VACLAV SMIL

MATERIALS AND DEMATERIALIZATION

MAKING THE MODERN WORLD

WILEY

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Preface: Why and How

The story of humanity – evolution of our species, the prehistoric shift from foraging to permanent agriculture, rise and fall of antique, medieval and early modern civilizations, economic advances of the past two centuries, mechanization of agriculture, diversification and automation of industrial protection, enormous increases in energy consumption, diffusion of new communication and information networks and impressive gains in quality of life – would not have been possible without an expanding and increasingly intricate and complex use of materials. Human ingenuity has turned materials first into simple clothes, tools, weapons and shelters, later into more elaborate dwellings, religious and funerary structures, pure and alloyed metals, and in recent generations into a still increasing variety of designs, machines and extensive industrial and transportation infrastructures, megacities, even as silicon, doped with small amounts of other elements, has been turned into substrate for solid-state devices that have enabled the new electronic world.

This material progress has not been a linear advance but it consisted of two unequal periods. First was very slow rise that extended from prehistory to the beginnings of rapid economic modernization, that is until the 18th century in most of Europe, until the 19th century in the US, Canada and Japan, and until the latter half of the 20th century in most of Asia. An overwhelming majority of people lived in those pre-modern societies with only limited quantities of simple possession that they made themselves or that were produced by artisanal labor as unique pieces or in small batches – while the products made in larger quantities, be they metal objects, fired bricks and tiles or drinking glasses, were too expensive to be widely owned.

The principal reason for this limited mastery of materials was the energy constraint: for millennia our abilities to extract, process and transport biomaterials and minerals were limited by the capacities of animate prime movers (human and animal muscles) aided by simple mechanical devices and by only slowly improving capabilities of the three ancient mechanical prime movers, sails, water wheels and wind mills. Only the conversion of chemical energy in fossil fuels to inexpensive and universally deployable kinetic energy of mechanical prime movers (first by external combustion of coal to power steam engines, later by internal combustion of liquids and gases to energize gasoline and Diesel engines and, later still, gas turbines) brought a fundamental change and ushered in the second, rapidly ascending, phase of material consumption, an era further accelerated by generation of electricity and by the rise of commercial chemical syntheses producing an enormous variety of compounds ranging from fertilizers to plastics and drugs.

As a result, the world has become divided between the affluent minority that commands massive material flows and embodies them in long-lasting structures as well as in durable and ephemeral consumer products – and the low-income majority whose material possessions amount to a small fraction of material stocks and flows in the rich world. Now the list of products that most of the Americans claim they cannot live without includes cars, home air conditioning, microwave ovens, dishwashers, garburators, clothes dryers, home computers and mobile phones (Taylor et al. 2006; Langlois 2020) – and they have forgotten how recent many of these possessions are because 60 years ago many of them were rare or nonexistent. In 1960 fewer than 20% of all US households had dishwasher, clothes dryer or air conditioning, first color TVs had just appeared, and (before the first microprocessors were made in 1971) there were no personal computers, mobile phones and other portable electronic devices – and also no SUVs (they began their rise to market dominance only during the late 1980s).

In contrast, those have-nots in low-income countries who are lucky to have their own home often live in a poorly-built small earthen brick or wooden structure with as little inside as a bed, a few benches and cooking pots and some worn clothes. Those readers who have no concrete image of this great material divide should look at Peter Menzel's *Material World: A Global Family Portrait* where families from 30 nations were photographed in front of their dwellings amidst all of their household possessions (Menzel 1995). The book was published nearly three decades ago, and during the intervening time hundreds of millions of people (mostly in Asia) have been lifted from the deepest poverty to a more dignified existence, but its message still resonates. The latest World Banka data show that by the early 2020s large shares of national populations in Asia (about 20% in India, Bangladesh and Pakistan) and Africa (40% in Nigeria, 60% in Congo) still live below poverty line, beyond the reach of adequate material consumption (World Bank 2022a).

And this private material contrast has its public counterpart in the gap between extensive and expensive infrastructures of the rich world (transportation networks, functioning cities, agricultures producing large food surpluses, largely automated manufacturing) and their inadequate and failing counterparts in poor countries. These contrasts make it obvious that a further substantial material mobilization and transformation will be needed just to narrow the gap between these two worlds. And an even larger demand for old and new materials will arise from the unfolding energy transition.

The world's primary energy supply remains dominated by fossil fuels (they provided 86% of all primary energy in 2000 and still 83% in 2020) and a new (as yet uncertain) pattern will emerge during the coming decades, consisting of a mixture of electricity generated without carbon combustion (mostly by wind turbines, photovoltaic cells and nuclear reactors), biofuels and (much more importantly) fuels produced by using non-carbon electricity (for electrolysis to make hydrogen used directly for combustion or in fuel cells and in ammonia synthesis) or (less likely) by syntheses relying on carbon from captured CO_2.

And new energy converters necessarily accompanying this transition – ranging from electric vehicles and other means of transportation relying on batteries to heat pumps and new ways of energy uses by industries (with electricity displacing direct fuel combustion – will create further substantial material needs, including much higher demand for cobalt, copper, lithium and nickel as well as new substantial demand for steel, aluminum and cement needed for requisite infrastructures (ranging from new high voltage lines to water electrolysis, and from massive wind turbine foundations to new hydrogen pipelines).

This new demand surge will only intensify a truly global extent of environmental pollution and degradation resulting from extraction, processing and use of materials and it will involve some unprecedented challenges. As for the extraction, even the last intact domain, deep ocean floor, will see considerable amount of activity before 2050 and at the opposite end of the chain we will have to come up with new, effective ways of recycling and disposal of hundreds of thousands of massive plastic blades (some are now longer than 100 m), millions of PV panels and hundreds of millions of discarded vehicular batteries. In the absence of such measures our use of indispensable materials would pose even more worrisome threats on scales ranging from local degradation and contamination to concerns about the integrity of the biosphere.

These impacts also raise the questions of analytical boundaries: their reasoned choice is inevitable because including every conceivable material flow would be impractical and because there is no universally accepted definition of what should be included in any fairly comprehensive appraisal of modern material use. This lack of standardization is further complicated by the fact that some analyses have taken the maximalist (total resource flow) approach and have included every conceivable input and waste stream, including waste flows (sometimes called hidden flows) associated with the extraction of minerals and with crop production as well as oxygen required for combustion and the resulting gaseous emissions and wastes released into waters or materials dissipated on land.

In contrast, other studies have restricted their accounts to much more reliably quantifiable direct uses of organic and inorganic material inputs that are required by national economies. I will follow the latter approach, as I will focus in some detail on key materials consumed by modern economies, an approach easily justified by their magnitude or their irreplaceable properties. Their huge material claims lead us to ask a number of fundamental questions. How much further will the affluent world push its already often excessive material consumption? To what extent is it possible to divorce economic growth and improvements in average standard of living from increased material consumption – in other words, how far we can push relative dematerialization?

This reduction in the use of materials is most often expressed per unit of product (standard soft drink aluminum can gets lighter) or per unit of economic output (less copper or steel is needed per unit of GDP), and it has been a common phenomenon that has been well documented in sectors ranging from construction to transportation and with products ranging from small consumer items to large high-bypass jet engines. Ultimately, relative dematerialization runs into fundamental physical limits: a standard soft drink container cannot be made to weigh just one gram, and the law of conservation of mass requires that in every chemical synthesis the total mass of the reactants must equal the total mass of products. For example, ammonia synthesis requires a molecule of nitrogen and three molecules of hydrogen to produce two molecules of NH_3 ($N_2 + 3H_2 \rightarrow 2NH_3$) and this means that to synthesize one ton of ammonia we will always need 176.47 kilograms of hydrogen, no more but no less.

Synthesis of ammonia cannot be decoupled from hydrogen, but the use of nitrogenous fertilizers per unit of harvest can be reduced by improving the rate of their uptake by crops (a difficult task to do since the compounds are subject to leaching, volatilization and denitrification). The only way to uncouple it completely would be to endow cereal and oil and sugar crops with the ability to supply their own nitrogen as legumes do in symbioses with nitrogen-fixing bacteria – but this is not coming anytime soon to wheat or sunflower field near where you live. The more realistic dematerialization questions in food production are thus to ask to what extent we can limit the use of fertilizers by growing less feed for animals and eating less meaty (and less dairy-rich) diets, and how much we can reduce the current, unacceptably high but persisting, level of food losses?

But before I get to answer such questions in convincing manner, I must review first the evolution of human material uses, describe all the principal materials, their extraction and production and their dominant applications, and take a closer look at the evolving productivities of material extraction, processing, synthesis, finishing and distribution and at the energy costs and environmental impact of rising material consumption. And as always in my books, I will not offer any time-specific forecasts regarding the future global and national use of materials. Instead, I will look at possible actions that could reduce our dependence on materials while maintaining good quality of life and narrowing the gap between affluent and low-income economies.

We must realize that in the long run even the most efficient production processes, the least wasteful ways of design and manufacturing and (for those materials that can be recycled) the highest practical rates of reuse may not be enough to result in absolute dematerialization rates that would be high enough to negate the rising demand for specific materials generated by continuing population growth, improving standards of living and universal human preferences for amassing possession. And any dreams of circular economy are just that: we should strive for maximum practicable rates of recycling and reuse but it is impossible to have a closed global material economy akin to the reuse of carbon, nitrogen and sulfur by grand global biogeochemical cycles. This makes it highly likely that in order to reconcile our wants with the preservation of biosphere's integrity we will have to make deliberate choices that will help us to reduce absolute levels of material consumption and thereby redefine the very notion of modern societies whose very existence is predicated on incessant and massive material flows.

1

What Gets Included

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Any study aiming to elucidate the complexity of material flows of modern societies, their prerequisites, and their consequences should be as comprehensive as possible and its coverage should be truly all-encompassing. But this easily stated aspiration runs immediately into the key categorical problem: what constitutes the complete set of modern material uses? There is no self-evident choice, no generally accepted list,

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only more or less liberally (and also more or less defensively) defined boundaries of a chosen inclusion, a reality best illustrated by reviewing the selections made by the past comprehensive studies and adopted by leading international and national databases of material flows.

The first comparative study of national resource flows (Adriaanse et al. 1997), subtitled *The Material Basis of Industrial Economies*, excluded water and air but included all agricultural harvests (not just raw materials but all food and feed as well), all forestry products, aquatic catches, extraction of minerals, and fossil fuels but also hidden (waste) flows accounting for extraction, movement, or losses of materials that create environmental impacts but have no acknowledged economic values. These hidden flows are dominated by overburden materials (soil and rocks that have to be removed before reaching mineral deposits, obviously most massive with open-cast coal and ore mining), processing wastes (particularly tailings, massive flows associated with separation of relatively rare metals from rocks), soil, sand, and rocks that have to be removed and shifted during large construction projects, and soil erosion originating from fields and permanent plantations.

Waste flows are not monitored, their quantification is, at best, a matter of approximate estimates, more often of just informed guesses – but their volume and mass have been increasing, both because we have been exploiting minerals in deeper overcast mines (more massive overburden) and because we require more metals (from Co to Zn) whose ores are not as rich as the ores that we extract to produce the world's two dominant metallic materials, iron and aluminum. While hematite, the most commonly exploited iron ore, contains 50–60% of the metal (when pure it is about 70% Fe) and bauxite (the only commercially exploited aluminum ore) contains 15–25% aluminum, copper ores that dominate the metal's extraction in the early 2020s have only 0.3–1.7% Cu, and in Chile, the world's largest producer, they average 0.6% Cu (Schlesinger et al. 2022). Mass of materials wasted during the extraction phase is thus roughly equal to iron's output, it is as much as nearly seven times larger than the production of aluminum, and it is about 170 times larger than the output of Chilean copper.

Thanks to the coming mass-scale electrification of transport and of many industries, it will be copper whose production will grow faster than any other of the five metals now produced in largest quantities (Fe, Al, Cu, Zn, Pb). Uncertainties about mass flows are even greater with the annual totals for hidden flows associated with imported raw materials: obviously, this reality will make the greatest difference in the case of large affluent economies that import a wide range of raw materials, including precious metals, from scores of countries. For example, in 2020 US imports of gold, silver, platinum, and diamonds equaled 3.4% of all purchases abroad, a share three times as high as the imports of integrated circuits (OEC 2022). But that gold came mostly from Switzerland, an intermediate source whose gold imports come mostly from other intermediaries (Hong Kong, UAE, Thailand, UK), making it exceedingly difficult to trace the flow to its origin in order to determine the total mass of waste flows behind these transactions.

Not surprisingly, Adriaanse's study resorted to using worldwide averages for these calculations: for example for overburden it applied the rate of 0.48 t for a ton of bauxite and 2 t per ton of iron ore, global generalizations that must result in considerable errors when used as national averages. Soil erosion rates are even more variable, their detailed national studies are rare, annual soil losses (depending on precipitation, extent of drought periods, wind speed, cultivation methods, deforestation) can differ by up to an order of magnitude even within relatively small regions, and yet the study used only the rates derived from the US inventory. Another highly uncertain inclusion was quantifying the mass of grass grazed by cattle (other animal feed was included in crop harvests): obviously an average Maasai cow in Kenya will consume only a fraction of grasses digested every year by beef cattle in Alberta or Colorado.

Three years after this first comparative study came another project led by the World Resources Institute (WRI), *The Weight of Nations* (Matthews et al. 2000). That study presented material flows for the four nations included in the original work (US, Japan, Germany, and the Netherlands) as well as for Austria and that extended the accounting period from 1975 to 1996 (the original ended in 1993). Its subtitle, *Material Outflows from Industrial Economies*, indicated the report's concern with outputs produced by the metabolism of modern societies. As its predecessor, this study included all fossil fuels, estimates of hidden material flows (dominated by the removal of overburden in surface coal mining), as well as the totals of all processing wastes.

The report had also quantified earth moved during all construction activities (highway, public, and private and also for dredging), soil erosion losses in agriculture and waste from synthetic organic chemicals and from pharmaceutical industry. But unlike the original study, the 2000 report also includes data on additional inputs (oxygen in combustion and in respiration) and outputs, including the total output of CO_2 from respiration and water vapor from all combustion and it separates waste streams into three gateways, air, land and water. The air gateway quantified gaseous emissions (CO_2, CO, SO_x, and NO_x, volatile organic carbohydrates) including oxygen from all combustion, the outputs to land include municipal solid waste, industrial wastes, and dissipative flows to land (manure, fertilizers, salt spread on roads, worn tire rubber, evaporated solvents), and water outputs trace organic load and total nitrogen and phosphate burdens.

Eurostat has been publishing annual summaries of domestic material consumption for all EU countries since the year 2000, disaggregating the total flows into fossil fuels, biomass (crops and forest products), metal ores, and nonmetallic minerals (Eurostat 2022a). Eurostat's methodological guides for economy-wide material flow accounts offer detailed procedures for the inclusion of biomass (food, feed, fodder crops, grazed phytomass, wood, fish, hunting, and gathering activities), metal ores, and nonmetallic minerals and for all forms of fossil fuels as well as for all dissipative uses of products, including organic and mineral fertilizers, sewage sludge, compost, pesticides, seeds, road salt, and solvents (Eurostat 2018).

Eurostat aggregates also include unused materials (mining overburden, losses accompanying phytomass production, soil excavation, dredging, and marine by-catch) and quantify emissions (CO_2, water disposal, and landfilled wastes) but leave out oxygen and water. The latest compilations at the time of writing, for the year 2021 (Eurostat 2022a), show the expected recovery from the Covid-induced lows of 2020 and equally expected long-term decline in the EU's fossil fuel extraction (down to about 1.1 Gt from just over 1.5 Gt in 2012) but continued growth in the mobilization of nonmetallic minerals (about 3.3 Gt in 2021 compared to 2.9 Gt in 2012). OECD publishes annual estimates for its 34 member states and for 170 other countries and city states, with some data going back to 1970. These totals include domestic consumption of all materials originating from natural resources and forming the bases of economies: all metals, nonmetallic minerals, biomass (wood and food), and fossil fuels (OECD 2022).

In 1882, the US Congress mandated annual collection of statistics for mineral commodities produced and used in the country. The US Geological Survey became the first agency responsible for this work, then the US Bureau of Mines and since 1995 the task reverted to the USGS. This statistics were the basis for preparing the first summary of America's material flows aggregated by major categories and covering the period between 1900 and 1995 (Matos and Wagner 1998). The series was subsequently extended and by 2022 updates for most commodities are available until 2018–2019 (Matos 2009; Kelly and Matos 2016 with updates). The latest data on individual elements, compounds, and materials are updated annually in *Mineral Commodity Summaries* (USGS 2022a).

The USGS choice of items included in its national material accounts is based on concentrating only on the third class of the material triad by leaving out food and fuel and aggregating only the materials that are used in all branches of the economy. The series offers annual totals for domestic production, exports, imports, and domestic consumption; it excludes water, oxygen, hidden material flows, and all fossil fuels; and it includes all raw materials produced by agricultural activities (cotton, seeds yielding industrial oil, wool, fur, leather hides, silk, and tobacco), materials originating in forestry (all kinds of wood, plywood, paper, and paperboard), metals (from aluminum to zinc), an exhaustive array of nonmetallic minerals (be they extracted in their natural form, such as gypsum, graphite, or peat, processed before further use, such as crushed stone or cement or synthesized, such as ammonia), and nonrenewable organics derived from fossil fuels (asphalt, road oil, waxes, oils, and lubricants and any variety of solid, liquid, or gaseous fossil fuel used as feedstocks in chemical syntheses).

Very few of these inputs are used in raw, natural form as virtually all of them undergo processing (cotton spinning, wood pulping, ore smelting, stone crushing or cutting, and polishing) and, in turn, most of these processed materials become inputs into manufacturing of semifinished and finished products (cotton turned into apparel, pulp into paper, smelted metals into machine parts, crushed stone mixed with sand and cement to make concrete). This compilation of agriculture- and forestry-derived products, metals, industrial minerals, and nonrenewable organics gives a fairly accurate account of annual levels and long-term changes in the country's material flows. While all imports and exports of raw materials are accounted, the series does not include materials that were contained in traded finished goods: given their mass and variety their tracking would be very difficult.

Where does this leave us? Those material flow studies that conceive their subject truly *sensu lato*, as virtually any substance used by humans, include everything with a notable exception of water, that is not only biomaterials used in production of goods, all metals, nonmetallic minerals, and organic feedstocks but also all agricultural phytomass (harvested food and feed crops, their residues, forages, and grazed plants), all (biomass and fossil) fuels and oxygen needed for combustion. Slightly more restrictive studies exclude oxygen and all food and feed crops, and they consider only those agricultural raw materials that undergo further processing into goods but include all phytomass and fossil fuels. In contrast, the USGS series exemplifies a *sensu stricto* approach as it includes only raw biomaterials used for further processing and as it excludes oxygen, water, all fuels (phytomass and fossil), and all hidden (and always tricky to estimate) material flows. My preferences for setting the analytical boundaries are almost perfectly reflected by the USGS selection but instead of simply relying on that authority I will briefly explain the reasons behind my exclusions.

Leaving out oxygen required for combustion of fuels is a choice easily defensible on the basis of free supply of a virtually inexhaustible atmospheric constituent. Claims about danger of serious O_2 depletion through combustion were refuted long time ago (Broecker 1970; Liu et al. 2019). Complete combustion of 1 kg of carbon consumes 2.67 kg of oxygen and burning of 1 kg of methane (CH_4), the simplest hydrocarbon, requires 4 kg of O_2. This means that in 2021 the global combustion of more than 11 Gt of fossil carbon (as coal, refined oil products, and natural gas) claimed about 40 Gt of O_2 (Liu et al. 2019) – or about 0.0027% of the atmosphere content of 1.5 Pt of the gas. Even a complete combustion of generously estimated global resources of fossil fuels (a clear impossibility, just a theoretical consideration) would lower the atmospheric O_2 content by no more than 2%.

There is thus no danger of any worrisome diminution of supply (to say nothing of exhaustion) of the element, and yet once the choice is made to include it in material flow accounts, it will dominate the national and global aggregates. For example, as calculated by the comparative WRI study, oxygen was 61% of the direct US processed material output in 1996, and in Japan in the same year the element's share was 65% (Matthews et al. 2000). Consequently, magnitudes of national material flows that would incorporate oxygen needs would be nothing but rough proxies for the extent of fossil fuel combustion in particular economies.

Reasons for excluding waste flows from the accounts of national material flows are no less compelling: after excluding oxygen they would dominate total domestic material output in all countries that have either large mineral extractive industries (especially surface coal and ore mining) or large areas of cropland subject to soil erosion. They are dominated by unusable excavated earth and rocks, mine spoils, processing wastes, and eroded soil, while earth and rocks moved around as a part of construction activities will make up a comparatively small share. Not surprisingly (after excluding oxygen), in the WRI analysis these hidden flows accounted for 86% of the total domestic material output in both the United States and Germany, but with much less mining and with limited crop cultivation, the rate was lower (71%) in Japan (Matthews et al. 2000).

Daily flow of materials a large copper mine illustrates the cumulative immensity of these waste flows (GRID 2017). Two-thirds of the 270,000 t of solid rock dug out daily (180,000 t) are dumped directly, while the processing of 90,000 t of ore requires 114,000 t of water and it yields 1,750 t of concentrate ready for smelting. Just over 200,000 t (88,250 + 114,000) of material are tailings retained behind dams that must be large enough to accommodate this waste flow for some two decades of operation: when the mine is closed, it leaves behind some 1.3 Gt of waste rock and more than 600 Mt of solid tailings, nearly 2 Gt of material that can be never recycled and that is most unlikely to be reused in any other way.

But the principal problem with the inclusion of hidden flows is not their unsurprising dominance of domestic output of materials in all large, diversified economies, but the indiscriminate addition of several qualitatively incomparable flows. Unusable mass of stone left in a quarry after it ceased its operation may be no environmental burden, not even an eyesore. Moreover, once the site is flooded to create an artificial lake those waste flows may become truly hidden as a part of a new and pleasing landscape. On the other hand, bauxite processing to extract alumina (to give one of many possible common examples) leaves behind toxic waste (containing heavy metals) that is also often slightly radioactive and acidic and its worst recent accidental release (in 2010 when about 1 Mm^3 spread over an area of some 40 km^2 in northern Hungary, killing 10 people and injuring 120) can cause serious long-term environmental damage (Gelencsér et al. 2011).

And no less fundamental is the difference between in situ hidden flows generated by mineral extraction (abandoned stone, gravel, and sand quarries, and coal and ore mines with heaps, piles, layers or deep holes or gashes full of unusable minerals or processing waste) and by rain- and wind-driven land erosion that transports valuable topsoil or desert sand not just tens or hundreds but as much as thousands of kilometers downstream or downwind. The first kind of hidden flows may be unsightly but not necessarily toxic and its overall environmental impacts beyond its immediate vicinity may be negligible or nonexistent.

In contrast, surface erosion is globally important, often regionally highly worrisome and locally devastating process that reduces (or destroys) the productivity of crop fields, silts streams, contributes to eutrophication of fresh and coastal waters, creates lasting ecosystemic degradation and substantial economic losses, or drives large masses of fine dust right across the Atlantic Ocean carrying persistent organic pollutants, metals, and microbes to the Caribbean (Garrison et al. 2006) or deposits Saharan dust over the Alpine snow (Di Mauro et al. 2018). In any case, magnitudes of these associated flows and their often undesirable environmental impacts dictate that they should not be ignored when analyzing particular extractive or cropping activities: as long as we remember that the flows cannot be quantified with high accuracy, we should try to include them in specific analyses of future material demand (I will return to this point when assessing material needs of the unfolding energy transition).

My reasons for excluding water are based on several considerations that make this indispensable input better suited for separate treatment rather than for inclusion into total material requirements of modern economies. The most obvious reason is, once again, quantitative: with the exception of desert countries, water's inclusion would dominate virtually all national material flow accounts and it would misleadingly diminish the importance of many inputs whose annual flows are a small fraction of water withdrawals but whose qualitative contribution is indispensable. For example, in 2015 (the date of the latest detailed nationwide USGS estimate), the total water withdrawals in the United States were about 445 Gt, while all materials directly used by the country's economy (the total dominated by sand, gravel, and stone used in construction) added up to less than 1% of the withdrawn water mass (USGS 2018).

At the same time, there are fundamental qualitative differences between these two measures that make any direct comparisons highly misleading. The most voluminous water withdrawal in the United States (accounting for 41% of the total in 2015), that of cooling water for thermal electricity-generating stations, is not a consumptive use: a small part of that flow is evaporated to become available later (downwind, after condensation and precipitation) and most of that water becomes available almost instantly after it is discharged (slightly warmed) for further downstream uses. In contrast, materials that become embedded in long-lasting structures and products are either never reused or are partially recycled only after long period of being out of circulation.

And most of the second most voluminous water use in the United States (37% used for irrigation), is also nonconsumptive: all but a tiny fraction of the irrigation water is evaporated and transpired by growing plants, and (as with the cooling water) after re-entering the atmosphere it is eventually condensed again and it is precipitated, often after a long-distance transport downwind. And if the inclusions of water were driven by resource scarcity concerns, then a critical distinction should be made between water supplied by abundant precipitation and water withdrawn at a high cost from deep and diminishing aquifers that cannot be replenished on a civilizational time scale.

At this point it might be useful to note yet another (comparatively minor) problem with aggregate measures of material flows that is usually neglected by the assemblers of national and global accounts, namely that of water content of sand and of harvested biomass. Even when looking just at those biomaterials that are used as industrial inputs, their water content is from less than 15% for raw wool to more than 50% for freshly cut tree logs (the range is wider for food crops, ranging from only about 5% for some seeds and less than 15% for harvested cereal grains to more than 90% for fresh vegetables).

Freshly excavated sand can contain more than 30% of water, purified sands have 15–25% of moisture, storage in drainage bins reduces that level to about 6% and drying in rotary bins or in fluidized bed dryers expels all but about 0.5% of moisture for sands used in such processes as steel castings or hydraulic fracturing under pressure. Moreover, sand used in hydraulic fracturing is also coated with resins reinforced with nanomaterials in order to alter its surface wetting properties, crush strength, and chemical resistance. The best solution would be to report the masses of any moisture-containing materials in terms of absolutely dry weight in order to make their flows comparable to those of materials that contain no moisture. This is not the case in practice, and hence all national material aggregates contain far from negligible shares of water.

Foodstuffs and fuels are obviously indispensable for the survival of any civilization, and their flows have been particularly copious in modern high-energy societies enjoying rich and varied diets, while traditional biofuels remain important in many low-income countries. Moreover, unlike with water or oxygen, their inclusions would not dwarf all other material flows combined: for example, even in the fuel-rich United States, the mass of annually consumed coal, crude oil, and natural gas is equal to about 50% of all non-energy minerals. So why to leave them out? Exclusion of food and fuel is justified not only because these two large consumption categories have been traditionally studied in separation (resulting in rich literature on achievements and prospects of energy and food production) but because they simply are not *sensu stricto* materials, substances repeatedly used in their raw state or transformed into more- or less-durable finished products used in all sectors of the economy.

Unlike raw biomaterials (wood, wool, cotton, leather, silk), metals, nonmetallic minerals and nonrenewable organics (asphalt, lubricants, waxes, hydrocarbon feedstocks), foodstuffs, and fuels are not used to build long-lasting structures and are not converted or incorporated into a still-increasing array of ephemeral, as well as durable industrial, transportation, and consumer items. Foods are rapidly metabolized to yield energy and nutrients for human growth and activity; fuels are rapidly oxidized (burned) to yield, directly and indirectly, various forms of useful energy (heat, motion, light): in neither case they increase the material stock of modern societies. And, a critical difference to which I will return later when noting the impossibility of circular economy, energy flows of any kind (fuels, electricity, food) cannot be recycled.

Finally, I must defend a conceptual change that concerns the handling of materials put by the EU's material balances into the category of dissipative flows. According to the EU definition, the eight categories of dissipative losses are a collection of disparate residuals: some of them add up to small total flows (think about solvents escaping from dry cleaning or about rubber tires wearing-away on roads), others are more substantial (leaching and volatilization of manures, sewage sludge, and composts applied to cropland) but dissipative losses contributed by both of these material categories are not monitored and are very difficult to quantify. The USGS approach accounts for the largest flows in this category (salt and other thawing materials, including sand and grit, spread on winter roads, nitrogenous and phosphatic fertilizers and potash applied to crops and lawns) by including them in the industrial minerals group.

While salt and sand are abundant materials whose production is not energy-intensive, inorganic fertilizers are critical material inputs in all modern societies that cannot be ignored and that will receive a closer look when I examine advances in the production of synthetic materials. But I would argue that most of the remaining dissipative flows add up to relatively small amounts whose inherently inaccurate quantification appears to outweigh any benefits of including them in any grand total of consumed materials. And while manures and sludges represent relatively large volumes to be disposed of, they do not recycle biomass but rather the products of its decomposition: water, carbon, and small amounts of nutrients (above all nitrogen); sludge contains at least 80% water, fresh manures 70–85%, but only a few percent of nitrogen. Moreover, in many instances sewage sludge should not be recycled as it contains heavy metals, pathogens, pesticide, and drug residues.

This leaves me with an argument for a single addition to the USGS list for the inclusion of industrial gases. Although air (21% oxygen) is needed for combustion of fossil fuels, the dominant energizer of modern civilization, adding air to the total material input would have (as I have already explained) a skewing and confusing effect similar to that of counting all uses of water - but assessing the use of gases separated from the air in order to enable many industrial processes is another matter. In simple mass terms, the global use of oxygen, hydrogen, nitrogen, and rare gases such as argon or xenon constitutes only a minor item, but in qualitative terms their use is indispensable in industries ranging from steelmaking (basic oxygen furnaces now dominate the production of the metal) to synthesis of ammonia (using nitrogen separated from air and hydrogen liberated from methane) and efficient lighting.

And although there is no way to anticipate accurately the global trajectory of hydrogen - an energy carrier whose ascendance has been promised for generations but whose production without carbon ("green hydrogen" liberated by electrolysis of water using only electricity from renewable conversions) began receiving both widespread and intensive consideration during the early 2020s (Green Hydrogen Systems 2022) - there is no doubt that without the introduction of substantial volumes of hydrogen into the global energy supply we cannot think about mass-scale decarbonization of future industrial and transportation energy uses. And in addition to green hydrogen, there has been also rising interest in green ammonia both as an industrial feedstock and as a possible transportation fuel: I will have more to say on both of these materials when I look at the unfolding energy transition.

2

How We Got Here

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Materials and Dematerialization: Making the Modern World, Second Edition. Vaclav Smil.

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The Earth's biosphere teems with organisms that use materials for more than just their metabolism. Moreover, in aggregate mass terms the material flows commanded by the humanity do not appear to be exceptionally high when compared with the work of marine biomineralizers. But it is the combination of the overall extent, specific qualities, and increasing complexity of material uses (extraction, processing, and transformation into a variety of inputs destined for structures, infrastructures, and for myriads of finished products) that is a uniquely human attribute. To set it into a wider evolutionary perspective, I will first note some of the most remarkable ways of material uses by organisms ranging from marine phytoplankton to primates, particularly those distinguished either by the magnitude of their overall fluxes or by their unique qualities.

Afterward I will proceed with concise chronological surveys of human use of materials, focusing first on the milestones in our prehistory, above all on those still poorly explained feats of megalithic construction that required quarrying, transportation, and often remarkably accurate placement of massive stones. Then I will review and quantify some notable deployments of traditional materials (dominated by stone and wood) during the antiquity, the Middle Ages and the early modern era (1500–1800), concentrating above all on the advances in building roads, aqueducts, ceremonial, and religious structures and ships, as well as on the origins and developments in metallurgy and on materials used by households.

I will end this chapter by two closely related sections that will describe the creation of modern material civilization during the nineteenth century and its post-1900 spatial expansion and growth in complexity. I will focus on key quantitative and qualitative advances in the use of materials that laid the foundations to the 20th societies as they supported fossil fuel extraction, industrialization, urbanization, and evolution of modern transportation modes on land, water, and in the air. These developments were based on materials whose production required high energy inputs and whose introduction and use have been dynamically linked with enormous advances in scientific and technical capabilities. In turn, new materials have been the principal drivers of increased food production and improvements in sanitation that led to unprecedented gains in quality of life. They also expanded capabilities for mechanized and automated production and for long-distance travel, information sharing, and telecommunication.

2.1 Materials Used by Organisms

Inevitably, all organisms use materials: that is the essence of metabolism. Global photosynthesis, the foundation of life in the biosphere, creates new biomass by incorporating annually more than 60 Gt of carbon absorbed as CO_2 from the atmosphere (Smil 2013; Ryu et al. 2019) and millions of tons of the three key macronutrients (nitrogen, phosphorus, and potassium, absorbed by roots) that are incorporated into complex compounds forming plant tissues and organs. But these metabolic necessities – mirrored by the nutritional requirements of heterotrophs, be they herbivorous, carnivorous, or omnivorous organisms – are not usually included in the category of material uses that is reserved for active, extrasomatic processes.

In terms of the initial acquisition, these material uses fall into five major categories. The rarest, and in aggregate material terms quite inconsequential, category is the use of collected natural materials as tools. The second category with limited aggregate impact is the use of secreted materials to build protective or prey-catching structures; the latter use has been mastered, often spectacularly, by web-making spiders. The next one is the removal of specific biomass tissues (branches, twigs, leaves, flowers), and now also discarded man-made materials (bits of plastics, paper, glass, and metals) and their purposeful emplacement to create remarkably designed structures ranging from beaver dams to intricate nests or, in the case of birds of paradise, often elaborate decorated mating bowers. Then comes the removal and repositioning of soils and clays, invisible as intricate rodent burrows and prominent in termite mounds. And, finally, the most massive endeavor is the extraction of minerals from water, mostly to build exoskeletons, the process dominated by marine biomineralizers including phytoplankton, corals, and mollusks.

2.1.1 Tools and Construction

Tool-using activities have been well documented with species as diverse as otters, seagulls, elephants, and finches (Bentley-Condit and Smith 2009; Shumaker et al. 2011; Sanz 2013), but they have reached the greatest complexity, and have gone as far as resulting in specific cultures, among chimpanzees who use blades of grass or twigs to collect termites or as honey-dipping sticks, leaves, or moss sponges to extract mineral-rich liquids at natural clay-pits, and small stones and stone anvils to crack open nuts, with studied populations displaying some "cultural" differences in prevailing practices (Wrangham et al. 1996; Boesch and Tomasello 1998; Whiten et al. 1999; Gruber et al. 2011; Lamon et al. 2018; Bessa et al. 2021).

Spider silk (made almost entirely of large protein molecules) is certainly the most remarkable secreted material: some strands have tensile strengths comparable to steel and some silks are nearly as elastic as rubber, resulting in toughness two to three times that of such synthetic fibers as Nylon or Kevlar (Römer and Scheibel 2008; Brunetta and Craig 2010). On the other end of secretion spectrum are frothy nests excreted by spittle bugs. Use of collected materials is quite widespread among heterotrophs. Even some single-cell amoebas can build portable, intricate, ornate sand grain houses whose diameter is mere 150 µm (Hansell 2007, 2011). And perhaps the most remarkable collecting activity among insects is that of leafcutter ants (genus *Atta*) as they harvest leaves, drag them underground into elaborately excavated nests in whose chambers they cultivate fungus (Hölldobler and Wilson 1990). Garrett et al. (2016) estimated that 2.9 (±0.3) km of leaf-cutting with mandibles was needed to reduce a square meter of leaf to fungal substrate, with nearly 90% of the cutting taking place inside nests.

Beavers are active harvesters of wood used to build their dams, and when wood is not sufficient, they use stones (up to 30 cm in diameter) combined with branches stacked in layers. Most of the dams are less than 10 m wide, with head differences below 1.5 m, but the record sizes are equivalents of engineered structures up to 850 m long with heads up to 5 m (Müller and Watling 2016). But birds, rather than mammals, provide the most varied and sometime spectacular examples of construction using collected materials; they range from simple and rather haphazard assemblies of twigs or stems to intricate constructs produced by *Ploceidae*, family of tropical weaver birds, and they may use a single kind of a collected material or are made from an assortment of tissues (Gould and Gould 2007; Burke 2012).

Birds use not only a wide range of collected plant tissues (slender blades of grass to heavy twigs used by storks and eagles) but also feathers of other species and spider silk (most passerine birds), and some nests may contain thousands of individual pieces. Use of mud (by swallows) is not that common but many ground-nesting birds (including penguins) collect small stones, while elaborate structures prepared by some bower birds of Australia and New Guinea to attract females may include not only such colorful natural objects as shells, berries, leaves, and flowers but also discarded bits of plastic, metal, or glass, and some species even make courts creating forced visual perspective for the courted females (Endler et al. 2010). Some insect species also use collected material to build their nests: paper wasps cut tiny pieces of wood and mix them with their salivary secretions, and mud wasps shape mud into cylindrical nests. In contrast, primates, our closest animal predecessors, use branches and leaves to build only simple, temporary structures on the ground or in the trees.

2.1.2 Soil Movements

Soil-displacing species engage mostly in digging tunnels, burrows, and nest but also in using soils and clay to build above-ground structure range from insects to mammals. The earliest burrow constructs date to the pre-Cambrian (650–700 million years ago) oceans, coinciding with the emergence of macropredation (Turner 2000). As demonstrated by Darwin in his last published book, earthworms are capable of such prodigious effort of earth displacement (passing the particles through their guts and excreting the worm casts on the surface) that they can bury monuments of human activity in remarkably brief periods of time (Darwin 1881). Rodents are diligent builders of often extensive subterranean networks of tunnels and nests that may also help with temperature control and ventilation and that facilitate escape.

Termites are the greatest aggregate excavators and movers of soils in subtropical and tropical environments. They construct their often impressively tall and voluminous mounds by removing and piling-up soil to build their underground nests sheltering their massive colonies. Internal structure of mounds makes it clear that they provide induced ventilation driven by pressure differences (Turner 2000). Biomass densities of these abundant warm-climate insects range from 2 g/m^2 in the Amazonian rainforest (Barros et al. 2002) to around 5 g/m^2 in Australia's Queensland (Holt and Easy 1993) and 10 g/m^2 in arid Northeast Brazil, in Sao Paulo state as well as in dry evergreen forest of northeast Thailand (Vasconcellos 2010), while in African savannahs their total fresh-weight biomass can be more than twice the biomass of elephants (Inoue et al. 2001).

Species belonging to genus *Macrotermes* move clay particles to build conical mounds that are usually 2–3 m tall but can reach 9 m, with typical basal diameter of 2–3 m, but much wider mounds are not uncommon. In Northeast Brazil, mounds created by the excavation of vast tunnel networks by *Syntermes dirus* have persisted for nearly four millennia and they consist of some 200 million soil cones typically 2.5 m tall and 9 m in diameter covering about 230,000 km^2 and adding up to about 10 km^3 of volume (Martin et al. 2018). Typical mass of termite mounds (wall and nest body) is between 4 and 7 t but spatial density of mounds varies widely, with as few as 1–2 and as many as 10/ha (Fleming and Loveridge 2003; Tilahun et al. 2012).

As a result, the total mass of termite mounds varies widely, from just 4–8 t/ha to as much as 15–60 t/ha. A very conservative estimate of the clay mass used to build termite mounds (assuming average of 5 t/ha and area of about 10 million km^2 of tropical and subtropical grasslands inhabited by mound-building insects) would be 5 Gt, but the actual total may be several times larger. In any case, this means that the mass of soil displaced annually by these tiny heterotrophs would be of the same order of magnitude as our civilization's global extraction of metallic ores and other non-fuel minerals at the beginning of the twenty-first century.

In aggregate terms both the mass of materials collected by vertebrate animals to build structures and the mass of soils displaced by burrowing heterotrophs, earthworms, and termites are negligible compared to the mass of compounds excreted by species capable of biomineralization, above all by phytoplankton, protists, and invertebrates. Biomineralization evolved independently across phyla, transcending obvious biological differences: more than 30 biogenic minerals (two-thirds of them being carbonates) are produced by a small number of vascular plants (belonging to Bryophyta and Trachaeophyta), animal species ranging from Porifera to Chordata, some fungi, many protists, and some Monera (Lowenstam 1981; Boskey 2003; Gilbert et al. 2022). Some biomineralizers deposit the minerals on organic matrices but most of them produce extracellular crystals similar to those precipitated from inorganic solutions.

2.1.3 Biomineralizers

In mass terms by far the largest users of natural materials are marine biomineralizers able to secrete inorganic compounds they produce from chemicals absorbed from water. Marine biomineralizers use dissolved $CaCO_3$ to form calcite or aragonite shells, two identical minerals that differ only in their crystal structure. Reef-building corals (Anthozoa belonging to the phylum Cnidaria) are the most spectacular communal biomineralizers, while coccolithophores (calcareous marine nanoplankton belonging to the phylum *Prymnesiophyceae*) encase themselves with elaborate calcitic microstructures (smaller than 20 μm), and foraminifera (amoeboid protists of the eponymous phylum) create pore-studded micro shells (tests). Unicellular coccolithophores are abundant throughout the photic zone in nearly all marine environments of the Northern hemisphere and up to about 50°S in the Southern Ocean where their blooms account for a major share of global marine $CaCO_3$ production and export to the deep sea (O'Brien et al. 2012; Hernández et al. 2020).