MINIMIZING WASTE EMISSIONS FROM THE BUILT ENVIRONMENT: TOWARDS THE ZERO EMISSIONS HOUSE

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Abstract

The paper reviews the material inputs to the construction industry (i.e. those materials that are ultimately embodied in structures), and the wastes associated with materials processing. It also reviews the emissions associated with energy use for purposes of heating, air-conditioning, lighting, cooking and other energy services normally provided within structures. Of the two categories, the latter is more significant in terms of environmental damage. As regards abatement, the most promising strategy for reducing the damages associated with mining and processing the structural materials themselves is increased recycling, especially of metals. Two primary strategies suggest themselves with regard to reducing the environmental impact of energy services. The first is increased end-use efficiency e.g. by improved design, better thermal insulation and more efficient equipment, such as refrigerators and compact fluorescent lights). The second primary strategy is to shift as quickly as possible from dependence on fossil fuels for heating and cooking to electricity, especially by utilizing photovoltaic (PV) rooftop units together with heat pumps and microwave cookers. Government intervention may accelerate this shift in various ways, but policy issues are not discussed in the paper.

1. Background

The construction sector, together with the production of associated durable goods and consumables needed for purposes of maintenance and operation, constitutes by far the largest end-use for materials that are embodied in products — especially structures. In the year 1993, 2.13 billion tonnes of materials were embodied in new structures in the US alone, as compared to around 60 million tonnes of machinery and equipment (producer durables) and 20 million tonnes of consumer durables (some of which, like carpets and kitchen appliances, are essentially components of residential housing).

The materials in structures and durable goods are, for the most part, relatively inert and unreactive. By far the largest share consists of sand, gravel and crushed stone, which are natural mineral products processed only by grinding, sorting and washing. The next largest share consists of mineral substances further processed only by heating for purposes of melting, sintering, calcination (driving off carbon dioxide), or simply dehydration: these products include glass, bricks and ceramics, portland cement, and plaster-of-Paris. The construction
sector and its satellites also consumes fairly large quantities of organics such as lumber, paper, plastics, rubber and textiles. Finally, it is a major user of metals, especially steel and aluminum. Although metals constitute a very small part of the total, they do account for quite a large share of the indirect pollution associated with structures, as noted below.

Only the organics are inflammable and perishable. This means that they can become pollutants if they burn or escape in other ways. Chlorinated plastics like PVC, widely used in structures and for insulation of electrical wiring, can generate dioxins in fires. Plywood, paper, plastics and textiles also embody significant amounts of other chemicals, including adhesives, wood preservatives, fire retardants, coloring agents, plasticizers, fungicides, and so on. The chlorofluorocarbons formerly used in foam insulation and compressors, and the PCBs that were formerly used in electrical transformers and capacitors are further examples.

Surface protection of structures involves additional chemicals that can escape into the environment during application or use. Undeniably, there are significant environmental hazards resulting from some of the materials used in structures themselves. (Asbestos and formaldehyde are two examples). The residual toxicity due to past uses of lead-based paints, and mercury-based fungicides and anti-mildew agents, especially indoors, and the more recent pollution problems arising from solvents, adhesives, wood preservatives and plasticizers illustrate a few of the problems.

However, beyond doubt, the most significant environmental hazards arise from waste materials associated with metals and chemicals production or consumed in system operation, maintenance and repair. (Indoor air pollution is increasingly recognized as a more serious health hazard than outdoor air pollution, by a considerable margin). Fuel consumption for space heating is only the most obvious example. Inefficient combustion, especially in kitchens and wood-burning fireplaces, generates a witches brew of pollutants, including carbon monoxide, unburned hydrocarbons and micro-particulates (smoke). Solvents used in paints constitute another well-known hazard. Agents used for termite control, fungicides, insecticides and rodenticides leave residual toxicity. (Lead-based paints are still a hazard in some older tenement buildings.) Another less well-known example is the chromium-based algicides that are used in large commercial air-conditioning systems.

In terms of absolute priorities, the research objective should be lower operations and maintenance costs, longer life of metallic subsystems, and renewability, in that order. However, it is important to recognize that, although the total quantities of building materials used in our society per capita have not increased remarkably (Figure 1) there is a significant trend toward the use of more sophisticated materials involving more complex manufacturing processes. In particular, the use of aluminum and plastics in place of wood and other simpler materials has grown rapidly (Figures 2 and 3). This means that indirect pollution associated with manufacturing these materials is now much more important than it was a few decades ago. Therefore, I consider next the indirect pollution resulting from mining and manufacturing processes for construction materials. Next, I discuss household energy services, excluding transportation services (even though the two are not completely independent). In the remainder of this paper I consider potential emissions reduction strategies and speculate a bit about future trends.

2. Life-cycle emissions from manufacturing construction materials.

As noted above, mineral products are consumed in very large quantities by the construction industry, especially sand and gravel, stone, clay and derivative products like cement, brick, glass and plaster. Most of these are comparatively harmless, as such. Apart from dust and noise, largely associated with trucks, this is also true of their extraction
processes. Quarrying wastes are, in most cases except for clay, modest in comparison with total quantities produced. Emissions associated with downstream processing are overwhelmingly of two kinds, viz. (1) dust (particulates) from crushing and grinding, and (2) combustion wastes due to fossil fuel usage for thermal processing (calcination). Most dust from open air mining and quarrying operations can be reduced to tolerable levels by simple methods, such as water sprays. (Silicaceous dust, however, is the exception; it is a serious health hazard — albeit mainly to workers. Suppression requires special measures.) Dust from most grinding operations, cement plants and other manufacturing operations can be captured quite efficiently by electrostatic precipitators.

Fuel consumption is the source of the most important emissions, mainly of CO₂, CO, and NOₓ. Portland cement plants are by far the major consumers of fossil fuels (among construction materials producing industries) with glass and brick kilns a somewhat distant second. The cement industry of the US consumed a little less than 12 million metric tons (MMT) of fuel (mainly coal) in 1993, to produce 66 MMT of Portland cement from 117 MMT of mineral inputs, of which about 33 MMT was is emitted as carbon dioxide from calcination of input carbonates [USBM 1993 "Portland Cement"]. Allowing for ash, nitrogen, water and other non-combustibles, coal is approximately 75 percent carbon by weight, whence fuel consumed in cement plants contained about 9 MMT of carbon and generated about 33 MMT of CO₂ in that year, adding another 33 MMT of CO₂, or 66 MMT altogether, or 1 ton of CO₂ per ton of cement. Essentially all of this can be attributed indirectly to the construction industry.

It is worth mentioning, by the way, that the sulfur and ash emissions normally associated with coal burning are not problems in the case of cement plants. In fact, US cement plants in 1993 safely burned over 70 kMT of scrap tires, 90 kMT of other waste solid fuels and 670 kMT of waste engine and other lubricating oils.

Bricks and tiles produced in 1993 for the construction industry consumed about 13 million metric tons (MMT) of common clay, to produce a somewhat smaller mass of finished (dry) bricks and tiles [USBM 1993, "Clay" Table 8]. Data on fuel consumption by the brick and tile manufacturers is not readily available, but it is not unreasonable to assume that the fuel required per ton of carbon-free input material (adjusting for the CO₂ content of limestone used by the cement industry) is similar to that for cement manufacturing, since similar temperatures are needed. In this case, the brick and tile industry must have consumed about 1 ton of fuel for 7 tons of clay, or a little less than 2 MMT altogether. If the original clay had a water content of 30 percent, or 4 MMT, it would follow that 9 MMT of finished bricks and tiles were produced, entirely for the construction sector. Assuming the fuel was mostly natural gas (75 percent C), the carbon content would have been 1.4 MMT, generating 5.1 MMT of CO₂ in the processing, or about 0.55 tons of CO₂ per ton of bricks.

Approximately 15 MMT of glass is produced each year in the US, of which roughly two thirds is used for containers and part of the remainder is used for vehicles (40 kg per car), TV screens, computer monitors, and so on. The quantity used by the construction industry for windows and doors is probably between 3 and 4 MMT. Detailed data on fuel consumption by the glass industry are not available. However, higher temperatures are needed to melt glass than for baking bricks or producing Portland cement. On the other hand, the calcination contribution in glassmaking (from soda ash, or sodium carbonate) is proportionally smaller. The glass used in construction accounts for roughly its own weight of CO₂ emissions, or 3-4 MMT.

Roughly 18 MMT of calcined gypsum products (mainly plaster wallboard) were produced and consumed for construction purposes in the US during 1993 [USBM 1993, "Gypsum" Table 4]. This includes the weight of other minor materials incorporated in the products, such
as paper and metal. Calcination involves low temperature heating (up to 350 degrees F) to drive off part of the water of hydration of the gypsum. This water is later added back to the finished material. There is no data on specific fuel consumption, but it must be considerably less than for brick kilns. Lacking other data, we estimate that heat energy requirements for plaster products (by weight) would be a quarter to a third of the requirements for bricks. This implies CO₂ emissions of around 3 MMT, give or take 0.5 MMT.

Detailed calculations of life cycle emissions generated by metallurgical and chemical processes involved in the manufacture of construction materials are much more complex and cannot be reproduced here in detail. An overview of the US steel sector for 1993 is shown in Figure 4 [Ayres & Ayres 1998 Chapter 5]. Wastes generated within the sector per ton of steel (including ore mining and concentrating) amounted to about 1.1 tons of overburden, 1.5 tons of concentration waste, and around 1.1 tons of CO₂ (allowing for some small contributions such as CO₂ emissions during prior calcination of lime, from limestone). Minor wastes include steel slag (about 0.05 tons), ferrous sulfate or chloride 'pickling' wastes, and so on. (Note that iron slag from blast furnaces is no longer considered a waste, nor is blast furnace gas, which is recovered and burned as a low grade fuel).

Shipments direct to the construction sector accounted for 15 percent of the total in 1993, but this is an underestimate, since it accounts mainly for structural steel such as girders and reinforcing bars, as well as cast iron pipe, purchased by very large contractors. The largest single 'consumer' of steel products, accounting for 26.6 percent of total output is 'distributors and service centers' which resells steel products to other sectors, including construction [USBM 1993, "Iron & Steel" Table 3]. It is reasonable to assume that, overall, construction uses also account for at least 20 percent of the sales of distributors and service centers, and probably more. This raises the total to at least 21 percent. But this figure still does not include small items of hardware like fasteners, hinges, or locks or steel embodied in machinery installed in structures, such as elevators, kitchen equipment and heating/ventilation equipment. When the latter are taken into account, it seems likely that between 25 and 30 percent of all iron and steel products end up in structures. On this basis, we estimate that the construction sector consumed roughly 26 MMT of iron and steel, with an uncertainty (plus or minus) of 4 MMT.

Translating into wastes and emissions, it follows that iron and steel used for construction purposes carries with it an environmental burden amounting to approximately 30 MMT of overburden from mines, 40 MMT of ore concentration wastes, 30 MMT of CO₂, 1.3 MMT of steel slag, plus waste pickle liquors, coal washing wastes, coke oven quenching wastes and other minor contributions.

Aluminum, copper, zinc and lead are other metals used by the construction sector. Aluminum is used for window and door frames, roofing and 'curtain walls' for some large office blocks. These uses accounted for 15 percent of total US shipments in 1993 [USBM 1993 "Aluminum" Table 7]. Copper is used in structures for wiring and water pipes, and as a constituent of brass for hardware. The construction industry accounted for 42 percent of copper and brass end uses, while electric and electronic products accounted for another 24 percent, of which a significant portion is also embodied permanently in structures as wiring [USBM 1993 "Copper" p. 331]. Zinc is used mainly for protective coating (galvanizing) of water pipes, gutters or sheet steel as a roofing or siding material. It is also a constituent of brass. Coatings accounted for 54 percent of demand for zinc metal in 1993, while brass alloys took 14 percent [USBM 1993 "Zinc" p. 1281]. The major end users included construction, transportation equipment and machinery. A detailed breakdown is not available, but as much as half of all galvanized metal and brass may have been embodied in structures. Lead was formerly used extensively for water pipes, and paint and is still used in small quantities for
soundproofing, roofing (in a few applications), and in solder. Quantities are relatively minor, but toxicity is still a significant environmental hazard.

Detailed accounts of mine wastes, concentration wastes, smelter wastes and so on due to extraction and processing of these metals cannot be undertaken here. A composite overview is shown in Figure 5. More details can be found in [Ayres & Ayres 1998, Chapter 5]. However one point worth emphasizing here is the importance of metal recycling as a way of reducing the environmental impact of metal use.

Every ton of metal that is re-used, remanufactured or recycled — or avoided by more efficient design — replaces a ton that would otherwise have to be mined and smelted, with all of the intermediate energy and material requirements associated with those activities. This is already very significant for iron and aluminum. Each ton of iron recycled saves 12.5 tons of overburden (coal and iron mining), 2.8 tons of iron ore, 0.8 tons of coal (exclusive of its use as fuel), and a variety of other inputs. It also eliminates at least a ton of CO₂ pollution and significant additional pollution of air and water from coking, pickling and other associated activities. See Figure 5. In the case of non-ferrous metals, the indirect savings are much larger, of course, although much depends on the original ore quality.

To the extent that the smelting is carried out in less regulated countries outside North America and Europe, recycling or remanufacturing a ton of copper or zinc also saves 1.0 tons of SO₂ that would otherwise be emitted into the air. In the US, Canada and Europe sulfur from non-ferrous metal smelters is recovered as sulfuric acid, which is subsequently used for the increasingly important heap-leaching process in North America, but this is not being done extensively elsewhere. A third factor is also increasingly important from an industrial ecology (IE) viewpoint. It is the fact that the gross supply of many minor metals, especially some of the most toxic ones like arsenic and cadmium is not determined by direct demand per se but by the demand for more important metals such as copper and zinc, with which they are normally associated as minor by-products of ore processing and smelting. Thus, the more copper is recycled, the less need be mined, thus reducing the aggregate arsenic supply. Similarly, the more zinc is recycled, the less cadmium will be produced to pollute the soil or find harmless uses for.¹

Table I shows calculated savings (indirect raw materials and other inputs not used) when a metric ton of metal is recycled [Ayres 1997]. It is, therefore, the calculated difference between inputs per ton of semi-finished metal produced from raw materials vis a vis the inputs per ton of secondary scrap recycled. Because of the complexity of the system, I have assumed simplified process-product chains as follows:

<table>
<thead>
<tr>
<th>Process</th>
<th>Raw Material</th>
<th>Benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td>(raw solids)-[Iron Mining]-(53% Fe ore)-[Beneficiation]-[concentrate]-[Sintering/Pelletizing]-[sinter/pellets]-[Blast Furnace]-[pig iron]-[Electric Arc/Basic Oxygen Furnace]-[steel]</td>
<td></td>
<td></td>
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<tr>
<td>(raw solids)-[Bauxite Mining]-(17.5% Al ore)-[Bayer Process]-[alumina]-[Hall Heroult Process]-[aluminum]</td>
<td></td>
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<tr>
<td>(raw solids)-[Copper Mining]-(0.6% Cu ore)-[Beneficiation]-[concentrate]-[Smelting]-[blister copper]-[Refining]-[copper ingots]</td>
<td></td>
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</tr>
<tr>
<td>(raw solids)-[Lead Mining]-(9.3% Pb ore)-[Beneficiation]-[concentrate]-[Sintering]-[sinter]-[Blast Furnace]-[lead bullion]-[Drossing]-[drossed lead]-[Refining]-[lead]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(raw solids)-[Zinc Mining]-(6.2% Zn ore)-[Beneficiation]-[concentrate]-[Sintering]-[sinter]-[Smelting]-[slab zinc]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(recycling scrap, all metals)-[melting]-[metal product]</td>
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All numerical values in Table I, except as noted specifically below, are calculated by
matching the elemental composition of outputs at each stage of processing, element by element, to the required elemental/chemical composition of inputs to the next stage. These elemental compositions are normally given as ranges in published process descriptions (for sources, see Table I). The final results are therefore consistent with published process descriptions, while satisfying the mass-balance requirement. For convenience, I have neglected the indirect contributions to processing of all other input materials used (explosives, acids, flocculants, fluxes, anodes, etc). Only the actual mass of these secondary input materials themselves was counted.

One final class of materials worth mentioning is plastics. Reliable recent data on uses in the building sector are not readily available. However, in 1987 the construction sector accounted for 4.23 MMT or 19.8 percent of all plastics (resins) consumed in the US, by weight [Duchin & Lange, 1998]. Similarly, 18 percent of all plastics production in Europe in 1991 was used in construction [Ayres & Ayres 1996, Chapter 12, Figure 12.2]. Polystyrene foam is used mainly for thermal insulation; polyethylene sheet is used for many miscellaneous purposes, including waterproofing. However the most important plastic used in structures is PVC, which is used for window and door frames, flooring and siding materials, electrical insulation and water pipes. These applications accounted for 2.47 MMT or 71.7 percent of all PVC consumption in the US in 1987 [Duchin & Lange 1998].

The major raw materials for PVC production are ethylene and elemental chlorine, which is a co-product (with caustic soda) of electrolysis of sodium chloride (as brine). PVC accounts for roughly 25 percent of all chlorine produced. The intermediate products are vinyl chloride monomer and ethylene dichloride, both of which are either toxic or carcinogenic. PVC itself is not harmful, but it is not easy to recycle (mainly due to the variety of different additives used) and disposal is something of a problem. In particular, incineration of PVC is a likely source of dioxins, which are classed as persistent organic pollutants (POPs) because of their affinity for animal fats and the resulting tendency to be concentrated in the fatty tissues of animals as they move through the food chain. Several of the dioxins are known to be very potent carcinogens for laboratory rats and dioxins are regarded as probable human carcinogens.

In summary, most structural materials, by weight, are harmless or nearly harmless to the environment throughout their life cycles. The principle exceptions, which account for very small total quantities, are metals and the plastic PVC. In the case of the metals the harm is mostly associated with mining and primary smelting operations, although secondary recovery of metals also tends to be a rather dirty process. In the case of PVC, both the manufacturing process and disposal by incineration generate some harmful emissions. However, given that these uses are all relatively long-lived, it can be argued that the environmental damage per unit of service to consumers is comparatively small in all of these cases.

### 3. Household energy services

The other major source of environmental damage associated with structures is fuel consumed in supplying energy services. Globally, households consumed 27 percent of total commercial energy in 1995 [Raskin et al 1998, p. A-13]. For the US in 1979, one of the last years for which detailed Census figures on energy were published, residences (R) accounted for 19 percent of the total consumption in that year and commercial establishments (C) accounted for 7.8 percent; detailed breakdowns by category of use are shown below [Ayres 1989, Appendix A]. (Other broad categories were agriculture, industry, transportation and commercial). Residences accounted for roughly half of the energy consumed by buildings, the other half being divided equally between commercial establishments and other buildings, including offices and factories. Energy consumption by these categories of users has increased.
modestly since 1979 (whereas industrial energy consumption has declined), and most of that increase has been in the 1990s.

As a matter of some interest, detailed statistics on energy consumption, both direct and indirect, have been carried out for the Netherlands, for 1990 [Vringer & Blok 1995]. In the Dutch study, energy use was allocated to households in terms of direct energy carriers (fuels) and indirect consumption via other purchased products and services. According to the Dutch data, 25 percent of total energy consumption was for home heating by oil or gas, 12.7 percent was for residential electricity consumption and the same amount (12.7 percent) was consumed indirectly as products and services used for the residence itself or in 'household effects'. It should be noted that Dutch households require more heat and much less air conditioning than US households.

Energy services consumed by residences (R) and commercial establishments (C) in 1979, as percentages of the total, can be classified as follows [Ayres 1989, Appendix A]:

- 3.1 Space heating and ventilation (R- 6.22, C- 2.51)
- 3.2 Space cooling/air-conditioning (R- 0.55 C- 1.84)
- 3.3 Water heating (R- 1.79, C- 0.285)
- 3.4 Cooking (including stoves, toasters, microwave ovens) (R-0.78, C- 0.88)
- 3.5 Refrigeration and freezing (R- 1.39, C- 0.31)
- 3.6 Laundry and dishwashers (R- 0.34, C- 0.95 including water and sewer services)
- 3.7 Lighting (R- 0.66, C- 1.88, including street lighting)
- 3.8 Radio, TV (R- 0.515)
- 3.9 Other electronic detection and signal processing devices, including fans, vacuum cleaners, mixers, electric tools, electric toothbrushes, hair dryers, shavers, sound recorders and amplifiers, video recorders, IR (fire) detectors, battery rechargers, personal computers, etc. (R- 0.29).

Since 1979 energy consumed for space heating has increased due to building activity, even though delivery efficiency has also improved modestly. The same is true for air conditioning, refrigeration, lighting and other standard appliances, where both the increased demand and the efficiency improvements have been more dramatic. Energy consumed for cooking has probably declined slightly, at least in residences. However, energy consumed by miscellaneous devices, especially personal computers, has undoubtedly grown substantially. However, these devices are not essentially part of the built environment, as such, and can be neglected hereafter.

4. Technological trends and future possibilities

It is evident that, in many of the energy service categories (notably categories 3.5 - 3.9) electricity has almost no competition. Electricity is also the only source of energy for purposes of ventilation, air-conditioning and cooling, and microwave cooking. Electricity competes with fossil fuels (gas or fuel oil) to supply hot water and space heating, by means of heat pumps. (See below). Thus electricity can — and eventually will — provide essentially all energy services in the future for both residential and commercial buildings. For all types of electrical services, there is a major future potential for using roof-based photovoltaic PV cells as a partial or total source of electricity supply. (Rural households may also utilize water power or wind). The cost of PV systems is declining rapidly (Figure 6). The mean price of a PV module has declined nearly 10-fold since 1976, due partly to technological advances and partly to
scale-economies and manufacturing efficiencies. Further cost reductions foreseeable, depending on market penetration and total installed capacity, range from 5-fold to 50-fold. But PV rooftop installations are currently available around $5000/kw, or around $17,500 for an average American house requiring 3.5 kw of capacity. There is a high probability that this up-front investment cost will drop to $5000 or less within 20 years. If rooftop systems can be integrated with the national power net, so that diurnal and seasonal fluctuations in supply and demand can be smoothed out by utilizing other sources, such as water power and wind power (and also nuclear or fossil fuel power) rooftop PV will be very competitive. It is estimated that 20-25 percent of total electricity demand (and a considerably higher percentage of household demand) can be met in this way by 2050.

It is true that household demand for energy services may increase over time as new applications (such as 3.9) are found. The introduction of electric washing machines, dishwashers and driers is a case in point Figure 7. Obviously the substitution of electricity for fossil fuels for cooking, water heating and space heating has also increased electricity demand — at the expense of fossil fuel use — in households and commercial establishments. This trend will continue.

At the same time, increased technical efficiency is also cutting power requirements in most applications. Refrigerators are a case in point. Power consumption by Swedish models, measured in kwh over 24 hr, per 100 liters of volume, have fallen from nearly 4 units in 1958 to 1 unit in 1962 and about 0.15 units in 1993 (Figure 8). The declining trend continues. Another example of this phenomenon is lighting, which accounts for a significant share of electric power consumption. But, because of the growing use of improved, compact fluorescent (CF) lights in place of conventional incandescent lights, the quantity of electric power consumed for illumination purposes may decline [Lovins & Sardinsky 1988; Gadgil et al 1991]. Other examples of increased efficiency include space heating, using more efficient heat pumps ², and cooking by means of newly developed and improved microwave hot air cookers that can fry, roast or bake and thus compete with conventional gas or electric ranges.

The three main areas of potential substitution of electricity for other sources of energy are considered in more detail below. It is worth mentioning at the outset that all of these applications except air-conditioning would result in significant environmental benefits in comparison with the major alternative. The main alternative to air-conditioning, however, is lack of air conditioning. The latter requires less energy, but may have adverse health impacts on some people living in areas where summer temperatures are very high. Hot spells appear to be increasing in frequency, possibly as a consequence of climate warming. Conditions of extreme heat and humidity can also result in irritability and increased likelihood of accidents, not to mention social discord.

4.1 Space-heating/cooling (climatization). Space-heating, ventilation, air conditioning and water heating are jointly the largest energy consumers in households. It must be said immediately that the entire process, as currently practiced, is extraordinarily inefficient. Both heating and air-conditioning requirements could be cut enormously — by 90 percent or more — by utilizing better insulation in walls and, especially, through the use of high-tech double or triple windows. This technology is well-known and entails a straightforward tradeoff between construction materials for energy. As it happens, the additional costs of optimal insulation would be rapidly recovered by reduced operating costs. Unfortunately, the majority of consumers are, or appear to be, more concerned with minimizing up-front investment costs than downstream operating costs.

An extreme form of the tradeoff between capital and operating costs is underground construction, utilizing the insulation capacity of the earth itself. This concept is unlikely to
achieve wide acceptance, however, for two reasons apart from cost. One is that underground spaces are incompatible with natural ventilation (and, in many locations, there would also be a buildup of radon gas from natural decay processes in granite). More important, perhaps, is the difficulty of combining underground construction with natural daylight. Humans are not troglodytes.

Heating systems in general are also typically very inefficient. New houses and apartment buildings today generally incorporate gas-fired central heating plants without central air-conditioning. However many older houses still lack central heating. In fact, in rural areas wood-burning stoves and fireplaces are common, with electrical resistance heaters also widely used as a supplementary heat source because of their low capital cost. However, it need hardly be pointed out that wood burning results in serious winter air pollution problems in many valleys, while electrical resistance heating is inefficient and therefore unnecessarily costly.

Direct solar heating is a straightforward technology that is known to be cost-effective by itself in few locations. It requires special designs, with south-facing windows and wide overhanging eves, as well as massive internal heat storage facilities, either dry or wet. The major disadvantage is that direct solar heat can rarely be a perfect substitute for other heat sources, during extended periods of cloudy, wet or cold weather. For such periods, either fireplaces, wood-burning stoves, gas heaters, or electric resistance heaters are needed.

However, solar heating (including water heating) can be a significant enhanced by the use of heat pumps, and conversely. It is well-known that heat pumps can be several times more efficient than either resistance heaters, or gas heaters, especially if some of the resistance heat generated by the pump motor is also recovered. A current rule of thumb is that one unit of electricity can produce three units of heat by means of a heat pump, compared to one unit by means of a resistance heater. Heat pumps can be driven by electric motors or (for larger units) by diesel engines. The units can last as long as 60,000 hours, or 25 years, without maintenance.

The low temperature heat source can be either outside air or water from a well, a lake or a river, or — if combined with solar heating — from a specially designed internal heat storage unit. Water is generally preferable, since it requires a smaller heat exchanger. Of course, the water is cooled by the heat pump so it is important to operate above the freezing point, zero degrees Celsius. This is normally no problem for groundwater, which typically has a temperature of about 13 deg. C. Heat pumps are available for either closed or open loop operation with water. The former recycles the water (e.g. from a well). The latter takes water from an external source, such as a public water supply, and discharges it back into the sewers. This may be undesirable in areas where the water supply is constrained.

Air is a satisfactory heat source at typical daytime winter temperatures in much of North America (5-10 degrees C), but it becomes inefficient (essentially equivalent to a resistance heater) as outside air temperatures fall below freezing. Of course this means that an air-to-air heat pump, which is the easiest type to retrofit in an older house, is least efficient in the coldest weather when it is most needed. At very low temperatures, too, it may be necessary to use resistance heat to prevent ice buildup on the outside heat exchanger. Thus heat pumps are by far more attractive if built in, together with solar heating of water, with a suitable internal storage facility, at the time of building construction.

Air conditioning can be provided at very low marginal cost by a heat pump operated in reverse. This capability adds very little to the cost of the equipment. If groundwater is used for heat exchange, the summer use for airconditioning would warm the groundwater a few degrees, partially compensating for winter cooling. (Or a two-well system can be used with "summer" and "winter" wells).

The economics of heat pumps — with or without air conditioning — *vis a vis* other
heating systems obviously depend upon local conditions, including climate. Current installation costs for an open loop water-based system in the US (Indiana) for an average house are $8000. The closed loop system would cost about $2200 more to install. These prices can be compared to $7000 for a high-end propane furnace.\(^4\) Evidently, even the closed loop heat pump is not dramatically more expensive than a conventional furnace burning fossil fuels. Operating cost savings would make the heat pump even less costly than the conventional furnace on a life-cycle basis. Moreover, the capital cost of a heat pump can be traded off, to a significant degree, by improved insulation.

As noted, there is significant potential for combining heat pumps with solar water heating systems, or even photovoltaic solar power with heat recovery. In summer a water-cooled heat pump air conditioner could feed warm water to the water heater rather than dumping it, while a solar space heating system could raise the temperature of the external heat exchanger — and hence the efficiency of the heat pump — in winter. These possibilities have received little study, thus far, but more detailed analysis seems worthwhile.

A few recent news items are of interest:\(^5\) Recently the Norwegian Parliament instructed the government to set up a plan to introduce more heat pumps in the country, for purposes of reducing energy consumption. The city council of Christchurch N.Z. offers an incentive package with grants up to $500 to replace open fires by other systems, including heat pumps. Gothenburg, Sweden uses four large heat pumps to extract and concentrate waste heat from refineries and a municipal waste incinerator for district heating. Demand for heat pumps in Germany grew 40% in 1997 over the previous year. In Switzerland one out of every three new buildings now includes a heat pump.

The enhanced value of services to consumers is clear. In the first place, heat pumps are much more energy-efficient than any alternative source of space heating. This would translate into real monetary savings for most households. Second, the option of air-conditioning at very little extra capital cost is also attractive for some households, at least. Third, and very important, the increased use of heat pumps in place of wood burning stoves or fossil fuel burning furnaces would significantly reduce both local air pollution (especially smoke, but also other pollutants such as carbon monoxide and nitrogen oxides, NO\(_x\)) and the emission of greenhouse gases contributing to global warming, notably carbon dioxide (CO\(_2\)).

### 4.2 Microwave cooking

Up to now microwave cooking has been largely limited to `fast foods' and frozen foods. Thus the microwave oven is an add-on to the average kitchen, rather than a major alternative to conventional methods of cooking. The reason is that, while it is much faster and more energy-efficient than conventional cooking (because no energy is wasted heating water, crockery and pans, or the oven itself) it heats the `object' uniformly. It is, however, unsuited to the majority of types of cooking. Up until now, it has not been possible to use microwaves to simulate non-uniform "outside-in" methods of cooking, such as toasting, pan-frying, roasting, broiling or baking. In particular, it has not been possible to make foods crisp.

Combination units have been available for some time, combining microwave cookers with conventional resistive heating elements (electric grill) and convective hot-air units for baking. However this combination is mainly a space-saver.

The fundamental disadvantage of all conventional heating elements, whether electric or gas-fired, is that they heat everything within range, which takes time and costs energy. They also generate significant indoor air pollution. The first problem has been overcome by a more sophisticated design pioneered by Whirlpool Corp.\(^6\) The new prize-winning system utilizes a combination of forced air convection with a quartz plate like a frying pan located on the roof of the oven. This grill element absorbs microwave energy and reaches a temperature of 200
deg. C in about 2 minutes. Like most new units it can be programmed for different types of food and degrees of crispness. For instance, for meat the crust can be created (by searing) at the beginning to prevent loss of juices. On the other hand, for bread and pastry the crust can be created at the end to prevent water vapor in the air from being reabsorbed to make the product soggy.

In short, a sophisticated programmable microwave system with the whole range of capabilities is now available for both homes and restaurants. In a few years, as the news spreads and costs come down, the new technology can replace the existing gas stove and oven, as well as the existing electric stove, grill and microwave oven, not to mention the large number of stainless steel, aluminum or cast iron pans found in the average kitchen. (All of these cooking utensils will eventually be replaced by ceramics, glass or so-called engineering plastics).

This development constitutes a significant cost saving for domestic consumers. It will save significantly on the use of fossil fuels, even though it will also increase electricity consumption somewhat. Second, it will save time. And, third, it can sharply reduce householders exposure to certain types of indoor air pollution from cooking, especially particulates (smoke) from frying over open burners.

4.3 Rooftop PV. The declining costs of PV have been noted already. The chief drawback for rooftop PV as a substitute for central-station power is energy storage. This technology is currently being pushed by would-be developers of electric vehicles (EVs). However, even the most efficient storage batteries under development or under consideration (Li-Cl) would only store about 400 watt-hr per kg at 100 watts/kg specific power output. The highly touted nickel-metal hydride (NiMH) battery would store about 55 watt-hr at 100 watts/kg of power output. This is already a great improvement over lead acid batteries, of course. But the EV developers essentially all agree that the future belongs to either sodium sulfur or lithium ion batteries, either of which would increase performance by another 50 percent or so. However, this is probably the outer limit and such batteries will not be fully developed for at least several more years, even if the EV market grows rapidly.

A possibility that looks attractive technologically, but has received virtually no attention to date for the built environment, would be local energy storage in large structures, or even suburban neighborhoods, by means of high speed flywheels using modern high-tech materials. The use of flywheels has been promoted as a means of energy storage in heavy vehicles, such as buses, but essentially discarded for safety reasons. However, the safety problems would be much less severe if counter-rotating horizontal flywheels were confined in sealed, evacuated underground chambers. Facility for rapid stored energy dissipation in case of emergency, by flooding with water and release of energy as steam, (through a stack) could easily be made part of such a system.

5. Summary

The materials used in structures are, (local problems notwithstanding), relatively inert and not especially hazardous to the environment in extraction, use, or in disposal. Some non-trivial pollution problems are associated with the extraction and processing of metals, and chemicals. However, many of these problems are already being addressed. Moreover, sharply increased recycling of most metals seems both feasible and environmentally beneficial. The major unresolved problems are associated with dissipative materials used for purposes of
maintenance, and some construction materials, especially plastics like PVC that are hard to recycle.

The major opportunities for reducing environmental damages associated with the construction sector and the built environment, by far, are to be found in reducing fossil fuel energy consumption, both directly (for space heating, water heating and cooking), and indirectly for electricity generation. (The latter possibility is not discussed in the paper).

Fortunately, the technological potential for reducing the use of fossil fuels in the built environment is extremely promising, especially given the existing trend on the demand-side toward electrification of all non-mobile energy services. Specific examples include the increasing use of heat-pumps and microwave cooking. Another specific opportunity can be found on the supply side, notably the widespread application of rooftop photovoltaic (PV) systems.

All of these technological changes could be accelerated by a variety of government policy measures. However, this set of issues is not discussed in this paper.

References


Endnotes

1. Luckily, more and more arsenic is being used to make gallium arsenide for the electronics industry, thus reducing the supply available for pesticides and wood preservatives. Again, it is fortunate that nickel-cadmium batteries are now taking up most of the available supply. These batteries can be recovered and recycled, although this is not yet happening on a significant scale.

2. In the early post-war period electric utilities in the US actively encouraged consumer ‘electrification’ by cooperating with appliance manufacturers to advertise and demonstrate ‘electric kitchens’ and other appliances.

3. One of the major research projects on heat pumps is (or was) at the Centre des Etudes Nucleaires in Grenoble.


6. Cuthbertson, Ian. "Ian Cuthbertson Weighs Up Microwave Ovens" *Nationwide News Proprietary Ltd.* Australia, 9 M The most important advantages of EVs, apart from energy efficiency are silence and zero emissions. (In fact, silence could be a safety issue). It was the emissions that prompted the California State Legislature to mandate that 2 percent of motor vehicles sold in the state in 1998 should be zero emissions vehicles, which meant, in practice, electric vehicles or EVs. Moreover, similar laws have been adopted by New York State and Massachusetts. The California mandate was recently reduced to 1 percent and delayed to 2003 and Massachusetts agreed, but as of late 1997 New York had not (yet) accepted any change or delay. A slightly different and less "hard line" approach has been taken in Europe, but with potentially similar impact. The Zero Emission Urban Society (ZEUS) project has initiated extended tests of EVs in several European cities. The Alternative Traffic in Towns (ALTER) project is an initiative launched by the transport and environment ministers conference of the EU. Six cities (Athens, Barcelona, Florence, Lisbon, Oxford and Stockholm) have agreed to set aside special areas from which all but ZEVs will be excluded. These may be historical city centers or sensitive areas. These cities will start to renew their bus and service fleets with ZEVs. There was a conference in October 1998 in Florence to which all 1400 cities in the EU were invited to consider joining the project. I do not know the most recent developments, however.

### TABLE I: RECYCLING SAVINGS MULTIPLIERS (tons/ton product)

<table>
<thead>
<tr>
<th>Iron/steel</th>
<th>Aluminum</th>
<th>Copper</th>
<th>Lead</th>
<th>Zinc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore percent</td>
<td>52.8% Fe</td>
<td>17.5% Al</td>
<td>0.6% Cu</td>
<td>9.3% Pb</td>
</tr>
<tr>
<td>Major source</td>
<td>[USS 1971]</td>
<td>[Parsons 1977]</td>
<td>[Gaines 1980]</td>
<td>[PEDCo-Pb 1980]</td>
</tr>
<tr>
<td>Energy Used (gJ/t)</td>
<td>22.4</td>
<td>256</td>
<td>120</td>
<td>30</td>
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<tr>
<td>Water Flow in/out (t/t)</td>
<td>79.3</td>
<td>10.5</td>
<td>605.6</td>
<td>122.5</td>
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</table>

**Material Inputs**

<table>
<thead>
<tr>
<th>Air</th>
<th>Solids</th>
<th>Total Material Inputs</th>
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</thead>
<tbody>
<tr>
<td>1.9</td>
<td>17.3</td>
<td>19.2</td>
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<tr>
<td>0.3</td>
<td>11.0</td>
<td>11.2</td>
</tr>
<tr>
<td>1.6</td>
<td>612.1</td>
<td>613.7</td>
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<tr>
<td>4.4</td>
<td>126.2</td>
<td>130.5</td>
</tr>
<tr>
<td>5.8</td>
<td>55.8</td>
<td>61.6</td>
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</table>

**Material Outputs**

<table>
<thead>
<tr>
<th>Product</th>
<th>Byproducts</th>
<th>Depleted air</th>
<th>CO2</th>
<th>SOX</th>
<th>Other gaseous material</th>
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<tbody>
<tr>
<td>0</td>
<td>0.2</td>
<td>1.5</td>
<td>0.5</td>
<td>0.01</td>
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<tr>
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<td>0.2</td>
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<td>1.2</td>
<td>0.03</td>
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<td>0.03</td>
<td>2.4</td>
<td>0.01</td>
<td>0.01</td>
<td>0.03</td>
</tr>
<tr>
<td>Category</td>
<td>Potential recycle</td>
<td>Overburden</td>
<td>Gangue</td>
<td>Other solid material</td>
<td>Sludges, liquids</td>
</tr>
<tr>
<td>------------------------</td>
<td>-------------------</td>
<td>------------</td>
<td>-------------</td>
<td>----------------------</td>
<td>-----------------</td>
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<tr>
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<td></td>
<td></td>
<td>37.3</td>
<td>16.3</td>
<td>0.1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

**Notes:**

- **Major byproducts** include SO₂ used for sulfuric acid production and saleable offgas.
- **Depleted air** = air from which all oxygen has been taken for combination with other materials.
- **Potential recycle** includes slag, scrap etc. potentially usable in the process chain, but not used.
- **Overburden** = That portion of solid material extracted during the mining process which is not part of the ore.
- **Gangue** = That portion of the ore extracted during beneficiation which is not part of the concentrate.
- **Sludges and liquids** do not include dilution water.

Source for aggregate energy values: [Forrest & Szekeley 1991]. The materials/energy costs of producing this energy are not considered in this table.

Source for water flow values: [Lübkert et al 1991]

Source for overburden & gangue percentages: [Adriaanse et al 1997]

Other sources used: [Battelle 1975; Bolch 1980; Davis-Cu 1972; Davis-Zn 1972; Davis et al 1971; Forrest & Szekeley 1991; Lowenbach et al 1979; Lübkert et al 1991; McElroy & Shobe 1980; Masini & Ayres 1996; PEDCo-Cu 1980; Thomas 1977; Watson & Brooks 1979]
Figure 1

5 construction materials: production & apparent consumption
Mass/capita; USA 1900-1995

steel, lumber, cement, bricks & gypsum

Production

Apparent consumption
Production: Plastics & Aluminum
Mass/capita; USA 1900-1995

Figure 2
Production: Lumber compared to aluminum plus plastic
Mass/capita; USA 1900-1995

Figure 3
Scrap consumption in iron & steel production is probably underestimated by up to 4 million tonnes. Recirculated scrap may be underestimated by a similar amount.

Figure 4: Mass flows in the US iron and steel sectors, 1993 (MMT)
Figure 5: Mass flows in the US non-ferrous metals sector, 1993 (MMT)
Figure 6: PV mean module prices
Energy consumption: Electrolux refrigerators (Swedish models)

Source: Electrolux

Figure 7: Energy consumption by Electrolux refrigerators; Sweden, 1958-1993
1. Luckily, more and more arsenic is being used to make gallium arsenide for the electronics industry, thus reducing the supply available for pesticides and wood preservatives. Again, it is fortunate that nickel-cadmium batteries are now taking up most of the available supply. These batteries can be recovered and recycled, although this is not yet happening on a significant scale.

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5. All news items taken from *Reuters "Business Briefings"* Spring, 1998.


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