

**"A LIFE CYCLE ANALYSIS OF AUTOMOBILE
TIRES IN FRANCE"**

by

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A LIFE CYCLE ANALYSIS OF AUTOMOBILE TIRES IN FRANCE

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Abstract

The disposal of used-tires represents a serious problem in France, as elsewhere. Narrow approaches, such as landfill bans, fail to tackle the root causes of the problem and also threaten to increase the proportion of tires disposed of under uncontrolled conditions. As well as a threat to the environment and human health, current disposal practices represent the loss of potentially useful materials (500,000 tonnes/year) and recoverable energy (390,000 tonnes oil equivalent/year). Greatest scope for waste reduction lies in product redesign and change in the approach producers take to delivering tire-service. Different disposal alternatives (incineration, landfill, etc.) should be reviewed together to make rational judgements about the disposal of inevitable wastes. By incinerating used tires, the volume of waste can be reduced at the same time as chemical energy is recovered. Incineration at cement plants is to be preferred over incineration at utilities since pollutants are captured within the cement and are either encapsulated into long-lived structures or, in respect to sulfur, neutralized. The paper demonstrates the role of materials balance principles and life cycle methods in providing an objective (and holistic) basis for decision making in the tire sector.

Introduction

This paper presents a life-cycle analysis - a cradle-to-grave history - of automobile tires in France. The product was chosen for analysis because of its economic and environmental significance and because it provides a useful illustration of how different approaches to production, consumption, and final disposal offer significant scope for reducing (or increasing) the environmental stresses with which a product is associated. Since the stress that a product generates is a function of the product life-cycle and since there is some evidence that the tire life-cycle has changed over the past 10 years, separate models are calibrated for 1983 and 1991. The analysis then focuses on the 1991 life-cycle, since it is this that would need to be changed to reduce current environmental stresses. The holistic perspective provided by the life-cycle methodology demonstrates clear opportunities for achieving such a reduction.

¹ At the time the work was done, Yves Guelorget and Véronik Jullien were students in the Mastere d'Ingenierie et de Gestion de l'Environnement Program at the Ecole des Mines, Paris. Their research project was undertaken at the Center for the Management of Environmental Resources (CMER) at INSEAD.

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The analysis shows, for example, that the disposal of used tires in France represents enormous losses of potentially re-usable materials and recoverable energy. If past recycling and material recovery practices were to persist, more than a half million tonnes of materials and almost 390,000 tonnes of oil equivalent energy (t.o.e.) will simply be thrown away when the useful lives of the 679,000 tonnes of tires produced in 1991 come to an end. Annual losses on this scale are made up through a continuous draw on virgin materials. In addition, more than two t.o.e. is dissipated in producing each tonne of new materials and a further 0.58 t.o.e. is expended in the tire manufacturing process itself. Both in producing the new materials, and in disposal of the used-tires, there are environmental damages and risks.

The "tire problem" tends to be characterized all too easily as a disposal problem per se. Moreover, the bureaucratic reductionist approach to disposal fosters "solutions" (such as landfill bans) that could have perverse environmental outcomes. But the most significant aspect of casting the problems as one of disposal is that solutions which lie in different forms of production or consumption are neglected. Yet the current materials and energy intensities of the tire sector are much higher than is technologically feasible. They are particularly high (perhaps between two and three times what is now attainable) when measured in terms of useful service delivered - kilometrage of tire service. The paper focuses on the opportunities that exist for solving the used-tire disposal problem by tackling it at source; i.e., through materials re-use and product redesign. It also touches on the economic and institutional changes that might lead to these options being adopted.

Methods and data

The study uses standard materials balance methods to derive a static balance between the draw on new material and energy inputs to tire manufacture and the aggregate losses incurred through the manufacture-use-disposal chain. When analyzing the life-cycle of any product that has many precursors, the level of detail for the analysis is a matter for judgement. One issue is how far up- and down-stream to go in the sequence that sees all materials used in manufacturing a product ultimately drawn from and returned to nature. Another is how specific to be in analyzing the material and energy inputs and outputs. Is an aggregate balance for materials sufficient? Having put the question in general terms, we admit to having drawn the boundary of our analysis around the tire manufacturing sector itself.

Though possible to perform in principle, a full analysis is seldom practical nor necessary. It is sufficient to measure the overall draw on materials and energy and only to track in detail those chemical elements that are i) known to be toxic, acidifying, ozone-depleting, climatically- or otherwise environmentally relevant, ii) unstable and which might react or transmute to an environmentally-relevant form, or are iii) emitted to especially vulnerable or sensitive media/receptors. With tires, the environmentally-relevant substances are sulfur, zinc (with a ca. 0.42% associated cadmium content), and carbon. The US Environmental Protection Agency (EPA) considers that, among human cancers resulting, at least in part, from exposure to chemical substances, the single most significant exposure is to butadiene 1,3 (which is a major input to the manufacture of synthetic rubber).

Although there are wastes in the precursor chain, during tire manufacturing and through tire use, the disposal of used-tires is the main source of environmental contamination associated with the tire life-cycle. Different disposal methods release the materials to different media and in different chemical forms. Tires are not biodegradable, being entirely immune to the attack of bacteria. This means that used-tires maintain their integrity for long periods (though not indefinitely) if put into landfills. Tires can be re-used by re-treading, but recycling through recovery of the original raw materials is impossible owing to the composite character of tires and the irreversible nature of vulcanization. If incinerated, the materials temporarily sequestered in the tire are re-released. Since some forms of incineration can be controlled more easily than others, the quantity of materials incinerated and the methods used are very significant environmentally. The paper focuses particularly on post-consumption issues of the tire life-cycle and the decision processes that bear upon these.

In addition, to draw comparisons between the current and possible alternative French tire life-cycles (for example, ones based upon higher levels of tire retreading and of energy recovery through controlled incineration), an attempt is made to estimate the use of materials and energy in tire manufacture. The energy used in extracting or manufacturing (but not in transporting) material precursors is also estimated for the majority of upstream processes. Calculations are based on unit quantities (in this case, one tonne) of the relevant materials. The data are partial, but at least provide minimum estimates of materials and energy use. They also offer insight into the nature and extent of associated waste streams. A more elaborate future study would provide more detail regarding the upstream manufacturing processes, especially in the chemical industry.

The tire life-cycle is represented in the form of a generalized input-output model. A description of the individual process stages that make-up the tire life-cycle is given first. Input-output coefficients for each process stage are then derived from several separate sources and studies. These do not all relate to the same year. Neither do they track a single tire cohort from cradle to grave. Nonetheless, taken together they provide a rather complete generalized picture of the life-cycle. This can be used to reconstruct balances for particular years' production or disposal on the assumption that the input-output coefficients are stable. The empirical evidence for and against this assumption is presented in the paper. On balance, the proposition of stability over the past 10 years is generally supported but there is evidence of some change in the proportional use of recycled materials and components (away from retreading). Because of changes in the level of materials recycling, separate life-cycles, are reconstructed for 1983 and 1991. The first year is chosen because this is the latest for which complete national data are available on used-tire disposal; the second, because this is the most recent year for which national production data are available. The reconstructions take the form of cohort studies, which attempt to track the "lives" of tires either produced or disposed of in the given year.³ The 1983 balance is estimated against that year's disposal figures. The 1991 balance is estimated against that year's production level.

³ As a result, the estimate for tire production for the 1983 cohort of used-tires is not an estimate for tire production in 1983. It is an estimate for the number of tires whose earlier production would have been needed to give rise to a 502,000 tonne disposal problem in 1983.

A Life Cycle Analysis of the French Tire Industry

For production and process data the paper draws upon information obtained directly from three French tire manufacturers (together representing the major part by tonnage of French national tire production). This is supplemented with data from published trade sources, such as the summary tables of the French Rubber Manufacturers' Association, and from several industry studies. It also draws upon a data-base of products and processes (in development at CMER) which contains input-output details for precursors (raw materials, mass commodities, and intermediate products). This is used to help build composite process chains, which are important for estimating overall energy and materials mobilization and losses to the environment. Data on used-tire disposal comes from surveys for 1983 [ANRED, 1986] and 1991 [ANRED, 1992].

Tires, tire manufacture, and the tire life-cycle

A basic description of tire manufacturing, of the materials used, and the properties of natural and synthetic rubbers is given by Shreve [Shreve 1956]. Tires are made from a polymer matrix of natural and synthetic rubbers which is strengthened and shaped through the addition of fillers and by the use of cords. Tires consist of several elements: the carcass, the belt, the sidewalls, the tread, and the bead. Each element performs a different function and is required to have different mechanical properties. Because of this, each is separately manufactured from rubberized fabric strips made from different cords and different blends of rubber compound. To maximize their strength, the sheets are generally cut on the bias so that the cords are at an angle within the strips.

The carcass - the basic structural unit for the tire - is formed by molding rubberized fabric strips over an iron core. It generally takes one of two forms, radial or cross-ply, depending on the disposition of the (usually textile) cords within the structure. The belt is a rigid element that in a finished tire lies between the tread and the carcass. It is made from several plies of parallel, rubber-coated, usually steel cords. The tread, a heavy strip of masticated and compounded rubber, is shaped around the carcass and belt. Since this is the part of the tire in contact with the road surface, it is made of rubbers that are specially processed to resist abrasion and cracking, absorb impacts, provide flexion, and dissipate heat. The sidewalls are an assemblage of flexible rubberized fabrics that are resistant to light and ozone damage. The bead is a strip of very hard rubber with embedded wire threads which forms the contact edge of the tire with the wheel rim.

The main polymers used in tire manufacture today are natural rubber, synthetic rubbers - of which the three most significant are Styrene Butadiene Rubber (SBR), Poly-butadiene, and Butyl - and reclaimed rubber (known as "reclaim"). The most widely used cords are made from rayon, poly-amide (Nylon 6-6), aramid (Kevlar), polyester, and steel.

Natural rubber is coagulated latex (the sap of the tree, *Hevea brasiliensis*). Chemically, it is a natural polymerized hydrocarbon of the C_5H_8 group. Synthetic rubbers are not "rubber" in the true sense, but elastomers. Essentially, they are rubber substitutes that are polymerized from different (oil based) chemicals. "Reclaim" is a material recovered from used rubber

products which must be specially reworked to make it suitable for re-use. Its mechanical and chemical properties are not the same as those of new rubbers (natural or synthetic), and this limits the proportion of "reclaim" that can be used in products, like tires, that require polymers with high elasticity, flection, and chemical resistance. The proportion of reclaim in tire applications is limited to 10%. Powdered rubber, also a material recovered from post-consumption rubber wastes, is used in the manufacture of some rubber products. Again, because of its inferior mechanical properties, its use in tire applications is limited to 5%.

In its raw state, natural rubber is too plastic and too inelastic to be useful in practical applications. To change its mechanical properties, it is vulcanized - combined with sulfur under the influence of pressure and (usually) heat.⁴ The process, which forms cross-links between the molecular strings, is catalyzed. The resulting product, vulcanized rubber, is strong, elastic, nonplastic and nontacky. Its precise characteristics depend upon the vulcanization process and are functions of the rate of cure at different temperature/pressure combinations. To achieve the highly specific mechanical properties needed in tires, several chemicals are added to provide control - activators, accelerators, retarders, and stoppers. The most important of these is zinc oxide, which is dissolved in stearic acid and used as an activator. The most important accelerators are sulfonamide compounds.

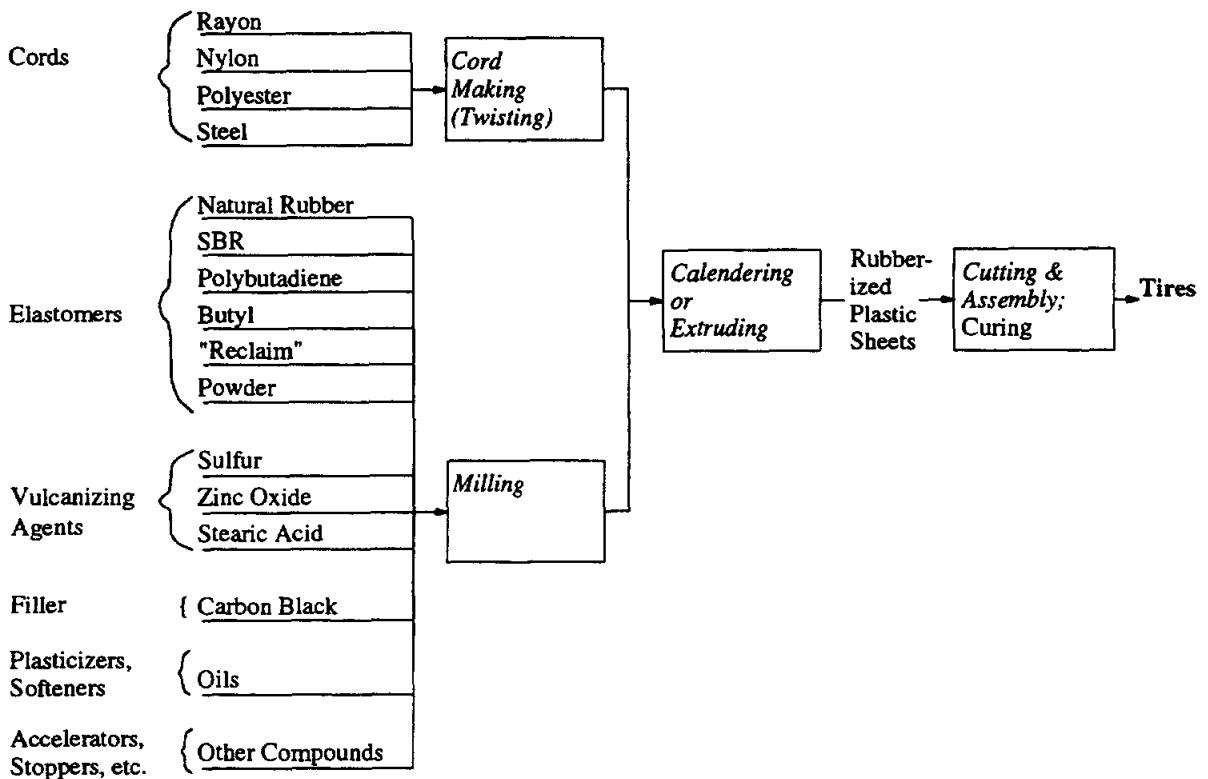
Fillers are added to further improve the mechanical properties of the natural and synthetic rubbers, prevent oxidation and provide greater abrasion resistance. The dominant material used is carbon black. Other fillers, now virtually restricted to the making of cycle tires, are kaolin, fine silica, and chalk. To allow the fillers to be incorporated into the rubber matrix during blending and to counter their effects on rubber hardness, plasticizers and softeners (mostly mineral oils) are also added.

Tire manufacture

Tires may be produced from new or through the retreading of an old tire carcass. A generic new tire manufacturing process is shown in *Figure 1*. Crude rubber (which has high viscosity) is broken down by mechanical action (mastication). Mastication lowers the viscosity by breaking the long rubber molecules. The fillers, vulcanizing agents, softeners, plasticizers and other compounds are then added and mechanically worked into the rubber (milling). The rubber blend is run together with the cords through rollers (calendering) to produce a rubberized fabric sheet. Different blends of rubber and different cords are used to make sheets for different parts (elements) and types of tire. The elements are assembled to form a complete tire (assembly). The assembled tire is placed into a mold into which the tread design is cut. By controlled application of heat - supplied by steam - and pressure, the rubber is vulcanized and molded to its final shape (curing). Retreading involves stripping the old tread from a worn tire and reclothing the old carcass with a tread made from new materials. The tire is then re-cured. The process uses only 20% of the virgin materials used in making a brand new tire. Also, when used tires are re-treaded, the old treads are routinely used for material recovery.

⁴ There are cold vulcanization processes that depend upon the use of catalysts and activators as an alternative to heat.

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*Figure 1: Tire production
source: authors*

A generic tire life cycle

A schematic diagram of a tire life-cycle is given in *Figure 2*. Production is made up of new and retreaded tires. During new tire manufacture, some materials are lost. After calendering, for example, the rubberized fabric sheets are immersed in water containing anti-cohesive agents. Similarly, cord-rubber adhesion is obtained in aqueous systems containing resins. In both cases, materials are lost to the water. There is also a fraction of mis-manufactured tires. These losses mean that the weight of virgin and recycled material inputs to tire manufacture is greater than that of the tires produced. Further losses are encountered after the tires enter service. Part of the material embodied within a tire is worn away during use and is lost dissipatively to the environment. The rest ends up as a post-consumption waste; a used tire.

Used tires may be sent for retreading. Along with mis-manufactured tires, they can also be used to recover raw materials, the most significant of which are "powdered rubber" and

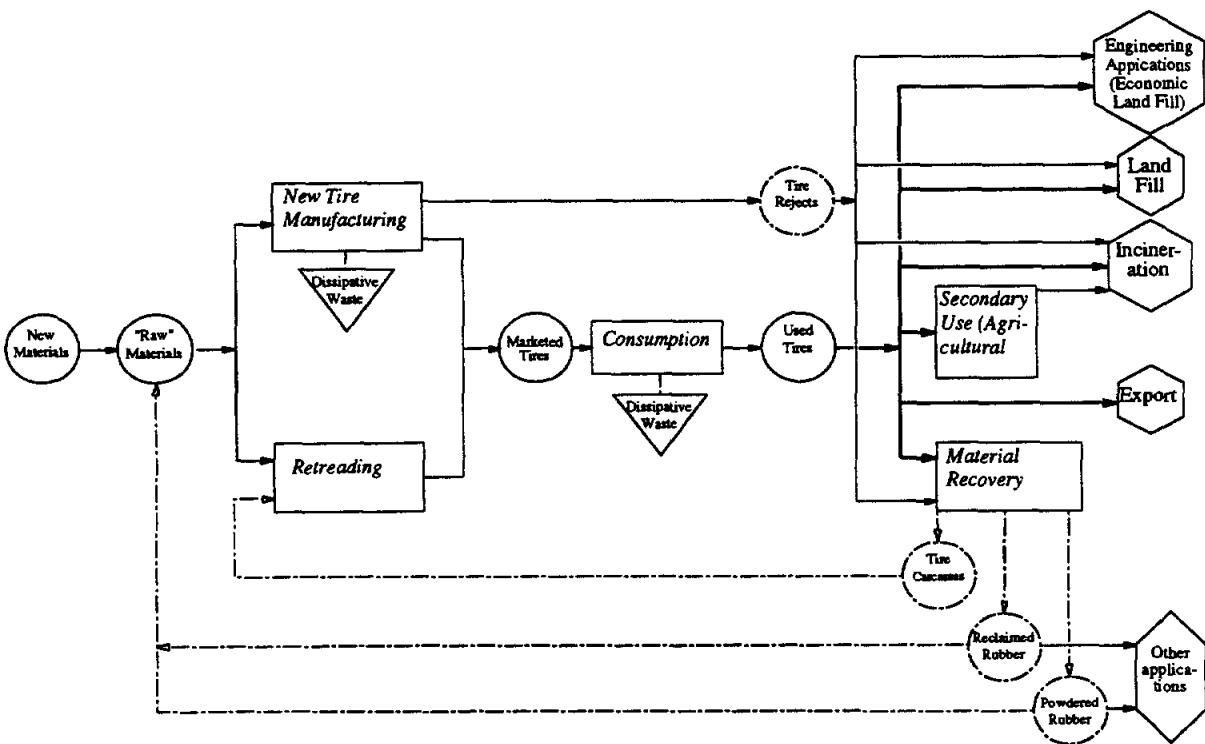


Figure 2: Tire life cycle
source: authors

"reclaim". These may be further used within the tire sector, to manufacture other rubber products (mats etc.), or as a substitute for asphalt. Both mis-manufactured and used-tires can be employed as a construction material in engineering projects; for example, to stabilize slopes or build offshore reefs for shoreline protection. Some used- and reject tires also find second (temporary) use in non-transport applications. In France it is common for old tires to be used on farms to hold down tarpaulins. A further possibility is that the used tires enter trade. Directly or indirectly, however, the fate of most used tires is either incineration (with or without heat recovery) or burial in landfills.

The French tire life-cycle

A breakdown of production for 1991 by type of tire and weight of output is given in *Table 1* [French Industry Ministry, SESSI, 1992]. This shows that around 10% by weight of tires produced in 1991 were retreaded. This percentage has been declining in recent years. Comparable statistics for 1983 show that just more than 14% by weight of that year's production was of retreaded tires.

Table 1: French tire production by type, 1991

	All tires (tonnes)	Retreaded tires (tonnes)
Car tires	355,811	6,999
Van tires	40,741	1,546
Truck/bus tires	102,171	57,059
Tractor tires	62,214	1,484
Others	118,039	0
TOTAL	678,977	67,087

There is little up-to-date published information on the extent of the losses of materials incurred during new tire manufacture. However, a comparison between the input quantities of raw materials and the output quantity of new tires (both sets of figures obtained directly from our sample tire manufacturers), shows a ratio of 1.05 to 1. At issue is how the losses are incurred; i.e., the split between dissipative manufacturing losses and mis-manufacture. A 1980 study [Agence de Basin, 1980], casts some light on this. It indicates a total water pollution from post-calender washing and immersion equal to 1.0% by weight of the raw materials used. In addition, some pulverization products (carbon black etc.) are known to be lost in the storage and weighing areas. This figure corresponds well with an estimate [ANRED, 1986] for other losses incurred during manufacture, through the production of non-conforming (mis-manufactured) tires. This indicates that in 1983 in manufacturing 460,000 tonnes of brand new conforming tires, 15,000 tonnes of reject tires were produced. We therefore estimate that the 5% total material loss during new tire manufacture is made up of 1.8% of emissions to the environment and 3.2% of mis-manufacture.

The current average tire life expectancy is around 50,000 km for a car tire and 250,000 km for a truck tire. By comparing the average weights of new and used tires, we can derive an estimate of the dissipative loss during use. The weight of an average new truck tire is ca. 68 kg. The weight of an average car tire is 6.5 kg. A truck tire loses between 3.5 and 4.0 kg during its lifetime in service (i.e., 5.5%) and a car tire, between 0.8 and 1.0 kg (i.e., 14.0%). Given the relative proportions (by weight) of different tires produced (*Table 1*) and bearing in mind that part of production will not be exposed to dissipative loss during use at all (for example, inner tubes), it is estimated that average dissipative losses are of the order of 7%.

Evidence on the fate of mis-manufactured and used-tires in France is given in *Table 2*. With respect to mis-manufactured tires, a little over half of the material involved (53%) is recovered as "reclaim". A further 20% is sent for engineering use. The remainder goes for landfill or incineration. The fate of post-consumption waste tires is also given in *Table 2*. Of the 502,000 tonnes of used tires in 1983, 72,000 tonnes (ca. 14.3%) was sent for retreading. A further 8,000 tonnes (1.6%) was used for direct raw materials recovery and 9,000 tonnes (1.8%) for engineering applications. Approximately 20,000 tonnes of used-tires (ca. 4.0%) was exported. All the remainder, 393,000 tonnes (78.3%) was disposed of directly or indirectly through landfill or by incineration.

Table 2: The fate of mis-manufactured & used tires: France, 1983

	<i>Used tires</i>		<i>Reject tires</i>	
	(tonnes)	(percent)	(tonnes)	(percent)
Material recovery				
a) carcass recovery	72,000	14.3		
b) powdered rubber	3,000	0.6	8,000	53.3
c) "reclaim"	5,000	1.0		
Engineering applications	9,000	1.8	3,000	20.0
Landfill	236,000	47.0	2,000	13.3
Direct incineration	7,000	1.4	2,000	13.3
Indirect incineration	150,000	29.9		
Export	20,000	4.0		
TOTAL	502,000	100.0	15,000	100.0

It is known that 236,000 tonnes (47.0% of the used-tire total) went to landfill and 7,000 tonnes (1.4%) to incineration. Since 150,000 tonnes of used-tires found second-use in agriculture, the precise fate of these is unknown, though the likeliest is uncontrolled incineration on open fields. The possibility of unofficial landfilling of some of these cannot be ruled out either. However, an estimate for 1990 [ANRED, 1991] placed the likeliest split for domestic⁵ disposal of used-tires that year at 40% by weight to landfill and 40% to incineration, with the remaining 20% being recycled or re-used. This would imply that virtually all the tires temporarily used on farms are ultimately incinerated; mostly in uncontrolled conditions on open fields to protect crops from frost damage.

From these data, we can begin to derive a generalized static tire life-cycle model for France. To complete the model, it was necessary to obtain detailed information on the inputs to the retreading and new tire manufacturing processes. Data on these were collected directly from our three sample French tire manufacturers. Together, these three represent the greater part (51%) of French national production. The percentage breakdown of material inputs (*Table 3*) are presented as the average across the three manufacturers, weighted according to their respective productions. These data are more detailed than those available from standard trade sources (which list only major constituents as a proportion of final national production). Nevertheless, the percentage breakdown of the minor components, the oils, accelerators, and protecting agents, was not given and had to be estimated from published blending formulae [Curchot J., 1984]. The estimated breakdown of these is given in *Table 4*.

⁵ These figures are for domestic disposal. They do not take into account exports. An earlier study [ANRED, 1986] estimates that 4% of all used tires are exported.

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Table 3: Material inputs as a percentage of all non-carcass material inputs

<i>Material</i>	(%)
Polymers	
- Natural rubber	17.0
- SBR	15.2
- Poly-butadiene	7.0
- Butyl	3.7
- Reclaim/Powder	0.6
Cords	
- Rayon	2.8
- Nylon	1.3
- Polyester	0.1
- Steel	13.1
Fillers	
- Carbon black	25.8
Vulcanizing agents	
- Sulfur	1.5
- Zinc Oxide	2.0
- Stearic acid	1.0
- Accelerators	1.2
Protecting agents	1.8
Oils	5.0
Others	0.9
TOTAL	100.0

Apart from the make-up of the virgin materials used, the significant finding for estimating the life-cycle model is the relative split between virgin and recycled materials in the manufacture of the hypothetical product. The data for the 1983 and 1991 situations show some discrepancies on this. In 1983, old carcasses accounted for 11.4% of the weight of input materials [ANRED, 1986]. For 1991, old carcasses represented only 7.6% of inputs. We have no data for the proportion of "reclaim" and powdered rubber used in 1983, but data from our sample manufacturers on the current situation suggest this to be 0.6% of the non-carcass inputs. Absent information to the contrary, this level has been assumed also for 1983. It is clear, therefore, that not all of the reclaim and powdered rubber recovered from mismanufactured and used-tires is reused within the tire industry.

Table 4: Minor inputs as a percentage of all non-carcass inputs

<i>Oils</i>		<i>Accelerators</i>	
Aromatic oil	4.06	CBS	0.78
Paraffinic oil	0.47	TBSS	0.06
Naphthionic oil	0.06	DCBS	<u>0.31</u>
Tacking resin	<u>0.41</u>		
Total	5.00	Total	1.15
<i>Protecting agents</i>		<i>Others</i>	
DPAA	0.45	Adhesive	0.45
ZMBI	0.06	Resorcin	0.29
TMQ	0.49	Polyethylene-glycol	<u>0.16</u>
6PPD	0.33		
DTMT	0.03		
MBTS	0.02		
DEDCTe	0.02		
Antiozon wax	0.40		
Antilight wax	0.02		
Phenolic P.A.	<u>0.02</u>		
Total	1.84	Total	0.9

(Source: Derived from Curchot J., 1984)

Figures 3 and 4 depict reconstructions of French tire life-cycles for the years 1983 and 1991. The estimate for 1983 is based upon a total post-consumption waste of 502,000 tonnes [ANRED, 1986]. The basic question asked is: What amounts and types of new and recycled materials were involved in generating 502,000 tonnes of waste? The reconstruction for 1991 is based on that years' production. The intent is to represent the likely pattern of materials/energy use and waste generation linked with the manufacture, use, and disposal of the 679,000 tonnes of tires produced that year. The basic difference between the life-cycles, apart from the higher volume of flows in 1991, is in the level of retreading. The material inputs and outputs for both years' reconstructions are balanced. The destinies of the make-up materials in the 1983 and 1991 life-cycles are given in Table 5. These are found by tracking and summing all the losses that occur during the life-cycle. Within the tables we distinguish three broad categories of material losses. The first encompasses those materials that are truly wasted. Their ultimate fate is known and, one way or another, involves the return of the materials to the environment. This includes the environmental emissions incurred during tire manufacture and use and the materials lost through incineration and landfill. A second category includes materials which find secondary use or are recycled in non-tire applications. These too, will ultimately be returned to the environment, though it is not clear precisely when or how. For the time being, however, it can be assumed that these materials stay in France. The final category includes those materials that are exported. They, too, will ultimately be returned to the environment but it not clear when, how, or where.

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1983

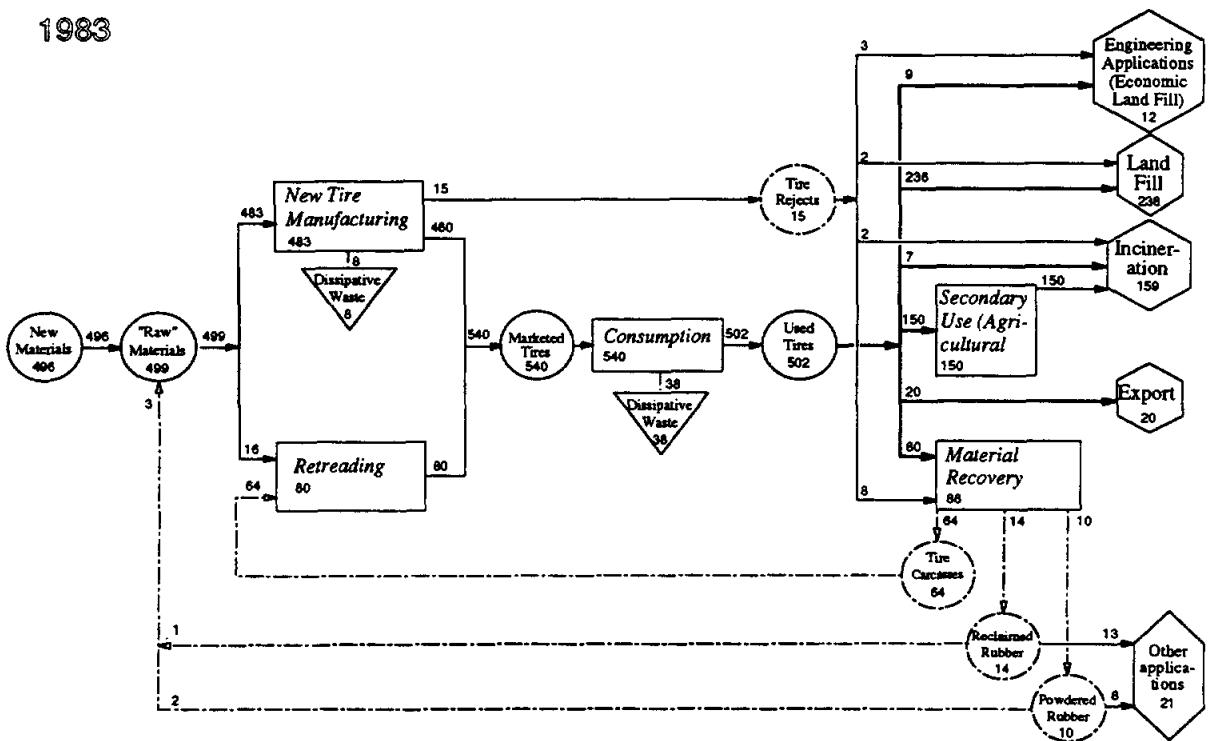


Figure 3: French tire life-cycle: 1983 disposal "cohort"
source: authors

Inputs, outputs, and wastes in the automotive tire life-cycle

Having estimated the 1991 life-cycle, the next step is to estimate the associated materials/energy use on a unit product basis. The unit product is one tonne of tires. Since the life-cycle has been estimated for total 1991 French tire production, the unit product considered is hypothetical; neither a brand new nor a retreaded tire, but the weighted average of all tires produced in France.

Material inputs

From the life-cycle for 1991, we can determine the relative proportions of new to recycled materials involved in tire production. We can also determine the ratio of material inputs to final product output. The latter is 1.045 as shown in *Table 6*. *Table 7* gives a breakdown of the material inputs used to manufacture one unit (one tonne) of our hypothetical product.

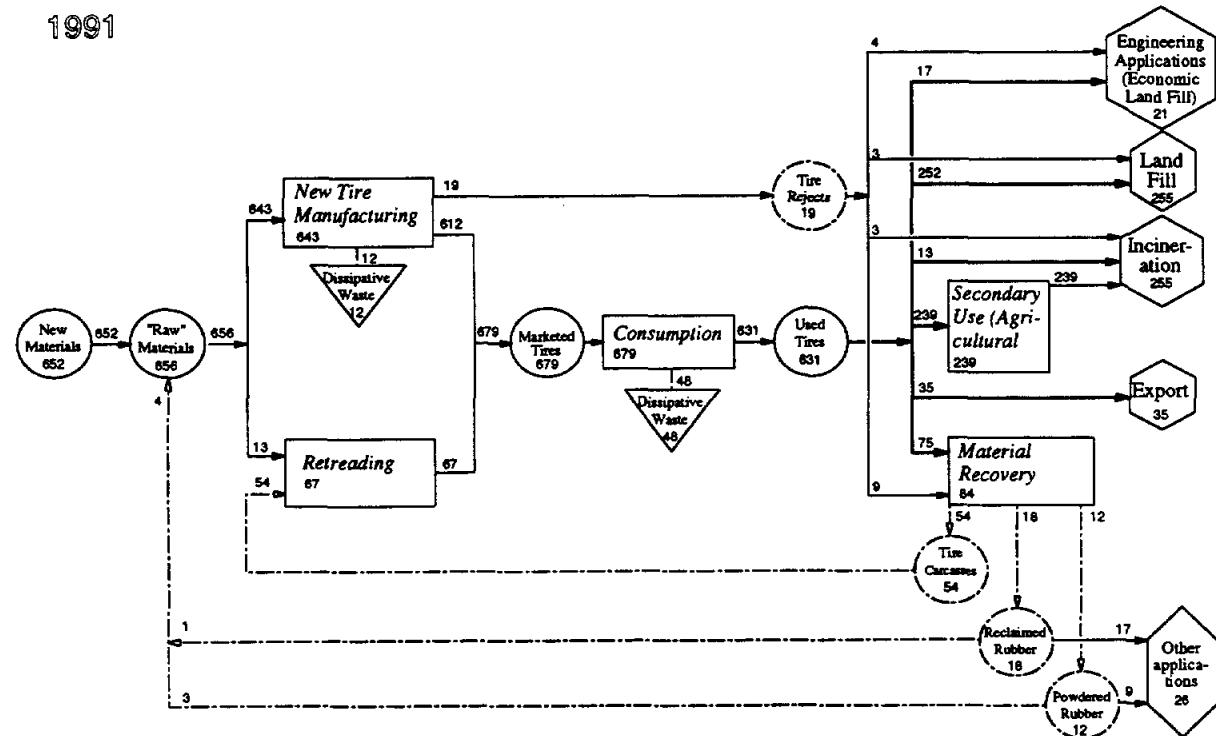


Figure 4: French tire life-cycle: 1991 disposal "cohort"
source: authors

**Table 5: Losses of materials in the French tire life-cycle
(1000 tonnes)**

Type of loss	1983	1991
Lost to the French environment		
- dissipative losses	46	60
- incineration	159	255
- landfill	238	255
Secondary use (return to the French environment postponed)	33	47
Exported	20	35
TOTAL	496	652

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Table 6: Inputs and outputs from tire manufacturing, France, 1991

		<i>Quantity (tonnes)</i>	<i>Proportion of Output</i>
Inputs	virgin materials	652000	0.960
	reclaim/powdered rubber	4000	0.006
	old carcasses	54000	0.079
	TOTAL	710000	1.045
Outputs	dissipative losses	12000	0.017
	reject tires	19000	0.028
	useful commodity	679000	1.000
	TOTAL	710000	1.045

Table 7: Materials and energy used to make one tonne of tires, 1991

<i>Material</i>	<i>kg/tonne of tire</i>	<i>required energy</i>	
		<i>kWh/tonne input</i>	<i>kWh/tonne product</i>
Natural rubber	165	11627	1918
SBR	147	24424	3590
Polybutadiene	67	30329	2032
Butyl	36	18240	657
Rayon	27	17764	480
Nylon	13	66207	861
Polyester	1	31465	31
Steel	126	9805	1235
Carbon black	247	39192	9680
Sulfur	15	7400	111
Zinc oxide	19	37600	714
Stearic acid	9	6889	62
Oils	48	11627	558
Other virgin inputs	39	22500	878
Reclaim	4	9055	38
Old carcasses	79	9055	715
TOTAL	1045		23560

Tables 3 and 7 provide breakdowns of the *direct* material inputs to tire manufacturing. In the case of table 3, the breakdown is of non-carcass inputs to new tire manufacturing. Table 7 gives the breakdown of virgin and recycled materials used in producing our hypothetical tire, which represents total French production including both new tires and retreads. As well as raw materials extracted directly from nature, the tables list intermediate products. To estimate the materials and energy used in tire manufacturing, information is needed on the likely mix of processes used up-stream in deriving pre-cursors and intermediaries.

Raw rubber is obtained directly from nature. We have assumed that SBR is produced by cold emulsion from styrene and butadiene. Other materials used are soap, sodium chloride, and H_2SO_4 . Styrene is produced by dehydrogenation of ethylbenzene, and ethylbenzene from alkylation of ethylene and benzene. Benzene is produced from crude oil via toluene. Ethylene can be produced using a range of pyrolysis processes from feedstocks including ethane, propane, naphtha, light gas oil or heavy gas oil. We have assumed a mix of feedstocks representing that used by the US ethylene industry, for which data are available [Gaines and Shen 1980, p. 84]. Butadiene is produced from n-butane and n-butene by catalytic- or oxidative dehydrogenation and from mixed C_4 by extraction. Again, because of data availability, we have assumed a mix of processes and feedstocks corresponding to US industry averages [Gaines and Shen 1980, p. 101]. Polybutadiene is produced from butadiene by a catalyzed polymerization process. Butyl is produced by cationic polymerization of isobutene with isoprene [Curchod 1984, Kirk and Othmer 1983]. Isoprene is made from isobutene.

Nylon (6,6) is produced by reacting hexamethylenediamide and adipic acid to form hexamethylene diammonium adipate ("nylon salt"). By dehydration and polymerization, "nylon salt" is transformed to polyhexamethylene adipamide (nylon), a linear polyamide. The two intermediaries are produced from benzene- or petroleum-derived cyclohexane (for the adipic acid) and petroleum-derived butadiene with chlorine, HCN, and hydrogen (for the hexamethylenediamide). High-tenacity rayon, as is needed for tire cords, is manufactured by the viscose process. The process converts cellulose, a natural short-staple polymer, into a polymer of almost unlimited length whose mechanical properties can be selectively influenced during production. The chemical formula for rayon is essentially the same as that for the cellulose from which it is derived ($C_6H_9O_4.OH$). The prime source of cellulose for viscose rayon is wood-pulp [Shreve 1956]. The process is a major consumer of sulfuric acid (H_2SO_4), caustic soda ($NaOH$), and carbon disulfide (CS_2). A significant co-product, sodium sulfate (Na_2SO_4), embodies most of the sodium and sulfur used by the process. Polyester is the condensation product of dimethyl terephthalate (DMT) and ethylene glycol. The DMT is oxidized directly from *p*-xylene in the presence of nitric acid and methanol. Steel is produced by smelting iron ore and scrap. The set of processes assumed is that for the US steel industry.

Of the three main processes by which carbon black is produced worldwide (furnace, thermal, and channel), one (the furnace process) dominates the French carbon black industry. The French carbon black industry is, in turn, virtually dedicated (95% of total output of 200,000 tonnes p.a.) to serve tire manufacturing. Carbon black is produced by burning high aromatic oil with low sulfur content in a controlled atmosphere, using natural gas to provide supplementary energy and process control.

Sulfur, the principle material in vulcanization, can be derived either from hydrogen sulfide by oxidation (the Claus process) or by direct extraction from nature (the Frasch process). The Claus process uses hydrogen sulfide obtained from the desulfurization of natural gas and petroleum refinery streams. The Frasch process uses high pressure steam to dissolve elemental sulfur from sulfur-bearing deposits (typically at salt-dome sites in the US). The US is the world's major sulfur producer and exporter. Since it is by far the more important source, we have assumed that sulfur used by the French tire industry is obtained by the Frasch process. Zinc oxide, used as an accelerator, is produced directly from Franklinite ore which is refined using coal and electric power. Stearic acid is produced from fats by continuous high pressure splitting and solvent crystallization. Oleic acid and glycerine are commercial co-products. Process diagrams and details (including sources) for all the above are given in appendix 1.

Energy inputs:

The energy requirement of French tire manufacturing was estimated on the basis of the set and mix of processes described above. As demonstrated in appendix 1, an attempt was made to trace back to its origins in nature each of the direct material inputs to tire manufacturing. The original materials (oil, natural gas, fat, timber, elemental sulfur, franklinite ore, iron ore, etc.) are the up-stream inputs to the processes described in appendix 1. Each process requires (or delivers) energy. In addition, the inputs to each process embody chemical energy. For materials derived directly from nature and used directly in tire manufacturing, such as sulfur, the *required* energy represented by the material is the sum of the dissipated process energy and the embodied energy. In the case of manufacturing an intermediate, unless there are bi- or co-products, the *required* energy of all the input materials plus the dissipated process energy can be considered as used to produce the intermediate. In the case of bi-products and co-products, the sum of the required energies of the material inputs and the process energy must be partitioned. When there are bi-products, we have ascribed a required energy to the main product equal to the sum of all the required energy for the input materials plus all process energy minus any embodied energy represented by the bi-product. In the case of co-products, we have partitioned the required energy for the input materials across the set of outputs on the basis of the weight and embodied energy of each co-product. The process energy has been partitioned in proportion to weight of output. The *required* energy represented by any material is therefore different from its own embodied (chemical) energy. It is also process and feedstock specific. Energy used in transporting materials has not been included in the analysis, which therefore represents an approximate and *minimum* estimate of the actual energy used in French tire manufacturing.

The relevant data are given on a unit product basis in *Table 7*. Some further explanation of these data are necessary. The embodied energy of natural rubber has been assumed the equivalent of that of crude oil; i.e., 11627 kWh/tonne. The analysis does not include the process energy dissipated in collecting and concentrating raw rubber. The energy analysis for SBR excludes the energy represented by the soap, sodium chloride, and sulfuric acid used in the cold emulsion process. In the derivation of benzene used to manufacture ethylbenzene

(up-stream of SBR production), it has been assumed that raffinate is a bi-product. In the derivation of ethylene for the same purpose, all pyrolysis products other than ethylene have been considered bi-products. The estimate for rayon corresponds to the sum of the represented energy of the wood pulp used and all the process energy of rayon manufacturing except that used to concentrate the sodium sulfate co-product. The represented energies of the other material inputs (sulfuric acid and caustic soda) are not included as these are passed on to the co-product. The represented energy for sulfur is based upon an averaged figure for the process energy used in the Frasch process, which varies from less than 700 kWh to more than 8,000 kWh per tonne of sulfur. The embodied energy of sulfur has been taken as 3,000 kWh/tonne. The embodied energy of steel has not been included since this is not relevant (unlike that of sulfur) to the tire manufacturing process and is not in an available form. In the case of unspecified virgin material inputs, these have been ascribed a required energy equivalent to the average of that of all the other inputs. The recycled materials - reclaim/powdered rubber and old carcasses - have been ascribed a required energy equivalent to the heat of combustion of tires. This underestimates the actual required energy since it omits the process energy of recycling. However, this will not significantly affect the outcome of the energy analysis.

The required (dissipated and embodied) energies of each direct input to tire manufacturing are given on a unit basis (per tonne) in *Table 7*. These are weighted and summed in proportion to the quantities of each material used in French tire manufacturing to give a *minimum* estimate for required energy of 23560 kWh (2.03 t.o.e.) per tonne of tires produced. Based on pro-rated data on total energy use by the French rubber industry, which is dominated by tire manufacturing, the energy used in the tire manufacturing process itself has been estimated at 0.56 t.o.e.e. per tonne of tires produced. At minimum, the energy used in manufacturing one tonne of tires is therefore 2.59 t.o.e. This translates to an average of 3.0 liters oil equivalent per kilogram for our hypothetical tire; around 21 litres for a 7.0 kg tire.⁶ It should be noted that not all of this energy is dissipated. Approximately 0.78 t.o.e. per tonne of tires is embodied within the tires and is potentially recoverable as heat of combustion.

Material wastes in the tire life cycle

Turning first to the wastes in the precursor chain, the most significant - from an environmental standpoint - are those associated with the production of the metal inputs (steel and zinc oxide), synthetic elastomers, and carbon black. Ore extraction and beneficiation results in mine and mill wastes. The metal content of zinc ore is typically 3.2%. For iron ore, the metal content is 59%. Based upon the processes for zinc oxide and steel production assumed above, we estimate that 0.2 tonnes of iron ore and 0.1 tonnes of zinc ore would be needed per tonne of tires. This implies mine/mill wastes of just less than 0.1 tonne/tonne of tires produced for each of the metal inputs.

⁶ An estimate by French tire manufacturer, Michelin places the energy requirement for the average new car tire at ca. 27 liters [Michelin, 1992]. The results from the two studies are broadly similar. Moreover, given that the method described above provides a minimum estimation and that Michelin's analysis is based upon a wholly new tire some small difference is to be expected.

Emulsion polymerization of SBR and polybutadiene requires high quantities of water - approximately 2.5 times the quantity of dry rubber produced. Before treatment, the waste water is polluted by salts, acids derived from the emulsifier soaps, catalysts and reaction stoppers as well as by rubber crumbs. At the end of the polymerization reaction, the rubber is in latex form and must then be coagulated to give dry rubber. The washing waters for reactors, clarifying tanks, and strippers contain suspended solids and toxic materials (such as unreacted monomers and hydrocarbons), but these pass through high performance treatment units to eliminate crumbs and toxic products in respect to existing legal norms.

By contrast, emissions to the atmosphere from polymerization of synthetic rubbers is neither well studied nor well controlled. The principal source of emissions is vaporization (of monomers such as ethylene, butadiene, and styrene) from storage facilities and polymerization reactors. There are also vaporization losses during the draining and drying of polymers and crumbs. Technologies for controlling hydrocarbon vapors - adsorption on carbon black, floating seals on reservoir storage etc. - are available, but it is not clear to what extent and with what success these are used.

Although not a serious problem, there are also emissions to the atmosphere from carbon black production. The significant potential pollutants are hydrogen sulfide, carbon monoxide, and hydrocarbons from the furnace. Most furnaces are equipped with efficient off-gas combustion units which reduce and transform the emissions. Nonetheless, oxides of nitrogen (NO_x) and some SO₂ are released. The US Environmental Protection Agency (EPA) estimates SO₂ emissions from carbon black production to range from essentially zero to 0.02kg/kg of carbon black. We have no data on actual emissions from the French industry.

Turning to wastes incurred through tire manufacturing, use, and final disposal, we can be much more certain about the quantities and types of wastes involved and the environmental media into which they are released. The loss of 652,000 tonnes of material in respect of 1991 French tire production is made-up through the addition of a comparable amount of non-carcass materials (95% of which are virgin). The losses can be divided in several ways. In *Table 6* they are given in terms of the fate of the materials concerned. But it is useful also to distinguish between avoidable and unavoidable losses; losses incurred for no useful gain versus those that arise during/after the product's useful economic life; and situations where choice can or cannot be exercised over the manner in which losses are incurred.

A high proportion of the materials used in tire manufacture - carbon (represented in the natural and synthetic rubbers and in the carbon black), sulfur, and zinc/cadmium - are environmentally relevant. Emissions during manufacture (especially of pulverized materials after calendering) are potentially avoidable. Moreover there is no economic utility derived from incurring these losses. These are both fundamental distinctions as compared with the dissipative loss of materials incurred during a tire's service lifetime. Some wear and tear during use (which provides utility) is inevitable. From an environmental perspective there is also a distinction between where the losses are incurred. In the case of manufacturing losses, there is a potentially controllable point source and a likely concentration of emissions. In the case of dissipative losses during use, pollutants are released over the road network in

proportion to the average traffic density. The most significant such pollutant is cadmium which is associated with the zinc oxide used in tire manufacture. The zinc content of the hypothetical tire described in this paper is 2.0% (as zinc oxide). The likely level of associated cadmium is 0.42% of the zinc. This gives an overall 0.08% cadmium content for the hypothetical tire and a total annual cadmium loss distributed across the French road network of ca. 5 tonnes.

But by far the greatest are the post-consumption wastes represented by used-tires. Depending on the method used, used-tire disposal can see the re-release to nature of almost all of the materials temporarily sequestered within the product. This is the main source of environmental contamination associated with the tire life-cycle. Since different disposal methods release the materials to different media and in different chemical forms, and since some methods can be controlled more easily than others, the quantity of materials disposed of and the disposal methods used are very significant environmentally. Depending upon how the tire is disposed of, the carbon may be returned directly to the atmosphere (incineration) or may be held temporarily in store (landfill). Depending on how efficient and controlled is the incineration, carbon may be released first in the form of highly toxic unburned hydrocarbons, as carbon monoxide (CO) or as carbon dioxide (CO₂). Hydrocarbons are carcinogenic, CO is a pulmonary irritant and toxic to humans, and (CO₂) is a greenhouse gas. CO₂ is also the ultimate entropic state for any released carbon. If used tires are incinerated in uncontrolled conditions, such as occurs when they are burned *in situ* on farmers' fields, the contained sulfur and cadmium will be released locally. Some will enter the local soils. Sulfur is acidifying. Cadmium is a highly toxic heavy metal. Through a potentially synergistic mechanism, heavy metals are likely to become biologically-available in soils that are acidified.

Materials and energy productivities

Using the information on the tire life-cycle reported above, the current materials and energy intensities of French tire manufacture can be calculated. These can be estimated in terms of both the unit product (per tonne of tire produced) and, of greater real interest, the end service delivered (kilometers of tire service). Of total current tire production, 90% is of brand new tires and 10% of retreaded carcasses. The current materials intensity - the draw on non-carcass materials for each tonne of tires produced - is then 0.965 tonnes (i.e., 0.9 x 1.05 + 0.1 x 0.2). To manufacture 679,000 tonnes of tires in 1991, the draw on non-carcass materials (of which 99% are virgin) was 656,000 tonnes. We have no information on the relative energy requirements (process energy) of new tire manufacturing and retreading. Assuming that the processes both consume similar amounts of energy (i.e. 0.56 t.o.e. per tonne of product), the overall energy intensity of current tire production is 2.59 t.o.e. per tonne of tires produced. As with materials intensity, energy intensity is related to the level of retreading, since this determines the draw on virgin materials. As noted earlier, most of the energy used in the tire sector is used in deriving the input materials. Given the current split between car/van and truck tires (a ratio of approximately 4:1) and the current average kilometrage of each (50,000 km. for a car tire and 250,000 km. for a truck tire), we can estimate the average service life of our hypothetical tire to be ca. 90,000 km.

Using these data as the benchmark, the energy and materials productivities of different possible tire life-cycles can be compared. Clearly, the energy and materials productivities both increase with the rate of retreading. They also increase as the kilometrage of service delivered per unit product increases. *Table 8* gives the material and energy requirements for different combinations of retreading (measured as percentage of retreaded tires by weight of total production) and different tire service lives (measured in kilometers). It should be remembered that the product considered is hypothetical and is intended to reflect all French tire production. As a result, kilometrages at the levels represented in the table are not unrealistic.⁷

Table 8: Virgin materials (tonnes) per 100,000 km of tire service

<i>% of retreads in total production</i>	<i>Average tire life (1000 km)</i>			
	<i>50</i>	<i>100</i>	<i>150</i>	<i>200</i>
0	1.88	0.94	0.63	0.47
10	1.73	0.86	0.57	0.43
20	1.58	0.79	0.52	0.40
30	1.42	0.71	0.47	0.35
40	1.28	0.64	0.42	0.32
50	1.12	0.56	0.37	0.28

If the current level of truck tire retreading (over 50%) was matched within the car/van tire sector, the overall materials requirement of the French tire industry would reduce by 35%. The energy requirement would also drop by an equivalent percentage. If the retreading rate was to remain at the current (10%) level, but the average service life of tires was increased to 180,000 km., the materials and energy requirement would drop to half the current level. If we assume a combination of more modest changes (say, a 40% retreading level and a 150,000 km. average tire life, it is not unrealistic to envisage materials and energy productivity gains of 230%.

Problems, opportunities, and policy options

It is no surprise that the analysis demonstrates that the current French tire life cycle is materials and energy intensive, that the current level of materials recycling (8%) is low, or that tire disposal in France has become a huge problem.

⁷ With a 4:1 ratio of car to truck tires, and an increase in the average longevity of a car tire to 130,000 km. (as is now technically possible) it is entirely feasible for the weighted average French tire life expectancy to be over 200,000 km.

Currently, in France, most used tires are disposed of by incineration or at land-fills. As well as the environmental problems these forms of disposal represent, to incinerate and bury used tires constitutes a major waste of energy and materials. Disposal in landfills in France is shortly to be banned. This raises the question of what, in the future, will be the fate of that proportion of used tires now being disposed of in this way. One possibility is that the proportion of used tires being incinerated under uncontrolled conditions - for example, on farmers' fields - will increase. Another is the risk of illegal dumping and stockpiling. In the US, where some states have instituted landfill bans on tires, the result has been a large increase in the number of tires "stockpiled" at official sites pending some final solution. The stockpiles represent a major fire hazard and there have already been several significant fires. Federal environment officials have recorded 176 since 1971 [Sweeney J., 1993]. If landfill is no solution, neither is stockpiling - though this is the perverse outcome of a bureaucratized approach to disposal problems. A solution lies in first lowering the materials intensity of providing tire service and in then ensuring safe disposal of unavoidable wastes. We turn to these options below. First, however, it is worth noting that the illegal dumping problem could likely be overcome by attaching a deposit to the tire purchase price which would be refunded on returning the tire to an authorized depot.

Increasing the materials and energy productivity of the tire sector is a real possibility. The average life expectancy of a car tire is around 50,000 km. For a truck tire, the comparable figure is 250,000 km. Yet one French tire company has recently developed a touring tire for cars that is designed to have a life expectancy of 130,000 km. This corresponds to the average lifetime of a car. That such developments are technically feasible is surely instructive. Nonetheless, it is not at all clear under current economic arrangements that manufacturers' interests are served by research to increase tire longevity or by moves to translate such research into products for the market. On the one hand, to increase tire life would be to reduce the overall tire market. Manufacturers would be left with unused production capacity and a host of related problems. On the other hand, to manufacture long-lived tires would be to restructure the tire market in favor of original equipment purchasers; i.e., the car manufacturers whose market strength would be commensurately increased.

The present tire market in France is one that, for the most part, holds the tire as the saleable commodity. In one market segment, however, that represented by the supply of tires to haulage companies, there are alternative arrangements based upon tire leasing. These are important not only because they are illustrative of the kinds of arrangement that can encourage a decrease in the materials/energy intensity per unit end-use service, but also because of their role in materials recycling. Almost all the re-treading that occurs in France is in the truck tire segment of the market. Tire producers lease tire service to haulage operators which allows the tires to be routinely recalled for retreading before becoming so worn that re-treading is infeasible. The manufacturers, selling tire service rather than tires, have an incentive to increase materials and energy productivity per unit of service delivered. The service delivered to customers is kilometrage. As a result, the life expectancy of a truck tire carcass is routinely increased to 600,000 km. This represents a significant reduction in materials use since only 20% of the material needed to produce an entirely new tire is used in the production of a retreaded tire.

By contrast, there is little incentive in the touring tire market segment for manufacturers to re-tread. The emphasis for R&D is rather on increasing tire performance, and with it, prices and market share. Few touring tires are considered for re-treading. Of those that are, 83% are rejected. The high rejection rate is, in part, because touring tires are often too worn for successful re-treading under current technologies. There are also other factors to consider. Retreads are generally considered by consumers to be inferior in performance to new tires. In a market where product improvement and innovation play an important element in competition, re-treading could constitute a brake on product development. And, for the manufacturer, there is a relatively high labor cost to strip worn treads from a potentially reusable touring tire carcass. For progress to be made in increasing the percentage of retreading in the car tire sector will at least require changes in marketing similar to those that have already occurred "naturally" in the truck tire sector. It might additionally mean grading tires by performance and price categories so that tires can be cascaded down the hierarchy each time they are re-issued. One way of bringing such changes about would be to require car tire manufacturers to be responsible for the ultimate disposal of their product. This would provide an incentive to reduce post-consumption wastes within the car tire sector generally; retreading (along with increasing tire longevity) would be among the more effective means of doing this.

Another, but less effective way of dematerialization is to increase the quantity of material and energy recovery from used tires. Powdered rubber is produced by grinding scrap rubber using one of several processes; ambient grinding, cryogenic grinding (in liquid nitrogen), or solution grinding in water. Each process produces powdered rubber with different particle size. Grinding costs are estimated at 200-300 F/tonne. Reclaim is produced using mechanical and chemical processes to sever the crosslinks of the vulcanized rubber; i.e., to partially reverse the vulcanization. There are three basic processes; digester, heater, and reclaimator. Tires are most commonly reclaimed by digesting. Scraps of rubber are prepared by mechanical shredding. The wires and fibers are removed by mechanical separation using hammer mills. An alternative is to use metal chlorides to reduce the tire fiber chemically during digesting. The scrap rubber is charged into a steam-heated pressurized tank (the digester) along with caustic soda, oils, and reclaiming chemicals (sulfides, mercaptans, and amino compounds). After several hours, the pressurized digester batch is forced into a blowdown tank and is washed and dried. Compounding ingredients are added to modify or maintain specific mechanical properties. Other potentially recoverable materials include many of those used in tire production. The Tosco II process pyrolysis research study, for example, was conceived to develop recovery equipment to maximize quality carbon black production. A pilot plant, designed to handle 15 tonnes of tires per day, successfully recovered carbon black, oil and steel. The main obstacle is cost. Such a process would only be economic if the costs of using virgin materials were to increase substantially.

In France, as elsewhere, only a small proportion (ca. 5%) of the potentially recoverable materials are, in fact, recovered. The biggest obstacle is that the mechanical properties of the recovered materials are inferior to those of virgin materials so that the proportion that can be used in high-specification products, like tires, is strictly limited. Powdered rubber has, to some extent, replaced reclaim in tire applications. Even so, its use in blending formulae for treads, carcasses, inner liners, and other tire elements is also limited. Meanwhile, the market

for reclaim and powdered rubber outside the tire sector - in mechanical products, footwear, asphalt, sports surfaces etc. - is relatively small. In part, this is because of technical difficulties. Rubber asphalt, for example, is difficult to lay thinly so that the costs of using it as a road surfacing material are high compared with other materials. A recent US survey [Sweeney J., 1993] reported that the costs are double those of regular asphalt.⁸ It is ironic that this economic obstacle stands in the way of road-paving as a means of used-tire disposal. Again, one solution would be to require manufacturers to underwrite the additional cost of safe and useful disposal.

A further possibility is to incinerate used tires for heat recovery under controlled conditions so that pollutants are captured and not released to the environment. Tires are highly combustible; they contain more than 90% organic materials and have a heat value of ca. 32.6 MJ/kg. By comparison, coal varies from 18.6 to 27.9 MJ/kg. In some countries, the UK for example, tires are classed as a non-fossil fuel and are used at utilities for electricity generation. In other countries, incineration is opposed by environmental pressure groups. The most interesting possibility is for tires to be used to fuel portland-cement kilns since the cement neutralizes and contains the sulfur released during combustion and encapsulates the other potential pollutants. This method for using waste tires was pioneered in Japan and is now widely used in Germany. In France, the method is still in its infancy.

There is one portland-cement plant in France using tires as fuel; the Lafarge plant of La Malle (Marseille) which has been operating since mid-1992. Entire tires are introduced with the other raw materials into the furnace. This avoids shredder costs. There is no waste: tire combustion residues including metal parts are incorporated in the clinker. The effluent gas emissions are the same as from a conventionally-fuelled plant. It is planned to extend this technology to 20 cement plants in France, providing capacity to burn 200,000 tonnes of used tires/year. However, there are some problems still to be overcome. Although the existing plant has capacity to burn 20,000 tonnes/year of used tires, it has been burning only 10,000 tonnes/year. The higher capital costs of the plant are offset by charging a fee for accepting tire deliveries, and this has led to a supply shortfall. Again, one solution would appear to lie in requiring manufacturers to contribute financially toward safe final disposal.

Conclusion

There are clear methodological limitations with all life-cycle analyses. This study is not exempt from the restrictions that the failure to fully count all the factors, up-stream and down-stream, imply on the precision of the quantitative analysis. To fully understand the effects of different disposal methods, for example, it would be necessary to characterize the average elemental composition (by atomic weight) of a standard unit (one tonne) of a representative French tire and to have detailed understanding of the different disposal processes. There are some ambiguities in respect of the energy analysis. And there are limitations in any analysis that omits both the transport of materials or that ignores the

⁸ It also estimated that 12,000 tires are used in paving a mile of two-lane road with rubberized asphalt.

industrial metabolism of the structures (factories, transport networks, etc.) that themselves require huge amounts of energy and materials to be mobilized so that tires can be produced.

These limitations notwithstanding, at very least we have minimum quantitative estimates of the material and energy intensities associated with the current French tire life cycle. We also have clear signals as to the technical means by which these intensities can be reduced. What conclusions might we draw for how these and other technical opportunities might be more easily seen and conditions created for them to be taken up? Clearly, better guidance for all concerned would be provided if energy and materials prices were more accurately to reflect the potential environmental harm that energy dissipation and pollution represent. Appropriate incentive structures must also be engineered to overcome some of the vested-interests that rule out the kinds of R&D activity and marketing that business could engage in, but under current conditions, chooses to ignore. Requiring manufacturers to be responsible for the final disposal of their products is one of the most promising potential measures. Finally, a more pragmatic attitude to final disposal needs to be developed based upon a systematic overview and appraisal of alternatives. We can no longer afford to accept either the bureaucratic or, as is commonly the case, environmental pressure group approach that singles each disposal alternative as unacceptable. Some wastes are inevitable. The issue is then to find the best disposal method. Anything less is simply irresponsible.⁹

Glossary

Accelerators:

CBS	:	N-cyclohexyl-2-benzothiazylsulfonamide
DCBS	:	N,N-dicyclohexyl-2-benzothiazylsulfonamide
TBBS	:	N-teriobutyl-2-benzothiazylsulfonamide

Protecting agents:

DPPD	:	N,N-diphenyl paraphenylene diamine
IPPD	:	N-isopropyl-N-phenyl paraphenylene diamine
6PPD	:	N-(dimethyl-1-3-butyl)-N-phenyl paraphenylene diamine
DPAA	:	Condensate diphenylamine-acetone
TMQ	:	Trimethyl-2-2-4 dihydro-2 polymerized quinoleine
ZMBI	:	Zinc mercaptobenzimidazolate

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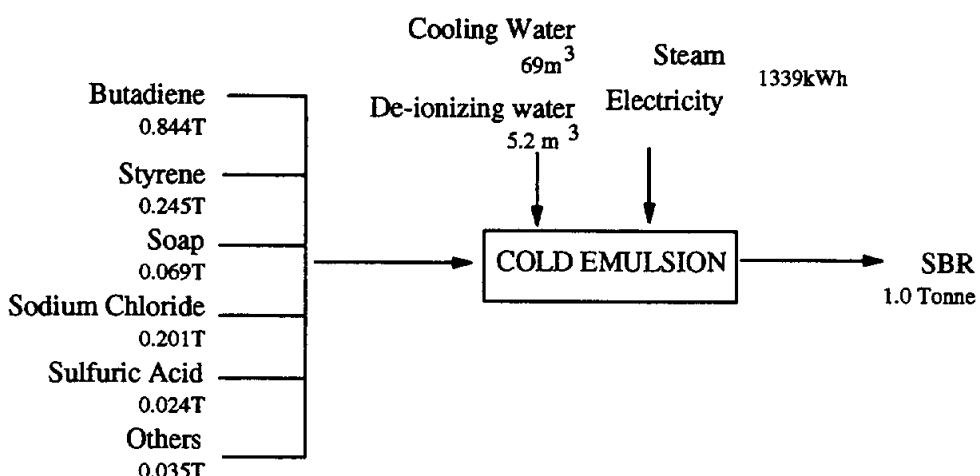
Sweeney, J.W., 1993, Tire business keeps recycling on, *The Earth Times*, March 21

Appendix 1

UP STREAM PROCESSES

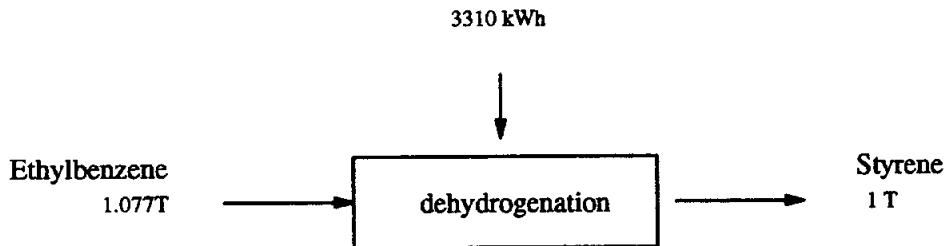
The following provides a set of unit process descriptions. The foregoing materials and energy analyses are based upon the assumption that these are the processes used in deriving the input materials used in French tire manufacturing. Where a set of different processes are possible, as with ethylene, the description represents the assumed mix of processes. The bases for the assumptions made are given.

PRODUCTION OF STYRENE-BUTADIENE RUBBER (SBR) BY COLD EMULSION (Stanford Research Institute, 1988)

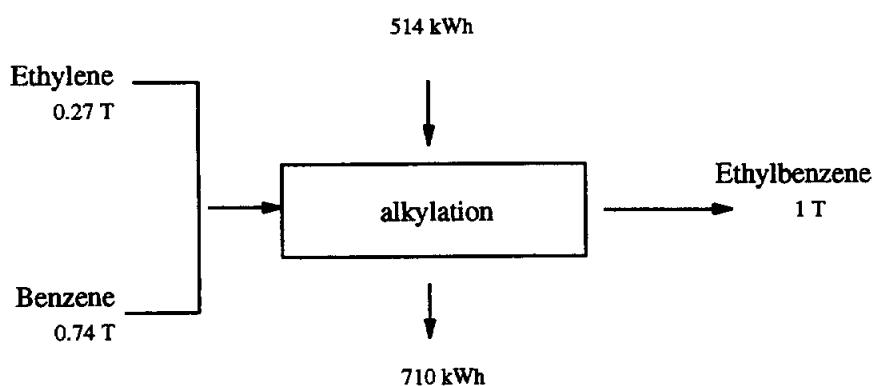


The following five diagrams describe the sequence of processes in deriving styrene and butadiene. The required energy is estimated to be 18,261 kWh/tonne for styrene and 22,051 kWh/tonne for butadiene. Excluding the energy represented by the soap, sodium chloride, and sulfuric acid used in the cold emulsion process, this implies a minimum required energy for SBR production of 24424 kWh/tonne.

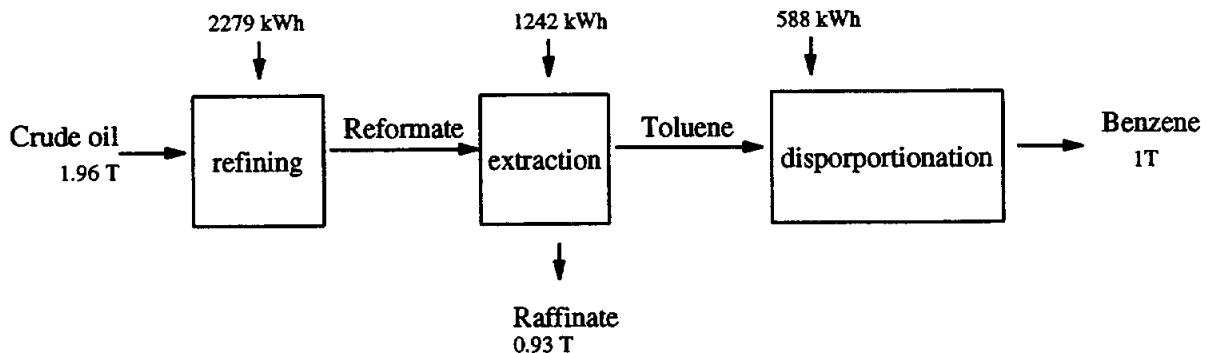
1) Styrene by ethylbenzene dehydrogenation (Gaines and Shen 1980)



2) Ethylbenzene by alkylation of ethylene and benzene (Gaines and Shen, 1980)

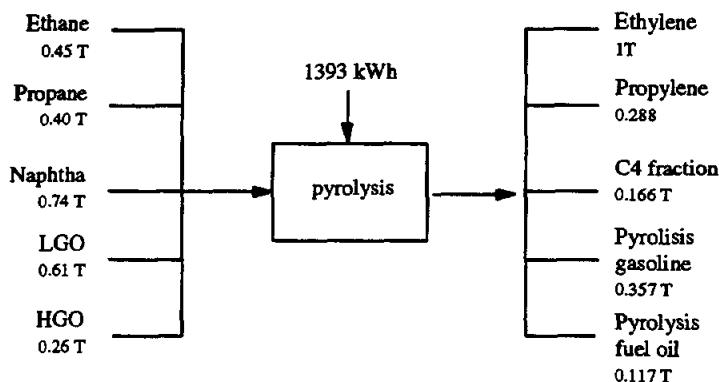


3) Benzene (Gaines and Shen 1980)



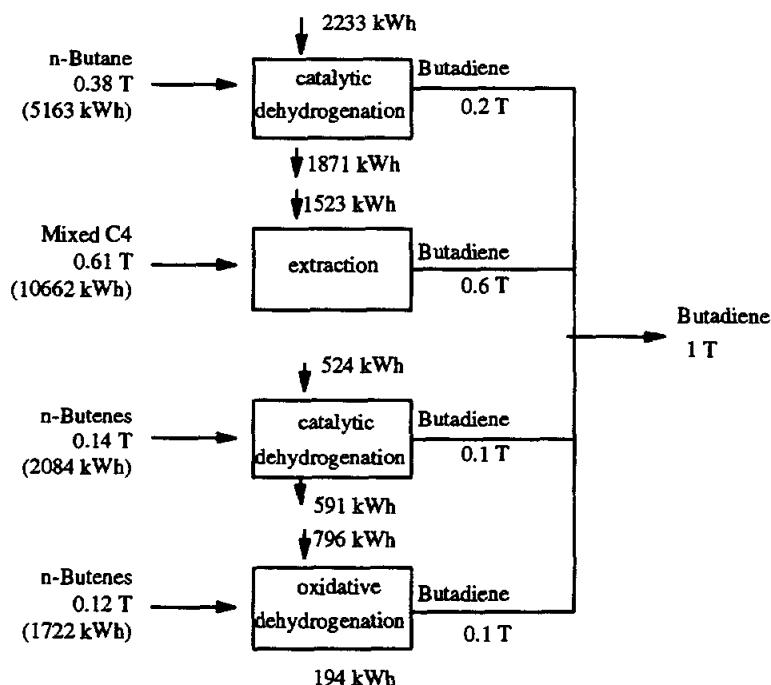
Raffinate is a co-product. However, it is assumed that benzene is the main product. Accordingly, the energy requirement for benzene has been calculated as the feedstock and process energy minus the energy content of the raffinate; i.e. all the process energy is ascribed to the production of benzene. Crude oil has an energy content of 11,627 kWh/Tonne. On this basis, the required energy for benzene is 16,350 kWh/tonne

4) Ethylene (Gaines and Shen 1980)



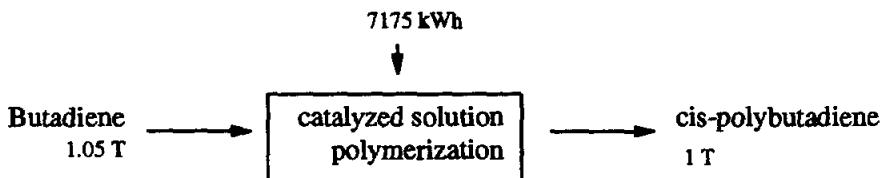
Several processes exist to produce ethylene depending upon the upstream compounds: ethane, propane, naphtha, light gas oil (LGO), or heavy gas oil (HGO). There are also different co-products: propylene, C4 fraction, pyrolysis gasoline and pyrolysis fuel oil. It is assumed that the ethylene used by the SBR industry in France is produced using the mix of processes corresponding to that of the US ethylene industry. Since ethylene is considered as the main product, all the process energy is ascribed to its production. On this basis, the required energy to produce ethylene is 18,710 kWh/tonne

5) Butadiene (Gaines and Shen 1980)



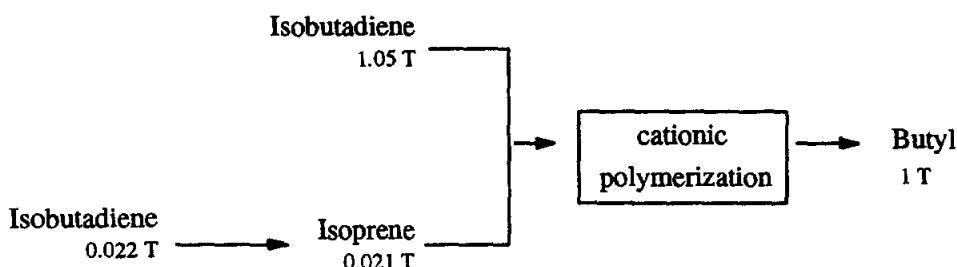
Several processes exist to produce butadiene depending upon the upstream compounds: nButane, mixed C4, nButenes. It has been assumed that the balance of processes corresponds to that reported for the US butadiene industry (Gaines and Shen, 1980). The required energy to produce Butadiene is 22051 kWh/tonne

PRODUCTION OF POLYBUTADIENE (Gaines and Shen 1980; Petrochemical Handbook 1977)



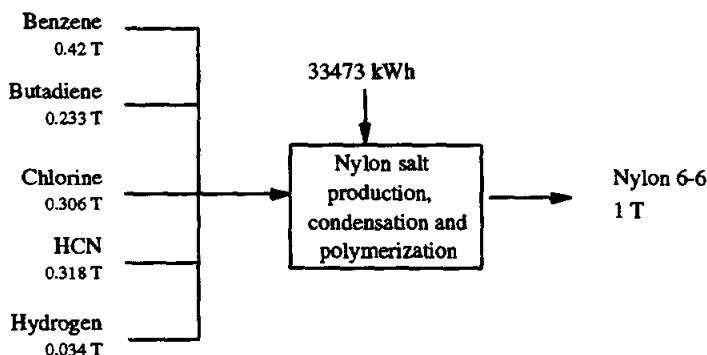
Butadiene is assumed to be produced using the mix of process described above. The required energy to produce polybutadiene is therefore estimated to be 30329 kWh/tonne

PRODUCTION OF BUTYL (Curchod, 1984; Kirk and Othmer, 1983)



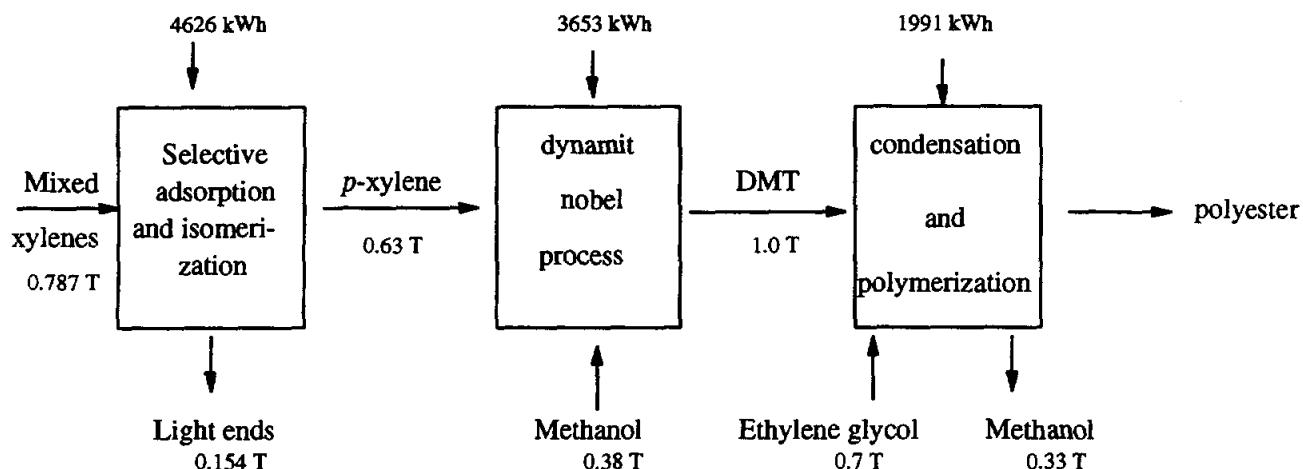
Butyl is produced by cationic polymerization of isobutadiene and isoprene. Isoprene is produced from isobutadiene. Since we have no information on process energy, we have considered only feedstock energy in estimating the equivalent energy consumption of butyl production. This is estimated to be 18240 kWh/tonne

PRODUCTION OF NYLON (Gaines and Shen, 1980)



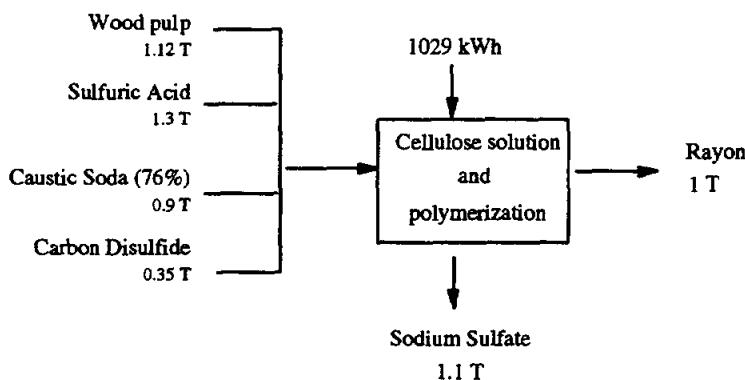
Nylon 6-6 is produced by condensation and polymerization of "nylon salt" obtained by reacting adipic acid with hexamethylenediamine. The energy content of benzene and butadiene have been carried forward from the earlier estimations. The estimated required energy for the other inputs are: chlorine, 5816 kWh/tonne; HCN, 32,113 kWh/tonne; and, hydrogen, 39402 kWh/tonne (derived from Gaines and Shen, 1980, p. 146). Based upon these assumptions, the required energy to produce nylon is 66,207 kWh/tonne

PRODUCTION OF POLYESTER (Gaines and Shen, 1980)



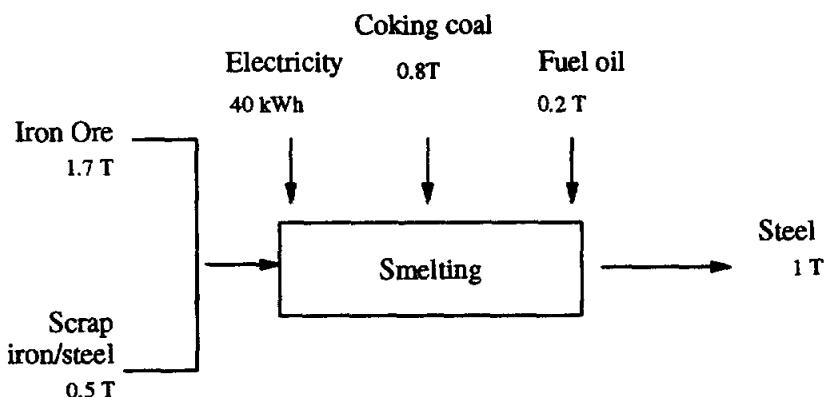
Polyester is the condensation product of dimethyl terephthalate (DMT) and ethylene glycol (Shreve, 1956, p. 760). The DMT is oxidized directly from *p*-xylene in the presence of nitric acid and methanol. The estimated required energy contents of the inputs and outputs are: mixed xylenes, 15,307 kWh/tonne; light ends, 12,959 kWh/tonne; methanol 7,755 kWh/tonne; and, ethylene glycol, 15381 kWh/tonne. The required energy to produce polyester is 31465 kWh/tonne

PRODUCTION OF RAYON (Shreve, 1956)



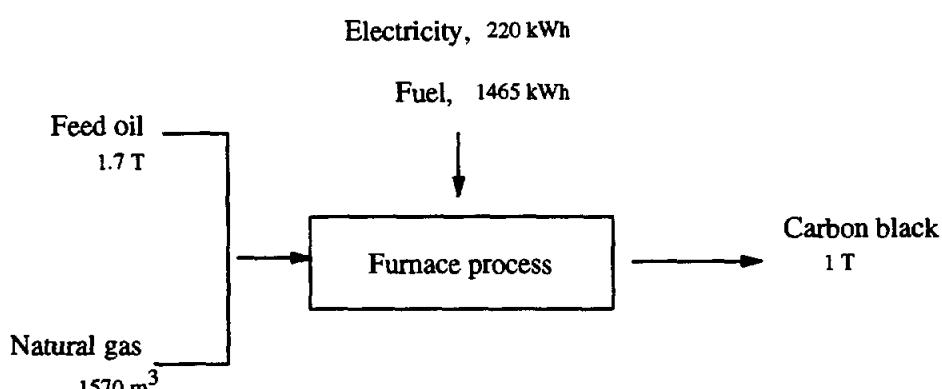
High-tenacity rayon for tire cords is produced by the viscose process. Sodium sulfate is a co-product. However, it is assumed that rayon is the main product. The required energy to produce wood pulp is 14,942 kWh/tonne (US Department of Commerce 1975). The sulfuric acid and caustic soda are embodied in the co-product, and in waste water. For this reason, the required energy for rayon production is estimated as the sum of the energy content of the wood pulp and the process energy. This gives a required energy for rayon production of 17764 kWh/tonne

PRODUCTION OF STEEL



The iron-ore and scrap are smelted using electrical power, coking coal (chemical energy 9300 kWh/tonne), and oil (chemical energy 11,627 kWh/tonne). This gives an estimate for the required energy of steel production of 9805 kWh/tonne

PRODUCTION OF CARBON BLACK (Gerstle et al. 1977)



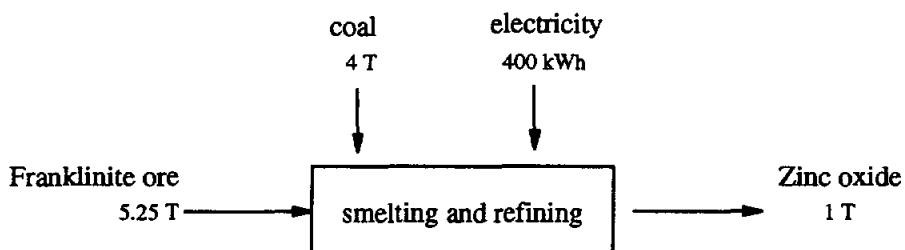
All French carbon black production is by the furnace process, which involves controlled burning of highly aromatic oil (with low sulfur content) and gas. The energy content of natural gas is taken as 213 kcal/mole (11,300 kWh/1000 m^3). The required energy to produce carbon black is therefore 39,192 kWh/tonne

PRODUCTION OF SULFUR (Gerstle et al. 1977)

It is assumed that elemental sulfur is produced by extraction from sulfur-bearing, porous limestone (the Frasch process). Large quantities of hot water are needed to melt the sulfur. Requirements vary from 4 to 50 tonnes of water per tonne of sulfur produced. The equivalent heat content of this water is 651 to 8135 kWh/tonne of sulfur. We have assumed a mid-range figure of 4000 kWh/tonne. In addition, sulfur has a chemical energy content of ca. 3000 kWh/tonne

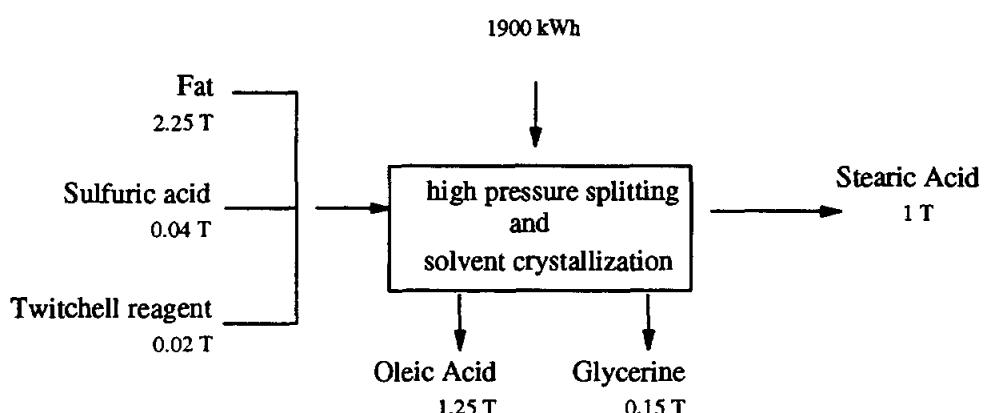
PRODUCTION OF ZINC OXIDE (Faith, Keyes, and Clark, 1975)

Zinc oxide is produced directly from franklinite ore. We have assumed ore with 20% ZnO content



The required energy to produce zinc oxide is estimated to be 37600 kWh/tonne

PRODUCTION OF STEARIC ACID (Faith, Keyes, and Clark, 1975)



It is assumed that stearic acid is produced by the Twitchell process. The principal inputs are fat and sulfuric acid. The co-products are oleic acid and glycerine. It is estimated that the chemical energy of the fat is 5000 kWh/tonne. The process energy and the embodied (chemical) energy of the inputs have been partitioned by weight and the embodied energy of the outputs. The required energy to produce stearic acid is thus estimated to be 6889 kWh/tonne