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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.