship between piping cost and power for overcoming friction that is tilted much more toward capital

> *"...the lifetime cost of supplying power approximates 1/5 the incremental capital for piping ..."*

With a closer look, the "cost of supplying power" includes the capital associated with pumps, compressor and the electrical system. These approximate the costs of the purchased power. Hence the {energy/ capital ratio} for piping is closer to 1/10. Piping is the prime reason why the industry runs a high capital cost to process energy ratio.

4.25 electrical cable

The incremental cost of electrical cable varies with the crosssectional area. The power lost in transmission varies inverseiy with this area. As a result, the balance between cable cost and losses due to electrical resistance follows the same relationship as for insulation.

In summary, ***k*** takes the following values for technical components in the capital/energy "trade":

	k energy cost / capital cost	1/ ***k***
- insulation	1	1
- heat exchanger thermal energy	~ 1.5	~ 0.67
- heat exchanger friction losses	~ 0.33	~ 3
- piping friction losses	~ 0.2	~ 5
or		
- piping+electrical+pumps/compressors	~ 0.1	~ 10
- electrical cable size	1	1

4.3 the bigger picture (price elasticity)

The price elasticity data, based on historical analysis of changes in energy use in response to changes in energy price, has a great deal of scatter (Ross, 1993). Values greater than -1 and lower than -0.2 have been regressed from industrial segments. Ross suggests an all industry value for electricity use of -0.55.

Again, price elasticity equals $-1/(1+k)$:

k	0.2	**0.5**	0.67	0.82	1	1.5	4
elasticity	-0.833	**-0.67**	-0.60	-0.55	**-0.5**	-0.4	-0.2

Thus Ross's value of -0.55 agrees with the values of -0.67 and -0.50 estimated from the k's of 0.5 and 1 in Section 4.1 from overall chemical plant cost data. Ross's value is also in general agreement with the technical component k values discussed in Section 4.2.

4.4 *total cost if energy price doubles*

If we start with an optimum design for k of 0.5, with energy costs at $10 million per year, the optimum tradeable capital would be $20 million per year. If for the base case the capital that is not tradeable against energy is $40 million, and feedstock and labor are $20 million, we would see the following impact on optimum total costs if we doubled process energy price:

-----ratioed to base-----						
energy price	E_{opt}	$\$_{opt\ energy}$	$\$_{opt\ tradeable\ capital}$	$\$_{other\ capital}$	$\$_{other}$	$\$_{total}$
1	1	10	20	40	20	90
2	0.63*	12.6	25.2**	40	20	97.8***

Note:

* A doubling of process energy price resulted in a 37% drop in process energy use.

** As in the case for insulation, the rise in energy price and the subsequent reoptimization against capital results in a reduction in energy use, but causes a major rise in the tradeable capital.

*** The net is an increase in total costs $90==>$97.8 or a 9% increase.

Suppose instead of a single plant we look at the overall chemical industry which runs an annual process energy bill of ~$10 billion dollars. If it followed the parallel above, we could cut the energy use in half with an incremental increase in capital costs of about $5.2 billion/year. But the option is not really the design of a new facility and an incremental increase, but rather the retrofit and replacement of existing facilities. This is a much more difficult thing (Ross, 1990). The result of replacement would be a capital cost more nearly equal to the total capital ~$65 billion/year, if we follow the parallel above. If we use the three year payout as a rough guide, this would mean a total capital expenditure of ~$200 billion.

4.5 *The Shape of the Curve*

Suppose an operator fails to operate at the optimum, what penalty is incurred? k also fixes the shape of the curve showing the impact of non-optimal energy use on total costs (energy + tradeable capital). See Figure 2. Note that the curves have an expanded vertical scale, and that the net cost impact for deviations from the optimum is very small when the curves are close to the optimum (the low point). These "gentle slopes" near the optimum say that economics sends "relatively weak signals" for small deviations. In Figure 2, a use of energy that exceeds optimum by 40% results in a penalty for energy costs plus tradeable capital costs of less than 5%. If these costs represent 30% of total costs, the net result is a penalty on total production costs of less than 1.5%. This would motivate concern but not immediate action.

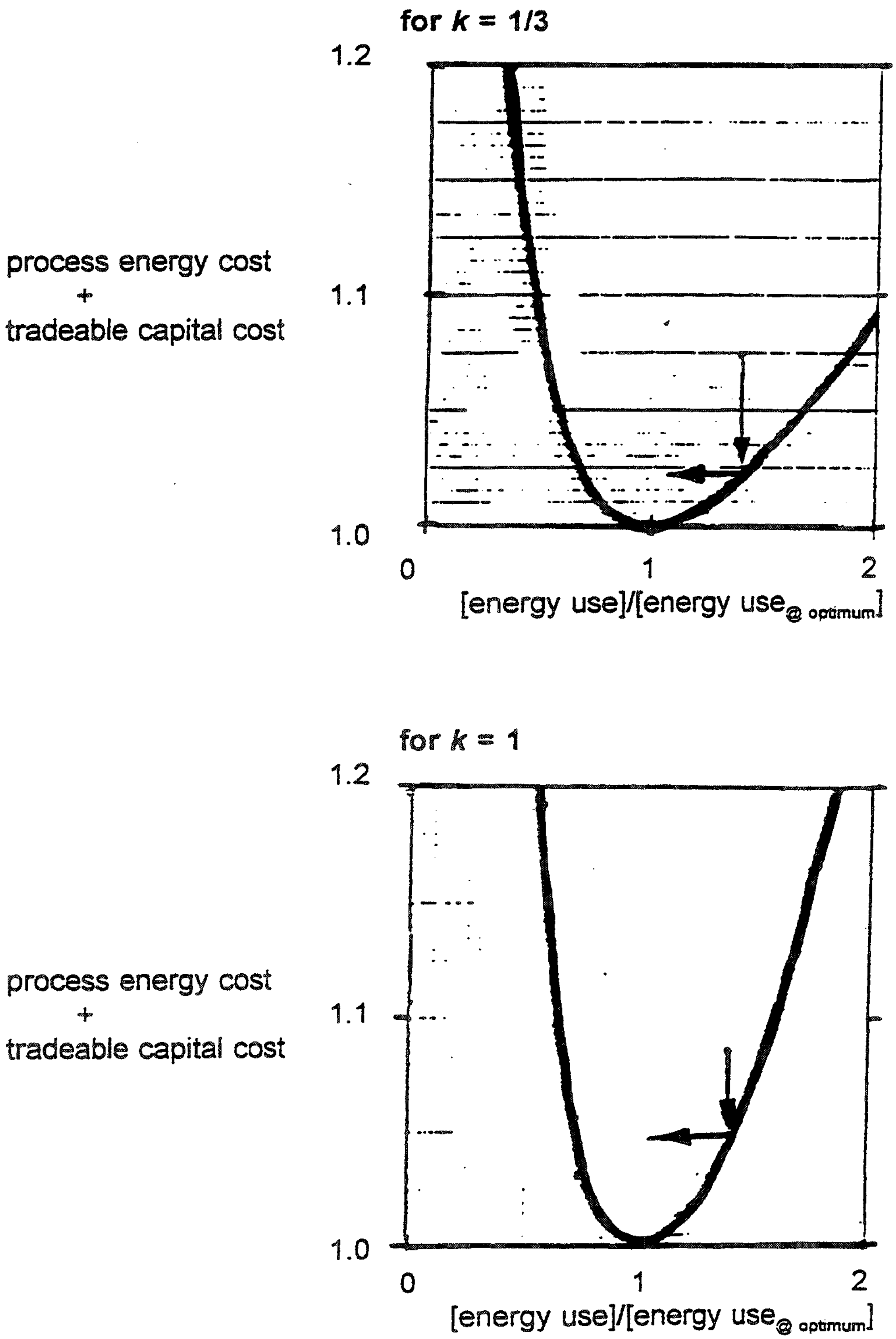
At first glance the modest penalties in Figure 2 are puzzling. The explanation for this modest penalty is that if a bit too much insulation (or surface) is used, the added investment earns an economic return, just not as high as the return at the optimum. For less than optimal insulation (or surface), a similar economic buffering occurs.

4.6 *"Capital Saving" Inventions*

Capital equipment improvements that appear to "only" lower the cost of capital equipment, like finned heat exchangers or plastic pipe, end up netting energy efficiency gains because of the lock of cost ratios. In fact, many of the significant contributors to increased energy efficiency have actually been ways to make equipment at lower cost.

FIGURE 2

THE SHAPE OF THE CURVE
what happens if we miss the economic optimum energy use?



[5] TECHNOLOGICAL PROGRESS

The preceding shows how the capital/energy trade together with a rise in energy price can be used to lower energy use, but also shows that energy price is a relatively clumsy, costly tool. The history of the chemical industry says that *technological progress* is a more effective tool.

Technological progress and the capital/energy trade are often confused but are distinctly different:

- The capital/energy trade is basically a game played with marginal economics in a static setting with a given technology. As Figure 2 shows, the rewards for playing the game perfectly (making the capital/energy trade perfectly) are only marginally greater than for playing imperfectly.
  Technology improvement is a game where the player with the best "information" wins. "Information" grows over time. The player that enters the game later has a large advantage, as shown by Figure 1.
- The capital/energy trade is driven purely by relative prices. One energy price increase, generates only one reduction in energy. The reduction is costly and the player is not really certain whether he has won or not. Again, see Figure 2.
  Technology improvement is driven by the time spent playing the game. It has no direct tie to energy prices although some economists speculate that it is sometimes driven by concern over shortages in energy availability. There is a new win generated every 20 years or so. Usually the win is clear and often it is dramatic. It typically comes along with "other wins" in other areas such as safety. It is not usually driven by the desire for energy improvement, and often is simply a byproduct of changes in other areas.

Most of the rise in energy efficiency that we've seen has come from *technological progress. Technological progress* evolves as a byproduct of the pressures of a competitive industrial society to increase productivity and lower costs. It includes "dematerialization" of the things we buy. It comes from technological progress much broader than energy -- for example, computers permit better designs and stronger plastics replace steel. It includes the long pattern of incremental changes referred to here as "learning". It also includes major new developments referred to here as "breakthroughs".

5.1 Learning Curves -- in Energy and Capital

Much discussion (Steinmeyer, 1992) has focused on the long term improvements in energy efficiency. These are real and are illustrated by the example of ethylene plants. Figure 1 tracks the energy efficiency of new plants offered by The Lummus Company, an engineering contractor. The gains can be traced to a mix of sources:

Better reactor designs giving higher yields and fewer byproducts:
- through better alloys permitting higher temperature cracking furnaces
- through better understanding of the fundamental chemistry, resulting in shorter residence time cracking furnaces

More efficient turbines and compressors
Adjustment of the purification sequence
- catalytic destruction of impurities
- computer optimized designs
- better distillation column internals

Lower losses in heat recovery
- use of lower cost heat exchangers like brazed aluminum
- bypass of heat exchangers by use of gas turbines.

The individual events are not exciting. Neither is the 3 percent annual improvement in energy efficiency. But the net result was a 60 percent drop in energy use of new facilities over a 35 year period.

These are all broadly referred to as "learning." In most manufacturing processes, for each doubling of cumulative production, total processing costs, including energy, drop by about 20 percent. Often energy and capital savings are merely a by-product of changes made to improve overall productivity which includes quality, reliability and safety. However, learning curve progress is inherently limited and would have run its course long ago where it not for fresh starts on new curves, due to fresh inputs of new science and radical innovations.

5.2 Breakthroughs

While the incremental, evolutionary improvements are important, *major breakthroughs are more important in the long run, particularly when we face barriers such as the world appears to be approaching today in the interface between energy and the environment.* Breakthroughs are the reason why the future rarely turns out the way we foresee it. It is usually much more exciting, and often happier.

Some economists believe that inventions and innovations come when they do in response to a generally perceived constraint (Haustein, 1982). An extrapolation would suggest that *if* the scientific/industrial community sees an imperative for more energy, it will find it -- and will probably find it in unexpected places. Convince them that global warming is real, and they will find a way to control the global heat balance. This may sound utopian, but consider our history. Energy and material constraints have been critical in the past. Examples are the concern about the ability to move coal (leading to railroads) and the concern about sufficient waterwheel power to drive machinery (leading to the steam engine).

Breakthroughs are probably due more to individual inventiveness than scientific discovery, though scientific discovery often plays a key role in *enabling* the breakthroughs. An example of how scientific discovery and innovation interact with "learning" is polyethylene. Polyethylene began its commercial life in the early 1940's with a very high pressure (1200 atmospheres) process. The high-pressure process saw continual improvement such that the energy required to produce a pound of polyethylene was cut in half in about 25 years. Meanwhile, two European chemists made some fundamental discoveries that led to a radically new production process that utilized a solvent and operated at low pressure. This in turn led to development in the 1970's of the low-pressure gas-phase process. It uses only 15 percent of the energy of the original high-pressure process. The new process is simpler, safer, and requires much less capital. It even yields a stronger polymer. Whether the low pressure was a "breakthrough" or just a big step on the "learning" curve is an arbitrary call.

Sometimes the progress is the byproduct of major scientific discovery in unrelated areas. Quantum physics and the invention of the transistor led to microprocessors and modern computers, which in turn produced an enormous array of changes in the design and operation of chemical plants.

Scientific discovery does not guarantee commercial innovation, but any discovery offers a set of possibilities that did not exist before. What breakthrough is likely to contribute to a sustainable economy? One can guess at some breakthroughs from scientific progress. If some of these lack an immediate, obvious tie to industrial energy use, so did the developments in microelectronics. As a start, some recent events are:

- Over two dozen species of crop plants have been transformed by molecular engineering to achieve an altered characteristic. Several have moved to market in the last 2 years.
- Computational chemistry has enabled much faster exploration of possibilities.
- Measured superconductivity has dramatically moved toward room temperature.
- Photovoltaic conversion efficiencies of 35 percent have been achieved.

Of these, the discovery that appears most latent with possibilities today is the understanding of molecular biology and the ability to insert desired genetic traits into plants. This is clearly a "breakthrough" and should have major practical consequences in the first half of the twenty-first century through the development of new and modified agricultural plants. For example:

- Genetically engineered plant systems could allow crops to fix their own nitrogen from the air (as legumes do now via a symbiotic process with bacteria). This could eliminate the need for nitrogen fertilizers.. Not only does the manufacture of these fertilizers consume 2 percent of all industrial energy, but their use is believed to be responsible for the major share of human-derived emission of nitrous oxide, a gas implicated in the greenhouse effect.

- Plants that can better tolerate drought and temperature cycles could double the fraction of land available for crops.
- Bioprocesses could recover fuel from municipal and agricultural wastes.
- Agricultural plants and bioprocessing could yield polymers with no petroleum feedstock.

5.3 Perspective

Change happen slowly.

- The typical career for both technical and operating individuals is in the range of 25 to 40 years.
- The typical useful life of a large scale chemical plant is in the range of 10 to 25 years.
- The cycle between key elements in past technical movements (Haustein, 1982), is roughly:

. first invention to peak inventive activity	~ 10 years
. inventive peak to peak in innovative activity	~ 30 years
. innovative peak to industrial production surge	~ 20 years
	60 years

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