Cairo University
Faculty of Engineering
Chemical Engineering Department

Environmental Conscious Process and Product Design

Industrial Ecology

Overview of Concepts and Applications

v09

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Outline

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    - Dematerializing Industrial Output
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3. Applications
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Natural Ecosystem

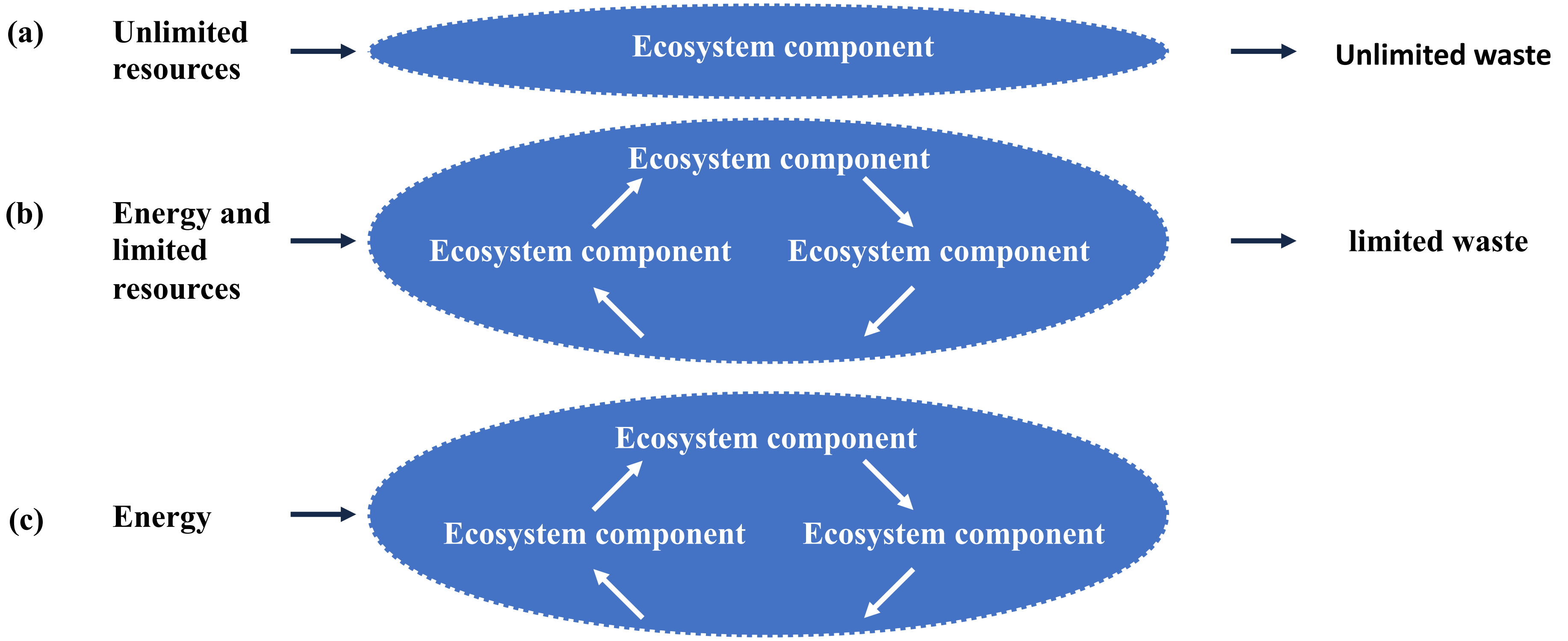
The natural ecosystems contain many levels or subsystems, from the fascinating metabolism on the cell level to vast cycles maintaining the biosphere. Each level of integrity manifests a working logic of its own. The cell lives in relation with its environment exchanging signals and nutrients. Organisms live in cooperation and competition by food webs and habitat. Each level: cell, organism, ecosystem, bioregion, biosphere – presents a series of critical design opportunities and constraints.

Natural Processes are inherently scale Linking: depend on flow of energy and material across scales: O2 from algae to a whale → CO2 → tree.

Global cycles link organisms together in highly effective recycling system crossing about seventeen tenfold jumps in scale, from a ten-billionth of a matter (the scale of photosynthesis) to ten thousand kilometers (the scale of the Earth).

Resource Flows within Natural Ecology

(a) Linear material flows in "Type I" ecology.
(b) Quasi-cyclic materials flows "Type II" ecology.
(c) Cycle materials flows in "Type III" ecology



Source : Graedel, T. 1994. In Socolow, Andrews, Berkhout, and Thomas, eds. *Industrial ecology and global change*. Cambridge MA: Cambridge University Press, p. 25. ©1994 .

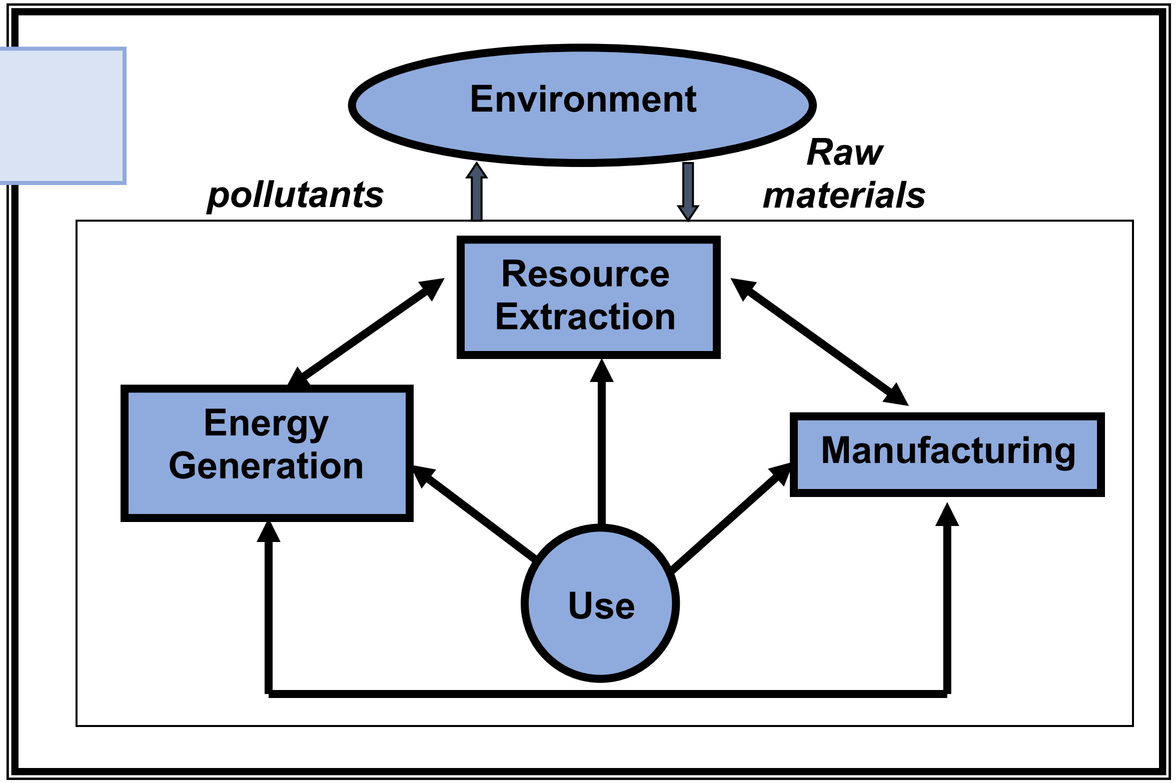
Industrial Ecology

Frosch, R.A and Gallopoulos, N.E, Strategies for Manufacturing, Scientific American, 261,3 – 1989:

“The traditional model of industry activity – in which individual manufacturing processes take in raw materials and generate products to be sold plus waste to be disposed of – should be transformed into a more integrated model: an industrial ecosystem. In such a system the consumption of energy and materials is optimized, waste generation is minimized and the effluents of one process – whether they are spent catalyst from petroleum refining, fly and bottom ash from electric power generation or plastic containers from consumer products – serve as the raw material for another process.”

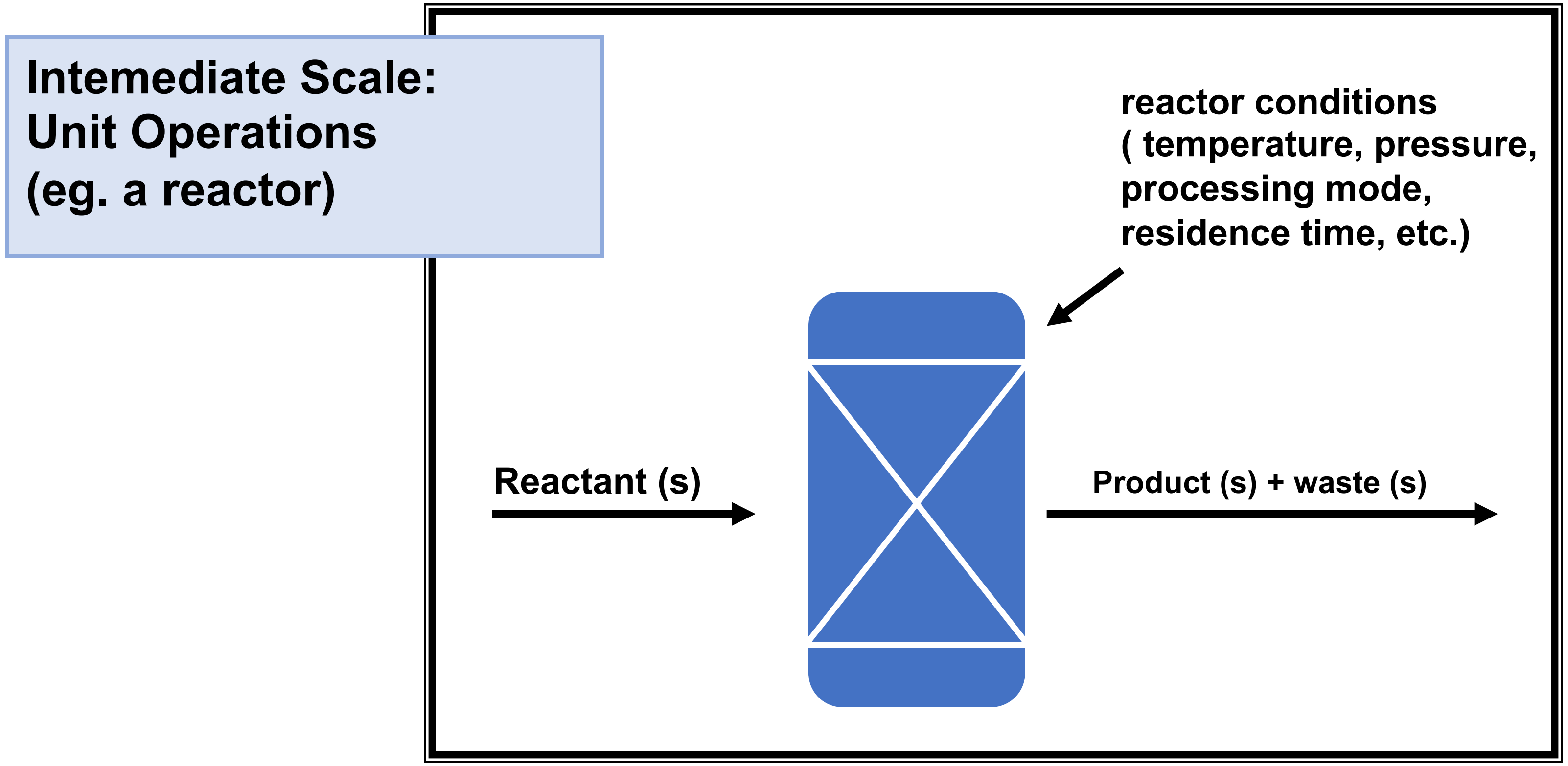
Industrial System 1

Macroscale:
Industry Sector



Source: Allen and Rosselot, Pollution Prevention for Chemical Processes, John Wiley, 1997

Industrial System 2



Intemediate Scale:
Unit Operations
(eg. a reactor)

reactor conditions
(temperature, pressure,
processing mode,
residence time, etc.)

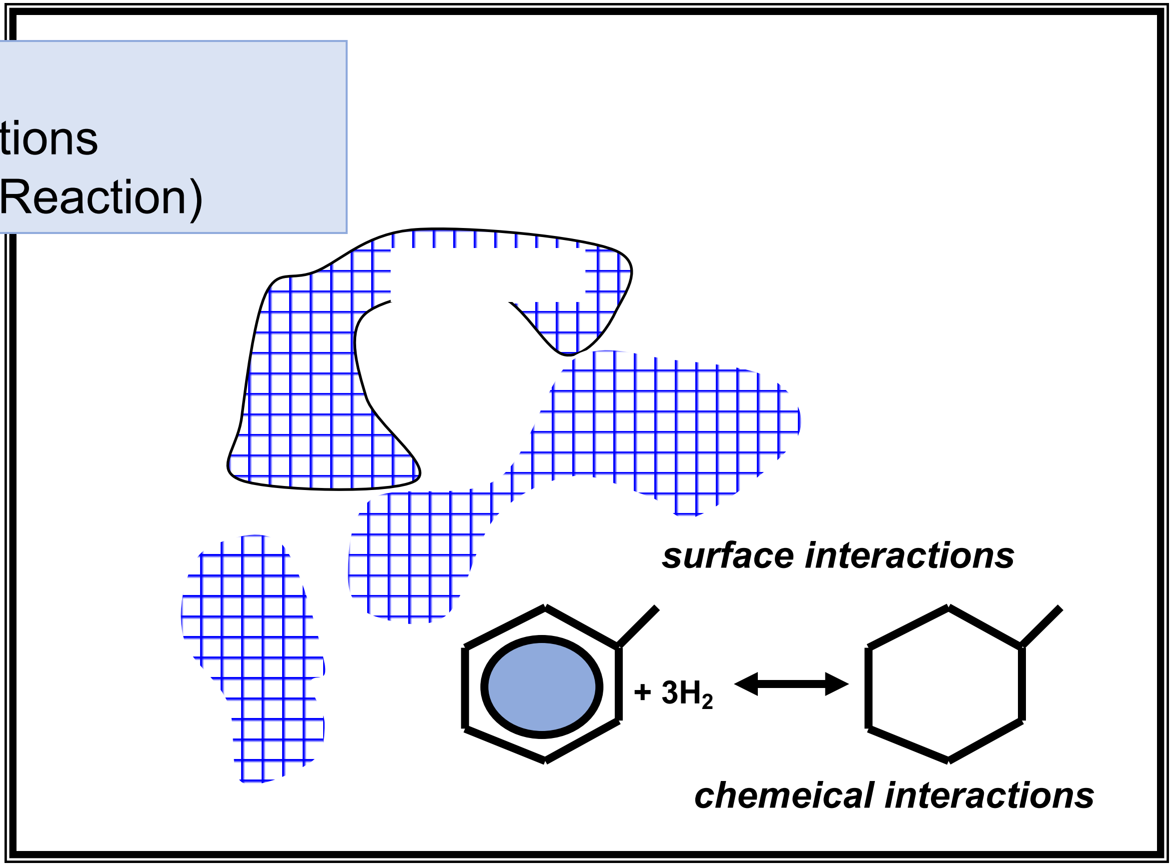
Reactant (s)

Product (s) + waste (s)

Source: Allen and Rosselot, Pollution Prevention for Chemical Processes, John Wiley, 1997

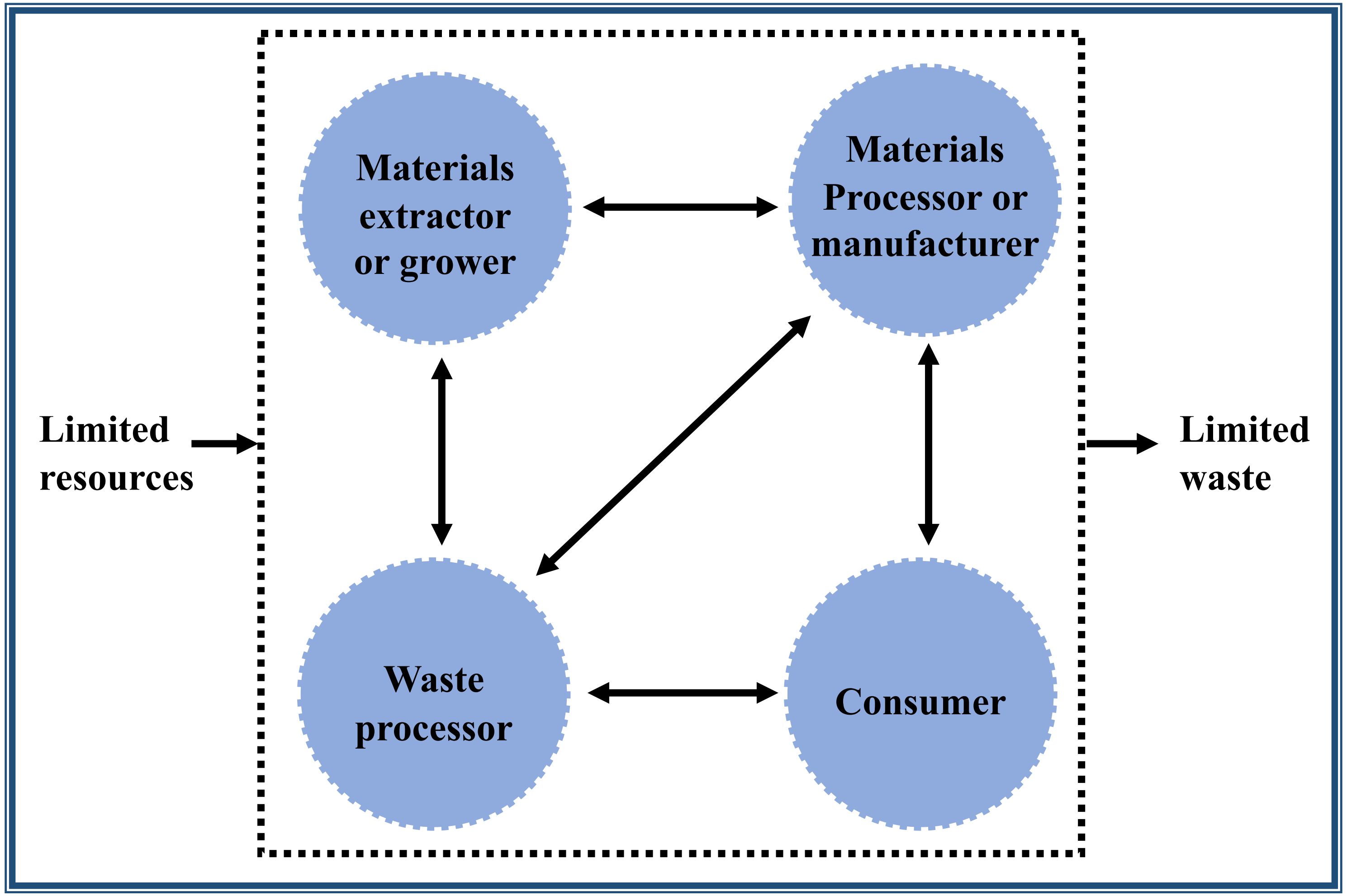
Industrial System 3

Mico Oscale:
Molecular Interactions
(Eg. A Catalyzed Reaction)



Source: Allen and Rosselot, Pollution Prevention for Chemical Processes, John Wiley, 1997

The Type III Model of the Industrial Ecosystem



Source: Graedel, T. 1994. In Socolow, Andrews, Berkhout, and Thomas, eds. *Industrial ecology and global change*. Cambridge, MA: Cambridge University Press, p. 27. ©1994.

The Type III Model of the Industrial Ecosystem

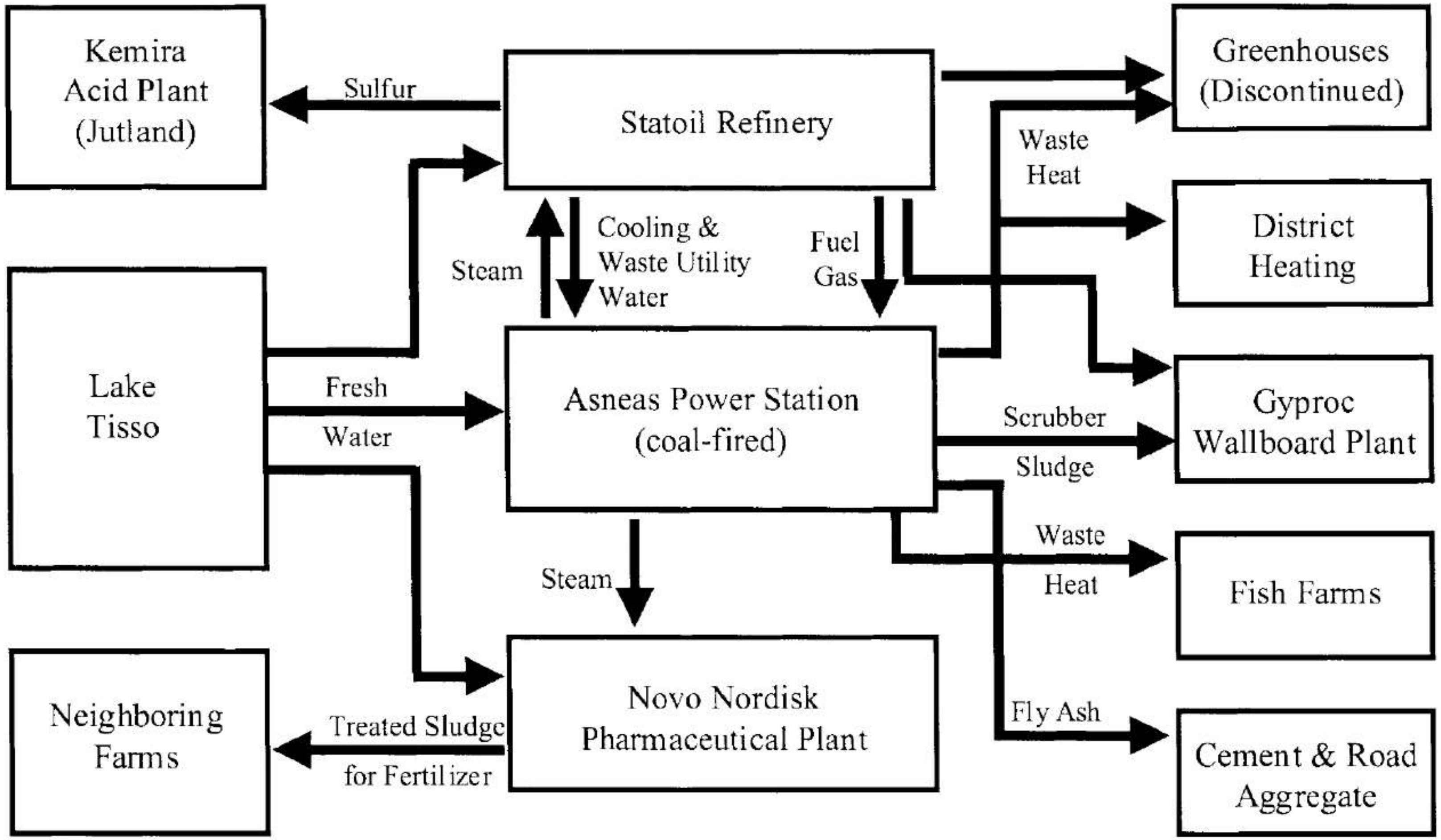
Industrial ecology, in this view, is more than a description of linkages among elements within a system. Rather, it is a prescription for the evolution of industrial systems to achieve an idealized state for long-term sustainability. Its ultimate goal is to transform industry and technology into something that is environmentally benign, industry that “closes the loop: between the system’s operations (its internal metabolism) and its external environment. Essentially, industrial ecology means evolving from a “take-and-dump” open system to a mostly closed system of flows.

Assignment # IE01

- Study den Hond paper, Industrial ecology: a review.
- Prepare a 2-pages summary of your review

Source: Hond, F., Industrial ecology: a review, Reg Environ Change, 1,(2), July 2000

Industrial Ecology Concept No. 1:
Zero Emission Systems



Source: Ecodecision, Spring 1996: 20

Environmentally Symbiotic co-location of Industries: the Kalundborg industrial park, source: Hond, 2000

Industrial Ecology Concept No. 1:
Zero Emission Systems

A fundamental concept in IE is the necessity of moving from the linear mode of production to a cyclic closed loop of production and consumption. The linear mode of production is characterized by direct flow of materials and energy from one production unit to another independent of all other flows. Cyclic ecology-like system is one in which resources are conserved, wastes from one production unit is used as raw material in another. Energy may be put into the system, but no waste shall come out. This is actually the basis for two other terms that appear frequently in the IE literature: industrial symbiosis and industrial ecosystems, it is also the basis for design of industrial parks.

Assignment # IE02

- Conduct a Critical Literature Review (CLR) on the subject of Industrial Parks, world-wide application
- Prepare a short technical report addressing the evolution of the concept of industrial symbiosis and its application in industrial parks planning

Industrial Ecology Concept No. 2:
Dematerializing Industrial Output

The importance of the concept of dematerialization is that it bears on one of the key aspects of IE, that of bringing demands on resources to an equilibrium with the ability of the environment to provide them.

Examples:

1. "Rent a chemical" marketing function or service instead of product .(one good example of Product Service systems, PSSs)
2. Light-weighting in cars, TV sets, cans …..
3. Plastics and lightweight new materials (fiber composites) in place of metals.

Assignment # IE03

- Conduct a Critical Literature Review (CLR) on the subject: Product Service Systems (PSSs)
- Present your results in a 3-pages technical report

Definitions of Dematerialization

“ …dematerialization refers to the absolute or relative reduction of the quantity of materials required to serve economic functions” (Wernick et al. 1996, 171).

“ …the decline over time in the weight of the materials used in industrial end products” (Herman et al. 1989, 50).

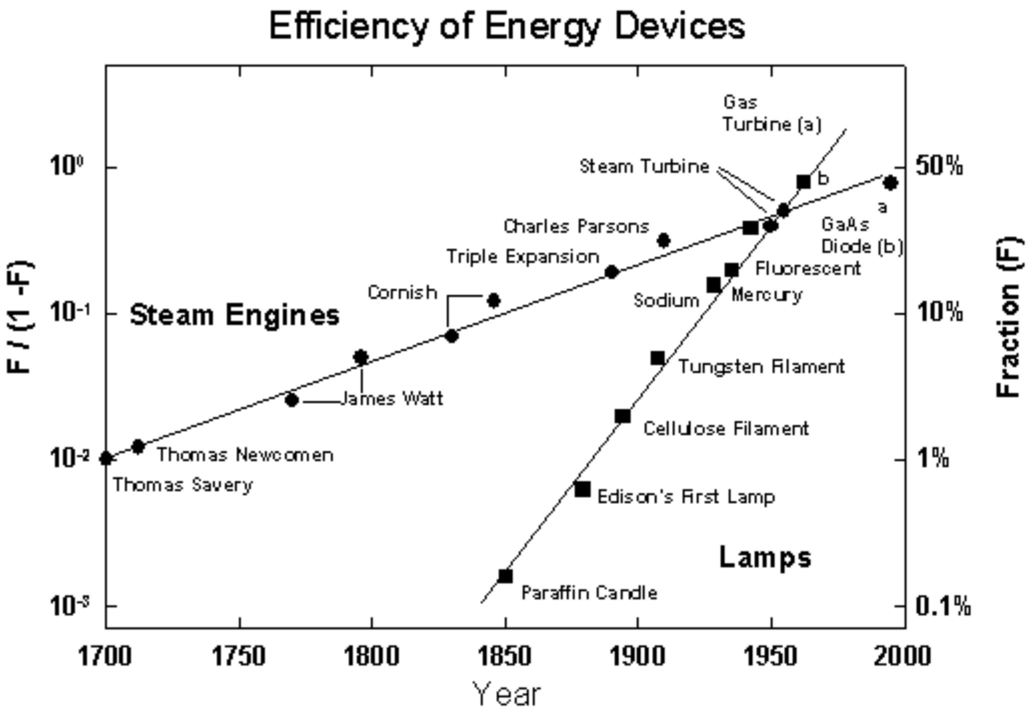
“ …the change in the amount of waste generated per unit of industrial products” (Herman et al. 1989, 51).

Definitions of Dematerialization (cont.)

“ …the reduction of raw material (energy and material) intensity of economic activities, as measured as the ratio of material (or energy) consumption in physical terms to gross domestic product (GDP) in deflated constant terms”
(Bernardini and Galli 1993, 432).

“Instead of a once and for all structural change, as implied by dematerialization, minerals demand experience phases in which older, transmaterialization suggests that lower quality materials linked to mature industries undergo periodic replacement by higher quality or technologically more appropriate materials” (Labys and Waddell 1989, 238).

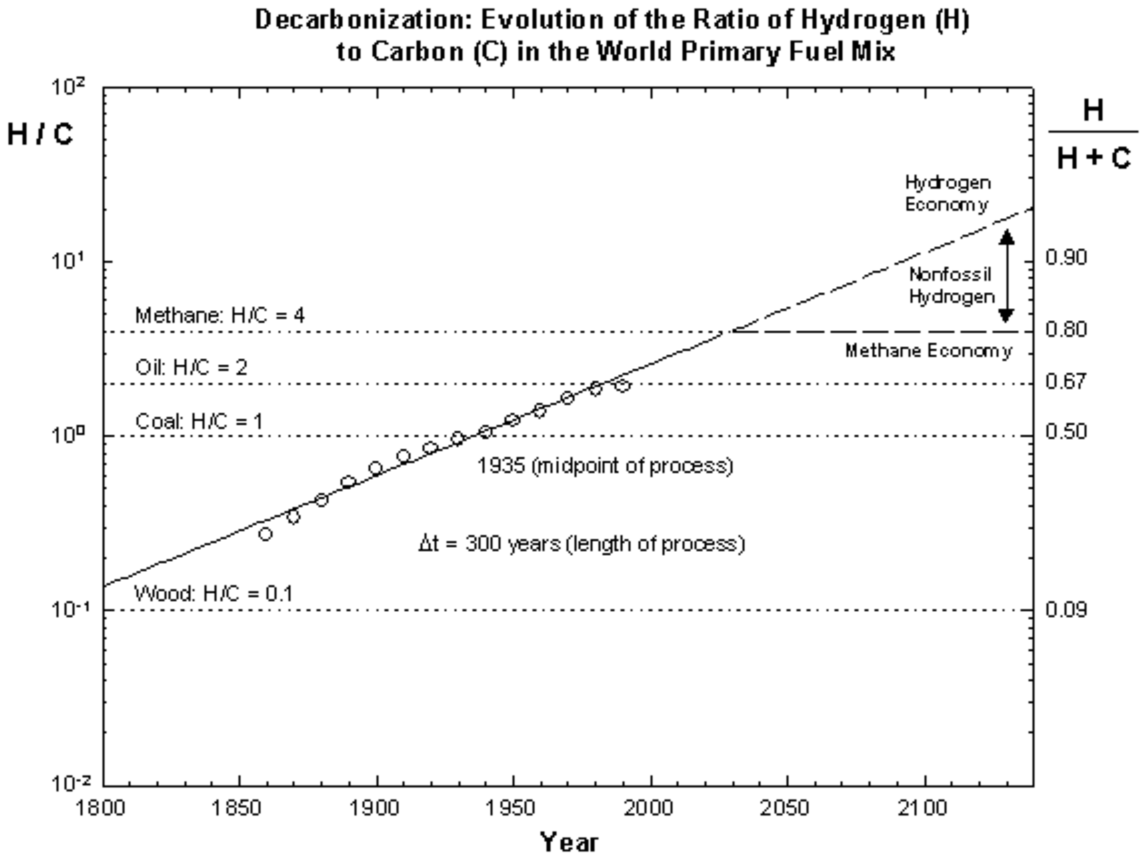
Efficiency of Energy Devices



The efficiency data for engines and lamps are plotted along a line fitted by a logistic equation. The scale used renders the conventional S-shaped curve of the logistic equation into a straight line.

Source: Ausubel and Marchetti, Daedalus 125(3), 1996.

Decarbonization: Evolution of the Ratio of Hydrogen (H) to Carbon (C) in the World Primary Fuel Mix



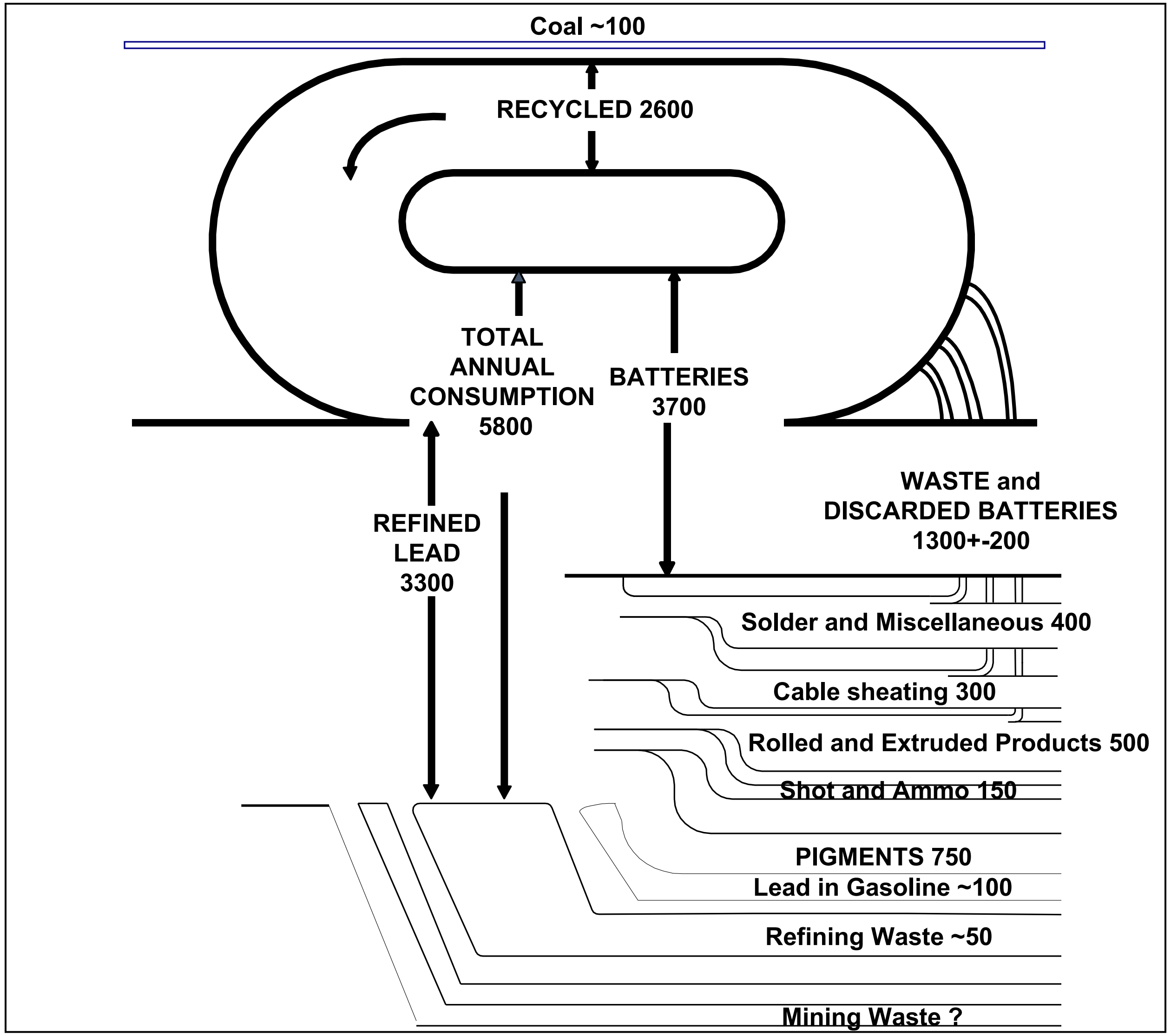
The ratio of H to C is plotted along a line fitted by a logistic equation. The scale used renders the conventional S-shaped curve of the logistic equation into a straight line.

Source: Ausubel, American Scientist, March-April 1996.

Resource Efficiency Factor Four Concept

- A New Paradigm that Reflects the Eco-Efficiency Revolution, Post-Materialist Values, Green Economics
- Defines a New Form of Progress that Meets the Imperative of the Future "Sustainability"
- Moves the Emphasis From Labor Productivity to Resource Productivity : Wealth Extracted Form One Unit of Natural Resources Can Quadruple in The Next Two or Three Decades
- Is Based on the Following Interventions:
    - ❑ Reuse of Chemicals In Process Engineering Leading to Reduced Waste Flows
    - ❑ Longevity and Reparability Of Products
    - ❑ Remanufacturing
    - ❑ Recycling
    - ❑ Reduced Transportation Needs

Industrial Ecology Concept No. 3:
Material Flow and Balance Analysis

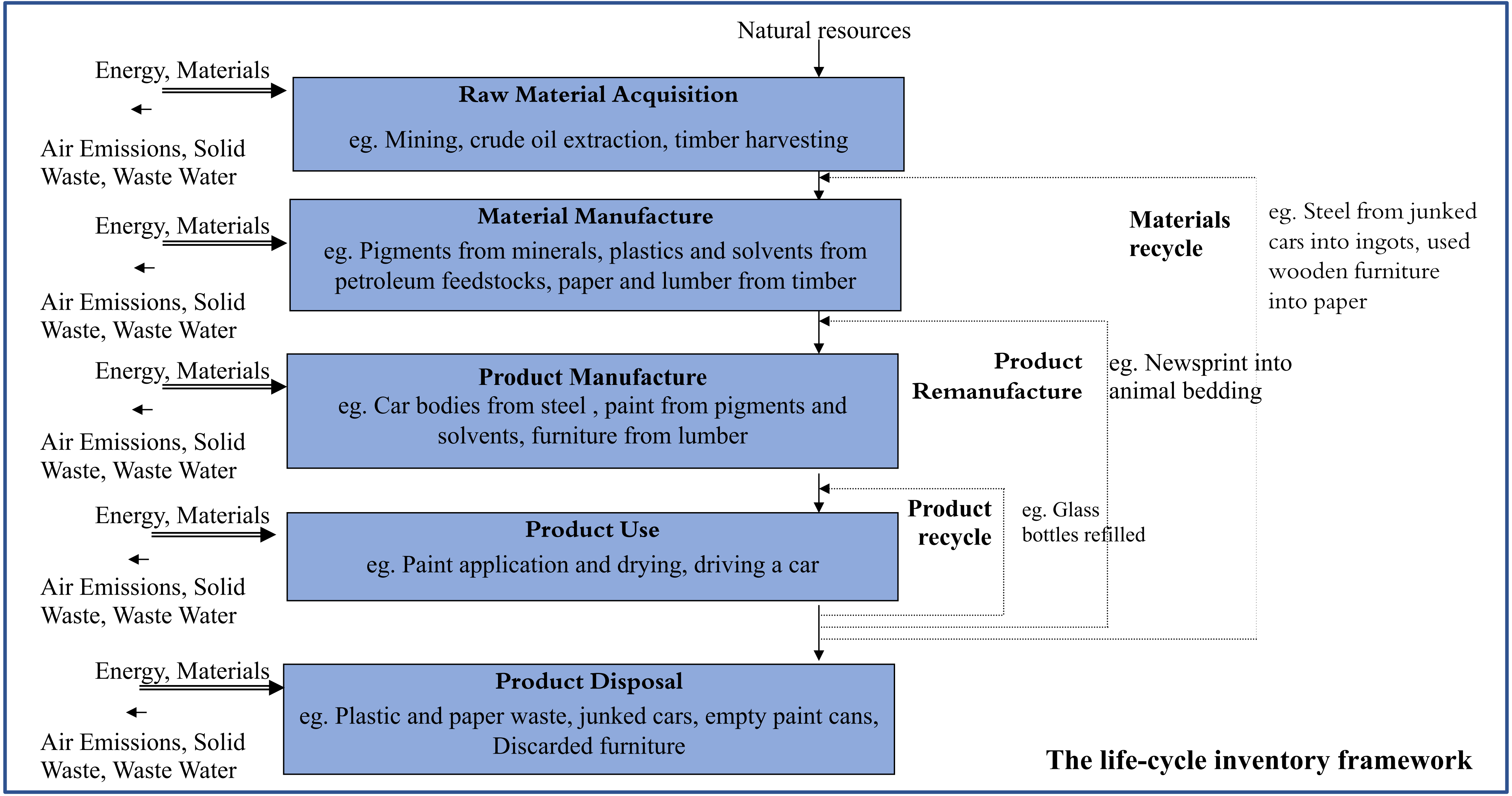


World extraction, use, and disposal of lead in 1990 in thousands of tons

Industrial Ecology Concept No. 3:
Material Flow and Balance Analysis $^{\text{(Cont.)}}$

Materials flow studies map the flow of natural resources into processing and manufacturing industries and the fate of products and wastes exiting them. The object for this kind of studies can focus on the mass of individual chemical elements, compounds, or entire classes of materials. The framework for such studies include individual facilities, whole industrial sectors, and geographic regions.

Industrial Ecology Concept No. 4:
Life Cycle Analysis



Natural resources

Energy, Materials

Air Emissions, Solid Waste, Waste Water

Raw Material Acquisition

eg. Mining, crude oil extraction, timber harvesting

Energy, Materials

Air Emissions, Solid Waste, Waste Water

Material Manufacture

eg. Pigments from minerals, plastics and solvents from petroleum feedstocks, paper and lumber from timber

Materials recycle

eg. Steel from junked cars into ingots, used wooden furniture into paper

Energy, Materials

Air Emissions, Solid Waste, Waste Water

Product Manufacture

eg. Car bodies from steel , paint from pigments and solvents, furniture from lumber

Product Remanufacture

eg. Newsprint into animal bedding

Energy, Materials

Air Emissions, Solid Waste, Waste Water

Product Use

eg. Paint application and drying, driving a car

Product recycle

eg. Glass bottles refilled

Energy, Materials

Air Emissions, Solid Waste, Waste Water

Product Disposal

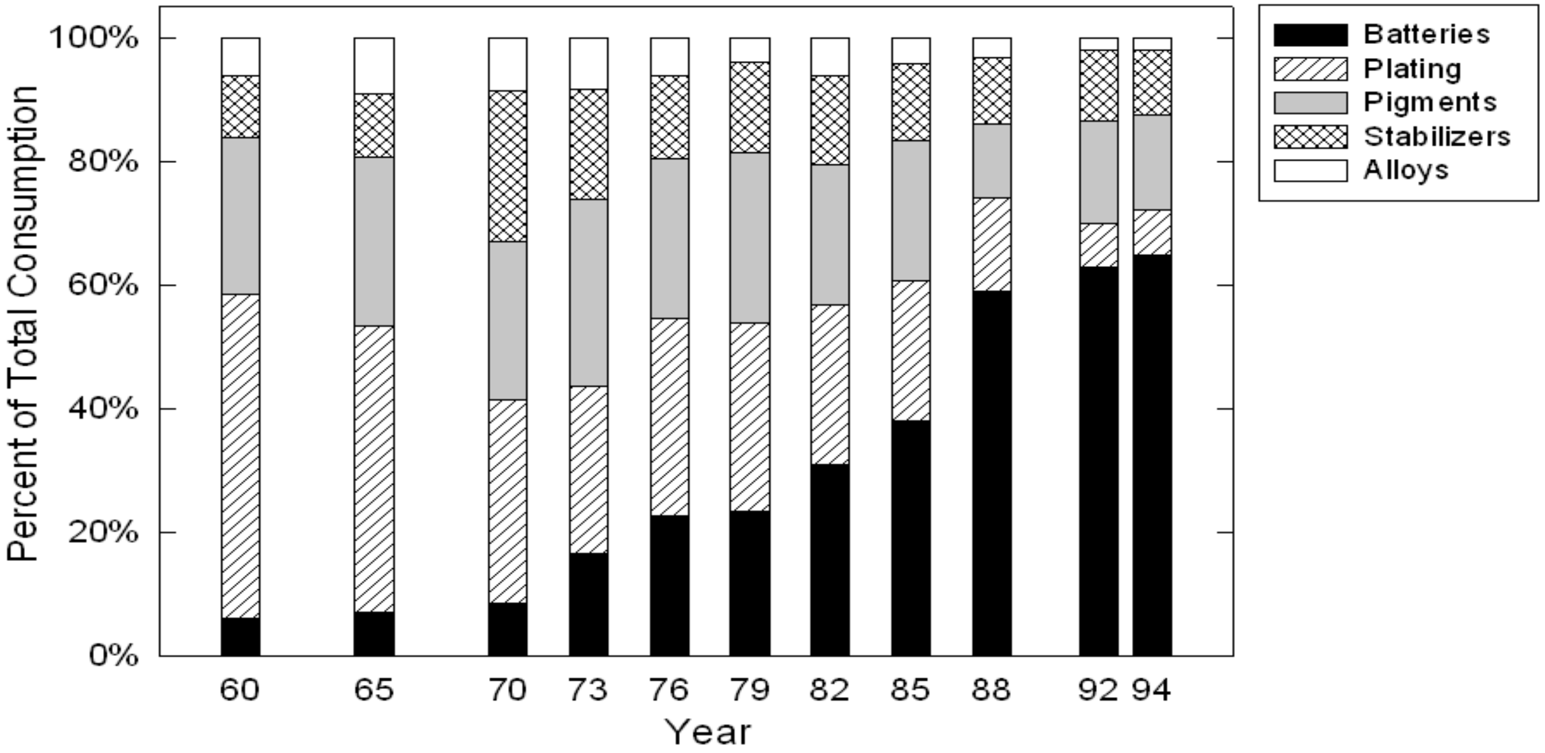
eg. Plastic and paper waste, junked cars, empty paint cans, Discarded furniture

The life-cycle inventory framework

I.E. Application No. 1:
Designing the Product

Research to improve the environmental performance of consumer products complements research on the component materials that comprise them. The purpose of IE is to help achieve the objective of a closed materials cycle. Research on product design aims to minimize the waste generated during product manufacture, simplify the reuse of products and their components, and minimize energy consumption and other negative impacts of product use.

I.E. Application No. 1:
Designing the Product (cont.)



The evolution of the uses of cadmium illustrates how a hazardous material can be incorporated either in dangerously dissipative products such as paint or in much easier to contain and recycle products such as batteries.

I.E. Application No. 2

Choosing the Process

The need to develop “cleaner” technologies in the chemical process industry has experienced high level of innovation and new technology that the industry has not seen in many years. Mature chemical processes, that are often based on technology developed in the first half of the 20th century, may no longer be acceptable in environmentally conscious countries.

I.E. Application No. 2

Choosing The Process (cont.)

Principles of Production – Integrated environmental protection:

1. New synthesis routes
2. Shifting the equilibrium
3. Improving selectivity
4. Developing new catalysts
5. Changing the reaction medium
6. Replacing or eliminating auxiliaries having harmful effect on the environment

The Case of HÜls Acetylene Process

Improvements Resulting from the New Process

The new process is characterized by a high degree of heat recovery and the use of closed cycles. This gives the following improvements:

1. Increase in the thermal efficiency from ca. 50% to the present figure of 75%
2. Drastic reduction in the amount of wastewater to be treated in the wastewater treatment plant
3. Prevention of emissions of hydrocarbons and HCN
4. Utilization of the residual carbon black and polyunsaturated hydrocarbons that are recovered in the scrubbing processes

The Case of HÜls Acetylene Process

Considerable economic benefits have been obtained:

1. Lowering of energy consumption and wastewater costs
2. Lower personnel requirements
3. Improvement in product purity

Flow Diagram of the old HÜls Acetylene Process

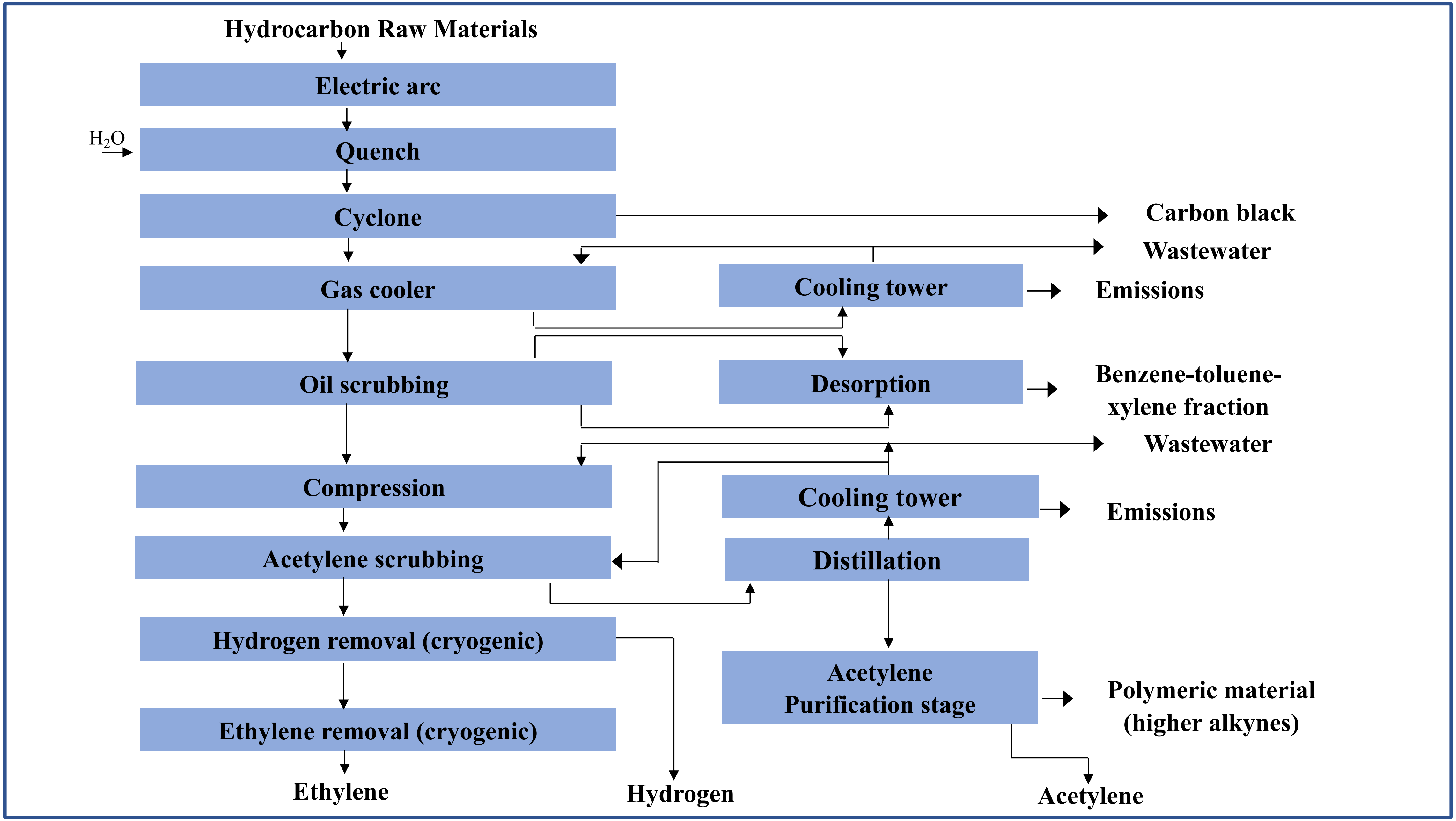
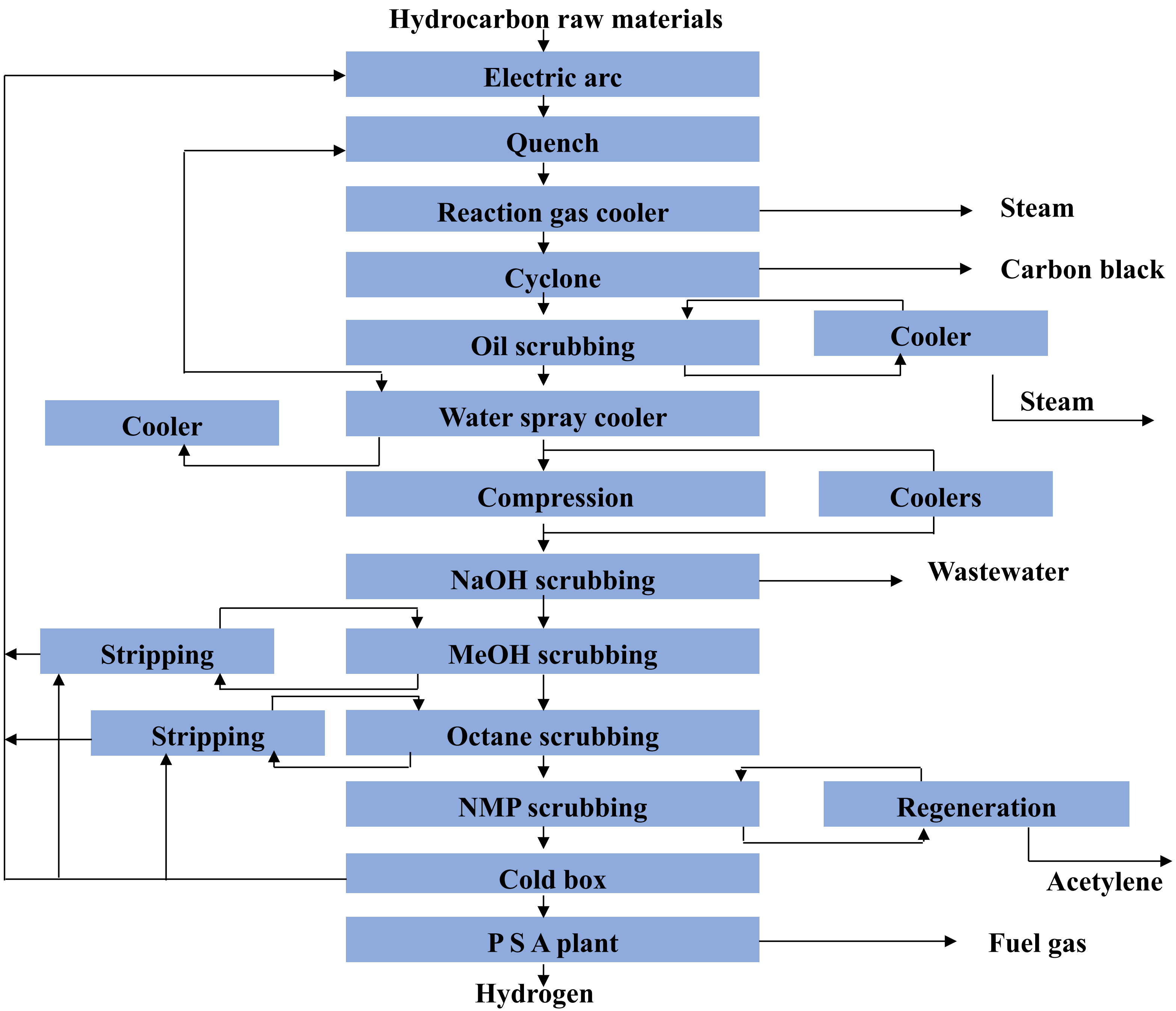


Diagram of the new HÜls Acetylene Process



Hydrocarbon raw materials

Electric arc

Quench

Reaction gas cooler

Steam

Cyclone

Carbon black

Oil scrubbing

Cooler

Steam

Water spray cooler

Cooler

Compression

Coolers

NaOH scrubbing

Wastewater

Stripping

MeOH scrubbing

Stripping

Octane scrubbing

NMP scrubbing

Regeneration

Acetylene

Cold box

P S A plant

Fuel gas

Hydrogen

I.E. Application No. 3:
Raw Material Selection

Careful selection of raw materials is an essential element of any process pollution prevention strategy. Waste reduction opportunities available in the selection of raw materials include:

1. The elimination of feedstock impurities
2. The use of less hazardous raw materials
3. A reduction in the number of raw materials used
4. The utilization of waste materials from other processes.

Raw Material Selection (Cont.)

Hydrogen peroxide in clean processes:

Role of H_2O_2 in greening of industrial chemistry:

Relative oxidant costs and oxidising equivalents

Oxidant	Relative cost per oxidising equivalent	Relative oxidising equivalent
Oxygen	1.0	1.00
Chlorine	1.9	0.22
Nitric acid	2.8	0.27[a]
Hydrogen peroxide	3.8	0.47
Peracetic acid	6.5	0.21
Bromine	9.4	0.10
Potassium permanaganate	10.9	0.15[b]
t-Butyl Hydroperoxide	19.4	0.18

[a] To N_2O_3 ; 0.54 to N_2O . [b] To MnO_2; 0.25 to Mn (II).

Raw Material Selection (Cont.)

H_2O_2 production and applications

Year	1987	1990	1992
Total production (Kt)	680	880	1260
% breakdown by end use	42	49	50
Pulp & paper	27	24	17
Chemicals	16	12	10
Textiles	8	8	14
Environment	7	7	8
Other/miscellaneous			

Note: Total H_2O_2 production figures include material used for persalt production, but this is conventionally omitted from % breakdown of applications of H_2O_2 itself.

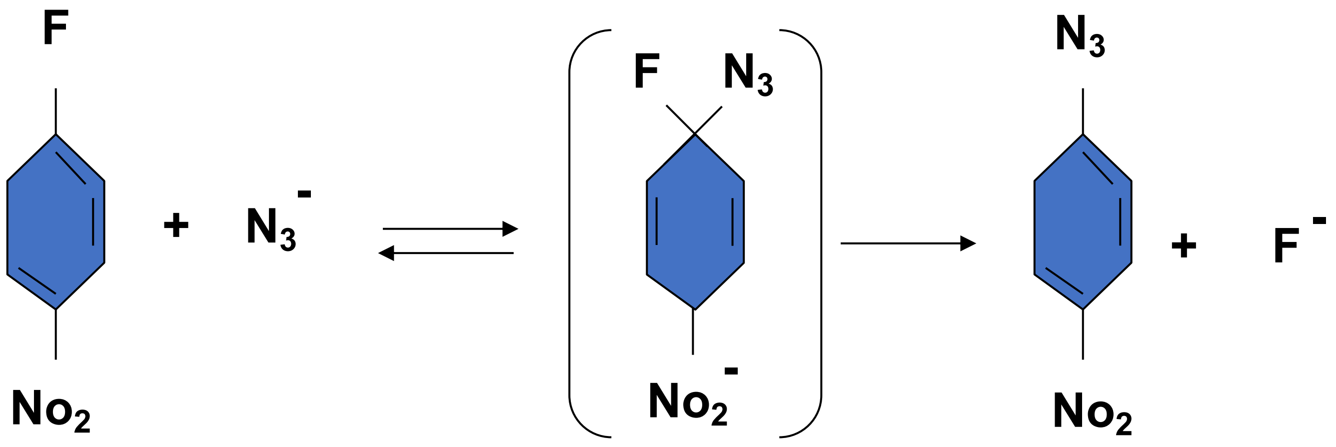
Solvent Selection

Two principal ways in which solvent selection can influence waste minimization:

1. Through the effect of solvent on the efficiency of the reaction: a higher reaction efficiency, means less waste
2. By facilitating solvent recycle: solvent which can be easily recovered and recycled can minimize process waste

Illustration of Solvent Effect on Reaction Rate

Parker and Cox measured the rate of a simple nucleophilic substitution reaction in a variety of solvents.

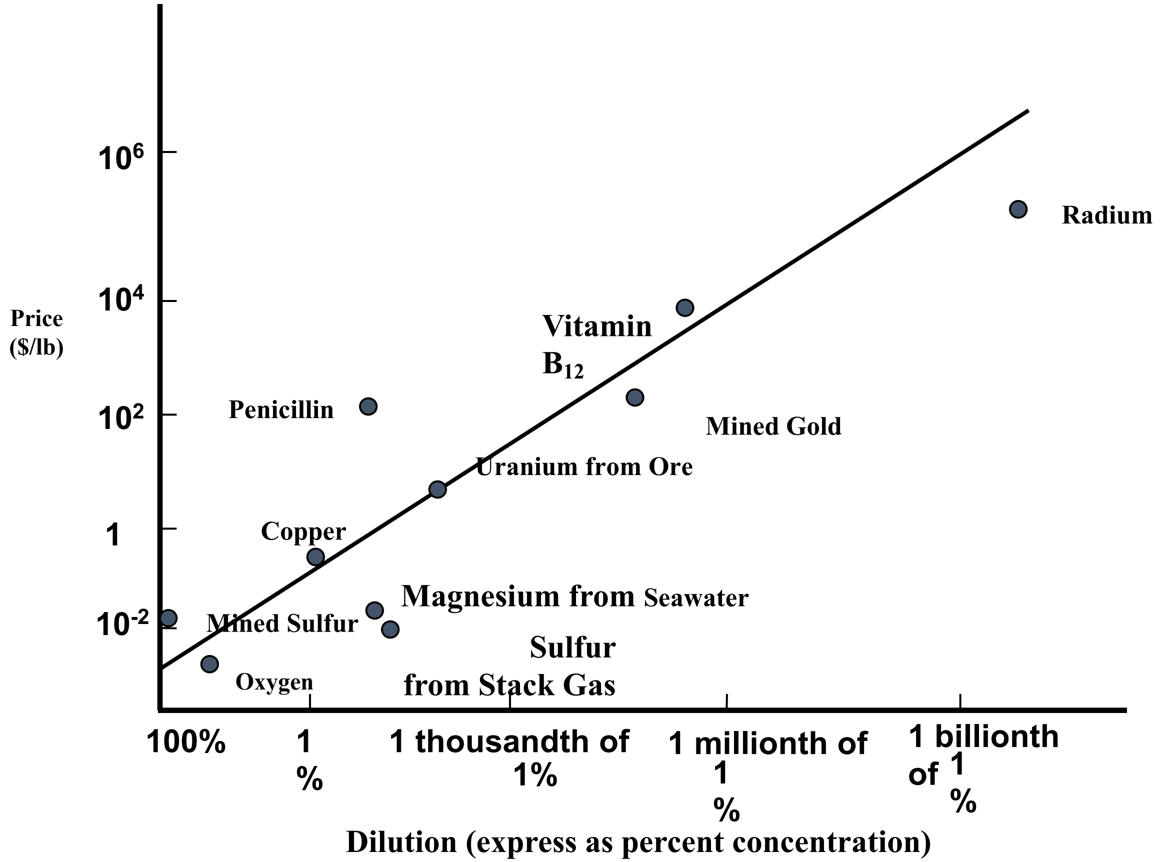


Relative Rates are shown in the following table

Relative rate constants (25°C) for the reaction of 4-fluor-onitrobenzene with tetra-***n***-butylammonium azide in selected solvents:

Solvents	Relative rate
Water	1
Methanol	1.6
Nitromethane	4.5×10^3
Dimethylsulphoxide	13×10^3
Acetone	13.8×10^3
Dimethylformamide	42.5×10^3
Hexamethylphophortriamide	1900×10^3

I.E. Application No. 4:
Recovering the Material



The Sherwood diagram showing the correlation between the selling price of Materials and their degree of dilution in the original matrix from which they are separated.

I.E. Application No. 4:
Recovering the Material

Viability of extracting valuable materials from waste stream depends on:

1. Concentration of the contaminant
2. Its market value

Analysis of Available Data:

- Value of the Sherwood Diagram
- Data about waste stream flow rates and composition is important
- Any practice which leads to higher concentration in a waste stream will improve the economics of materials recovery

Recovering the Material (Cont.)

The extent to which industrial wastes might serve as raw materials is dependent not only on the mass of resources present but also on their concentration.

The Potential for Recovery of Metals in Industrial Hazardous Waste Streams in 1986

Metal	Min. Concentration Recoverable, from Sherwood Diagram (mass fraction)	Total Loading in Hazardous Waste Streams (tons/yr)	Recoverable Fraction Of Metal In Waste	Percent of Metal Recycled from Waste Streams
Antimony	0.00405	17.000	0.74-0.87	35
Arsenic	0.00015	440	0.98-0.99	3
Barium	0.0015	59.000	0.95-0.98	1
Beryllium	0.012	5.300	0.54-0.84	11
Cadmium	0.0048	16.000	0.82-0.97	8
Chromium	0.0012	90.000	0.68-0.89	5
Copper	0.0022	110.000	0.85-0.92	10
Lead	0.074	190.000	0.84-0.95	56
Mercury	0.00012	5.400	0.99	16
Nickel	0.0066	3.600.000	1.00	0.1
Selenium	0.002	2.000	0.93-0.95	29
Silver	0.000035	17.000	0.99-1.00	1
Thallium	0.00004	280	0.97-0.99	5
Vanadium	0.0002	4.400	0.74-0.98	1
Zinc	0.0012	270.00	0.95-0.98	12

Summary

I.E. Reviewed Four Concepts are:

- Zero Emission Systems
- Dematerializing Industrial Output
- Materials Flow and Balance Analysis
- Life Cycle Analysis

I.E. Reviewed Four Applications are:

- Designing the Product
- Choosing the Process
- Raw Material Selection
- Recovering the Material

Conclusions

Industrial Ecology is a system approach which focuses upon the interaction of industrial systems and the ecological systems of which they are a part. IE seeks transformation from linear wasteful processes to a closed loop system of production and consumption. Chemical process industries, with its drive towards cleaner production can benefit from IE concepts. Mature chemical processes, that are often based on technology developed in the first half of the 20th century, may no longer be acceptable in environmentally conscious countries.

Conclusions (Cont.)

The need to retrofit existing plants and to design environmentally sound new plants and products would require chemical engineers to consider IE concepts and applications.

References

- The attached folder includes selected literature on the topic of IE