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Cooperation and competition among structural materials

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Abstract – Materials have been invented by mankind in the course of prehistory and history and have evolved during this long period of time to fit the parallel changes in technological epistemes. Materials, therefore, have been a cumulative technological commodity, because of the continuity that this mechanism of change has ensured Structural materials, of which all anthropogenic artefacts are made and with which they are made (machines, process tools, etc.), have been more especially enduring and have carved themselves specific roles in our world that survive across major paradigm shifts and Kondratief cycles. Materials are analyzed here in terms of their physico-chemical nature (or physio-chemical in the case of natural, renewable materials) and of their footprints on energy consumption and greenhouse gas emissions, two of the major lenses through which the sustainability of our economic world is presently observed. The picture that comes out of this examination is that of complementarity and cooperation between materials, with competition acting as a sting to avoid a slack in technology but no pushing any of them out of their market, at least globally. This cohabitation, akin to a natural selection mechanism in a global ecosystem, may be the real driver of dematerialization, a trend which population growth and urbanization forces on mankind.

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Structural materials have been with us, mankind, for literally eons, since man evolved into prehistory. Materials have been used to create boundaries between our ancestors and nature and to interact with it: to get food, to provide shelter, to master fire, i.e. heat and thermodynamics, and to live in groups, in society.

Speaking of boundaries, materials maintain gradients of properties between different milieus and thus make possible the coexistence of systems out of equilibrium with each other [1, 2]. This can actually be used as a definition of structural materials: they maintain barriers between very different milieus, providing an interface which is tight, robust, lasting and strong (they maintain the integrity of the barrier). Note also that the materials themselves are out of equilibrium with both milieus and with "nature" itself, from which they have been "extracted" by human technology, usually based on chemistry or metallurgy. The reason they function is because they have been quenched and thus maintained out of equilibrium, more or less effectively depending on the kind of materials they are.

Materials have been the extension of the body and of the mind of people. They have been used in tools, weapons, pots and pans, clothes – body shelters – and buildings – mass shelters for groups of people.

Time passed and the hunters-gatherers settled down and invented agriculture and villages and cities and religions and art and governments and political science and economy and philosophy and science and technology. They also invented change, civilizations, which live and die, cultural diffusion and mass migrations and invasions, paradigm shifts and technological epistemes.

Today, travelling along this timeline of history, we are rich of all these awesome inventions of mankind and particularly of some of the oldest of them all, materials, especially. Structural materials today are still used to build, make, manufacture things and provide the shape, strength, resistance, duration of things and artifacts that we live with, in, next to.

Because these materials have this long, historical connection with mankind, we are sometimes ill at ease to speak about them.

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Indeed, they do not fit easily into a narrative involving modernity, because they have been around since before the concept of modernity was analyzed – a concept which is very much time-stamped [3]. This is not true of "new" materials, a set of materials constantly renewed, which get in the limelight for a short period a time, ripe with dreams and myths about how they will wipe the slate clean and replace the old order of things, i.e. the old materials, these new materials do their little dance and then disappear into a small niche of applications – not oblivion – failing at playing a universal role, in a grand soir revolution.

Materials are also very much related to the present technological episteme, which is itself connected to the present Kondratief cycle. Thus, for example, steel, modern steel, is produced today in large integrated steel mills, which churns out 5 to 10 million tons per year and runs with very sophisticated metallurgical reactors, engineering monuments operating at very high efficiency based on process technology that operates with the most advanced automation and a small workforce of very educated workers and engineers. This steel is similar to the iron invented by the Hittites, several thousand years BC, but the technology used by the steel industry to produce it has not much to do with the handicraft techniques of our Asia Minor forefathers – except at an abstract level, which, anyway, has only been clarified recently by science.

Thus, the concept of materials has been enduring for historical time spans, but not the technology to make them. There is continuity in materials process technology, though, as it has evolved step by step through history in what is sometimes called a *cumulative technology*.

The materials that will be discussed in the present paper are the structural materials that mankind has grown with, i.e., in the order in which they have been associated with the growth of human culture:

- bio-sourced materials and more particularly wood;
- lithic, mineral materials, and more particularly cement and concrete;
- metals, and more particularly steel and aluminum;
- ceramics and more particularly glass;
- new materials with structural uses, mainly today plastics in vernacular language.

This does not cover everything that would be of interest, like skins-leather, fibers and textiles for example, one of the earliest materials used by mankind[1], or more recent "new" materials like nanomaterials, but this presentation is based on the work carried out by ArcelorMittal and Swerea in the European FP7 PACT Project, which covered these structural materials, mainly [4].

There were two reasons for this choice: the materials chosen account for more than 90% of the footprint of materials in terms of energy and carbon and they have been enduring over historical time, so that this footprint is likely to remain at a "high" level for a long time to come.

1 Methodological caveats

The energy footprint of a material is a complex issue and how it will change over this whole century is even more complex.

To make this point, the following issues ought to be stressed:

- a figure like a specific energy footprint expressed in GJ/t of steel or of wood is a very complex scientific and socio-economic construct. Indeed, each ton has a special footprint and we are interested in coming up with an average value in a large scale system, the world for example.
  Even before discussing the "biodiversity" of each ton of materials, one should be aware of the issues related to boundaries: things like cradle to gate, or gate to gate, or gate to cradle, etc., which the Life Cycle Assessment (LCA) Community is familiar and conversant with. Note that an international Agency like the IEA, which has the duty to know about energy issues and therefore to communicate extensively on them, usually refers to gate to gate figures, actually to sectoral figures, which arguably may be seen as

[1] *Textile* is actually often called "*material*" in English.

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the same thing even though they are not, exactly.

Let's assume that this can be sorted out. Then comes the rationale of defining an average value: the issue is raised only because we simply cannot know the footprint of each ton of steel and we have to make conjectures (educated guesses) based on the idea of species invented by Linné, or, more precisely on the fact that steel mills belong to a limited number of categories (process routes), e.g. integrated mills and EAF-based mills, each of these behaving in the same way – which has to do with the fact that process technologies are more or less the same and that they are operated in more or less the same manner, because steel is a (more or less) standard material across the world and that the economy and the regulatory, standardization world, push each operator to minimize costs and thus make steel "more or less" uniformly.

"More or less" should be mentioned at each step and thus stress the point that the average, which in principle could be calculated by aggregating figures for each process route category, has a spread, a natural dispersion related to the individual steel mills behaving (=being operated) differently. One likes to speak of best performers, worst performers, sectoral average, regional average, etc. to try and grasp this complexity, thus adding a layer of normative judgment stemming from a managerial standpoint. . . or bias.

It is true to say that the information needed to come up with these figures has been produced by various organizations and is accessible to experts with the proper connections, although it is not openly published or publicly available. Two different experts will probably access different information and come up with slightly (or greatly) differing figures. The complexity is back.

At the end of the day, if a figure is required by an authority, one will be provided by experts but it will be a political one which may have a strong or a weak connection with reality.

– When speaking about different materials, one has to refer to different sources of information, which have collected figures with methodologies that are not exactly the same. Much of this information comes from grey intelligence rather than from peer-reviewed scientific papers and thus this fuzziness cannot be easily circumvented.

  Again, the contingent, political nature of figures available in the open should be pointed out: figures published by a trade association will not be the same as those published by a small company, intent on being one of the "best in class", or by a large one operating both new and old plants/mills, or by the IPTS [5], why is interested in Best Available Technologies, or by the IEA, why is interested in pushing some specific agendas, like energy conservation or mitigation of Climate Change.

  Another point is that some sector will have spent more effort in dealing with the issue and thus have "better" figures than one which has been mainly stressing the point that it is constrained by economic hurdles which make progress difficult. In this manner, the Steel sector has developed a clearer vision of the post-carbon society, based on extensive research effort, especially through the European ULCOS program [6], than the cement sector, which has mainly contributed a roadmap [7].

  Finally, materials are not all the same, at the deeper level of their physical nature and of their role in our economy, e.g. metals are quite different from plastics or wood, and thus cannot necessarily be compared with the same indicators.

– The matter of foresight exercises is even more complex. What will happen in 2050 and beyond is a matter of conjecture, in simple words of guesses, and, even if they are made by educated people, they are still guesses, educated guesses. Sophisticated methodology may be applied to this kind of work, but it is always biased, as looking at old prospective work clearly shows. Again, the "principle of action" states that we will be better off with this type of vision, stressing the need to think in the long term, than in refusing it on the basis that it cannot be

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known and thus focusing only on the short term. Indeed, this is what we do in our personal lives, giving birth to children, who also have children, and thus extending ourselves in time over many generations and centuries.

The point of this section was to stress that we will be dealing with figures which do not have the same precision as a physical constant like the Planck's distance or as an accounting figure in a balance sheet. The caveats may actually help analyze the figures along interesting lines.

There is a point though beyond which we cannot know, "for we see now in a glass darkly". Being aware of this "cone of knowledge" is also is part of the challenge of providing society with numbers useful for decision and policy making.

2 Materials 101

Structural materials belong to very different categories of materials, the composition and the structure of which explains their socio-economic behavior and role. This section makes an attempt at summarizing the main features of each of them and at explaining how and why they differ from each other in a simple way Less simplistic presentations are available in the literature [8–11].

2.1 Metals

A metal is a chemical element made of a crystal of anions in which a cloud of free electrons roams about. Because of these simple features, a metal is stiff and elastic, strong, easily accepts defects in its structure which make it ductile and tough, and conducts heat and electricity. It also reflects light and exhibits the characteristic metallic shine. Metals have a high thermal expansion coefficient. Metals are more stable than non-metals, which means that they are more electronegative, have a higher melting point and higher heat of phase changes, solid-liquid or liquid-gas. They also have higher density. Some of the metals exhibit magnetic properties, especially ferro-magnetism.

Practically, this means that metals are not found in nature in their metallic state, except for precious metals and copper, but have reacted with oxygen and other non-metals early during planeto-genesis and thus are mostly found today as ores. They have become available to mankind at the speed at which the arts of fire were mastered, in an order related to their enthalpy of reduction and to their melting point. A special art, metallurgy, had to be developed to produce metallic metals and the corresponding technology uses high amounts of energy and high temperatures: metallurgy is thus labeled as an energy intensive activity.

Metals are strong and tough and thus can be shaped and used under stress with a limited risk of fracture, making them suited for constituting artefacts that require complex shapes and for making containers and machines, where strength is important. They resist aggressions from the environment like corrosion and thus constitute chemical barriers. Metals keep their nature and structure throughout the life of an artifact.

Metals are easy to collect at the end of life of things, as they can be separated by mechanical means such as shredding without being broken into powder and dispersed. Separation can be performed fairly easily either because of their magnetic (magnets for iron) or electrical properties (eddy current separation).

Since recovered metals are very similar to the virgin material, reusing them in a recycling loop requires lower amounts of energy and thus exhibits lower environmental footprints.

Metals are prone to mixing at an atomic scale, which is called alloying. Alloys exhibits higher properties than a simple rule of mixing would predict, for example higher strength. Some alloys like steel change properties with very small additions of elements like carbon, while stainless steel metallurgy or nonferrous metallurgy require a higher level of other elements, mostly other metals (e.g. bronze). Very dilute alloys are easier to recycle than more concentrated ones, which should be segregated according to their composition, a fairly demanding constraint.

2.2 Ceramics cement and glass

A large class of materials belongs to the family evolved from lithic materials, i.e.

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chemical compounds of metals and non-metals, mainly oxides but also nitrides, borides, etc., which are the major compounds of the earth's crust. In prehistoric times, lithic materials could be directly collected from nature, even if they had to be mined like in flintstone quarries. Technologies have been developed to produce consistent materials from a broad range of raw material sources and have led to the production of ceramics, of cement – and thus to the use of modern concrete, based on Portland cement – and then of advanced ceramics (*céramiques techniques*). Ceramics and cement have been produced by using the arts of fire, in processes which eventually were also used in metal production. Glass is a special kind of ceramics which exhibits interesting optical properties.

This class of materials is usually brittle and thus cannot be as easily shaped as metals. These materials are more fragile and they break easily. On the other hand, they require less processing "effort" – especially no chemical reduction – and thus less energy than metals to make. Their strength is also large under compression, but not tension or bending: they will be preferred for making buildings but not machines, usually. Bulk materials are usually crystalline but sometimes amorphous or glassy, such as glass. Concrete is a composite material where aggregates are glued together by cement, when it hydrates into several chemical compounds which give cohesion and strength to the composite. Mineral materials are insulators of heat and electricity; they usually exhibit a low expansion coefficient. They can be used at high temperature and a special class of them is called refractories.

Stone can be reused. Ceramics and glass (*cullet*) are commonly recycled, in the same sense that metals are recycled, because they are the same materials at the end of life as the virgin material.

This is not the case of concrete, where the initial cement has been chemically transformed. Concrete thus cannot be recycled into the same material: it can however be reused as aggregates for making new concrete.

Cement is produced by mixing raw materials and solid fuel and firing them in a rotating kiln. Raw materials are always virgin materials from a quarry (limestone and gypsum), but the fuel can be secondary raw fuel, like old tires or animal feed, i.e. a waste or a residue from other economic activities. The cement industry stresses the point that this eliminates a waste, which would have to be disposed of in a different manner, in a landfill or an incinerator, for example; it is also cheaper than coal or another fossil fuel. This might give rise to a credit regarding emissions, but this a complex and somewhat controversial issue which requires more discussion (see further).

2.3 Plastics

Plastics constitute a broad family of composite materials made mainly of polymers, i.e. organic chemical compounds produced by the polymerization of simpler molecules, e.g. vinyl chlorine monomers, sometimes of polymeric alloys, with additives introduced to enhance their properties. Plastics are easily shaped by molding at intermediate temperatures into objects of complex shapes. Thermoplastics also called thermosoftening plastics can be reused or recycled, i.e. ground and used again as a feedstock for new objects – although with some quality degradation after each cycle; thermosetting plastics, in which the polymer molecules are all interconnected, cannot be recycled. From a practical standpoint, recycling of thermoplastics is impeded by the difficulty of separating various plastics from waste.

The chemical nature of plastics explains why they are light, melt at fairly low temperature (thermoplastics) and exhibit lower strength than metals, ceramics, glass and concrete. They are mostly insulators, thermally and electrically. They are used mainly to make small construction and household items and other consumption products.

The raw materials from which plastics are made are usually petrochemicals, i.e. oil, although bioplastics are being developed, based on plant material, cellulose or starch. Plastics are thus made from a fuel, i.e. a very special raw material which has energy content in addition to being a feedstock for the carbon and hydrogen that are needed to make polymers. This is quite different from

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making metals, where the feedstock is the ore and the fuel or energy source is coal, oil, natural gas or electricity, sometimes hydrogen, both thus being separate inputs.

In principle, plastics can be turned back into a fuel, either through a chemical process or simply by combustion.

While metals and glass are mostly recycled and ceramic and concrete landfilled, plastics today are landfilled, incinerated or dispersed in the environment and recycled to a small extend.

2.4 Wood

Wood is a natural material, produced by tree growth: its feedstock is carbon mainly from atmospheric CO_2, and oxygen. The energy for wood genesis comes from solar energy, which is transformed into bio-chemical energy by photosynthesis. Wood is a composite material, made of cellulosic and hemicellulosic fibers embedded in a matrix of lignin; the material is porous after drying. Wood is lighter than water, has strength in tension and compression with a definite texture, is an insulating material and decomposes with temperature without oxygen into charcoal, tar and hydrocarbon gases (pyrolysis); with oxygen present, it catches fire and turns back into CO_2, H_2O, energy plus a few other compounds, depending on combustion circumstances. With time, it biodegrades into CO_2 or CH_4, depending on the kind of bacteria that carry out the job (aerobic or anaerobic ones).

Wood cannot (usually) be reused, nor recycled, but can be combusted to recover energy. At end of life, wood may be let to biodegrade, or landfilled, or incinerated, with ou without heat recovery. The greenhouse gas generated is released to the atmosphere. This can be neutral, if (and only if) a new tree replaces the old one in a managed forest or a steady-state plantation – except for the footprint due to transport and industrial activities related to the production of wood (cutting, drying, manufacture) and the complex issue of land use change.

2.5 Summary of materials 101

Structural materials are a very broad class of commodities or intermediary goods, which are used to manufacture things and to become part of them. They belong to very different families of physical entities, which have been "invented" by mankind to perform functions that have become necessary in the course of historical time, and this historical connection remains strong today: they have been bio-sourced, or simply extracted from the ground, or produced by sophisticated processes involving heat (fire), from earthware to ceramics, cement, glass, metallurgical products, metals and alloys and new materials, most of them produced by chemistry.

The more difficult materials to produce, mainly because of the need for high temperatures or large heat and for a sufficient understanding of physics and chemistry, have only been available recently, e.g. steel (as opposed to iron), aluminum, titanium, stainless steel, advanced ceramics, plastics and "new" materials.

Figure 1 shows the evolution of materials production over the 20th century and the relative importance of the major structural materials, with steel and cement developing at the same pace until the end of the 30 glorious years and then cement escaping upwards. Materials have been produced *en masse* only since the second half of the century [12].

Metals, which constitute most of the chemical elements, exhibit a rich array of properties, which have made them "useful": high density, high strength (in all directions), high toughness, high thermal and electric conductivities, the ability to multiply into an extraordinarily broad range of alloys, malleability, etc. They serve therefore both as structural and functional materials. They are also abundant and thus their price remains low, except for specialty metals, like precious metals or "rare" ones (Ti, W, Ta).

Various materials features are also shown in Figures 2–5, to flesh out the qualitative statements made previously with actual figures [13].

Light materials are bio-sourced materials or plastics. They also exhibit the lowest strength. Their time stability is different from metals, as they biodegrade or age more quickly than metals corrode and oxidize. They originate directly or geologically from solar energy and thus entertain a special

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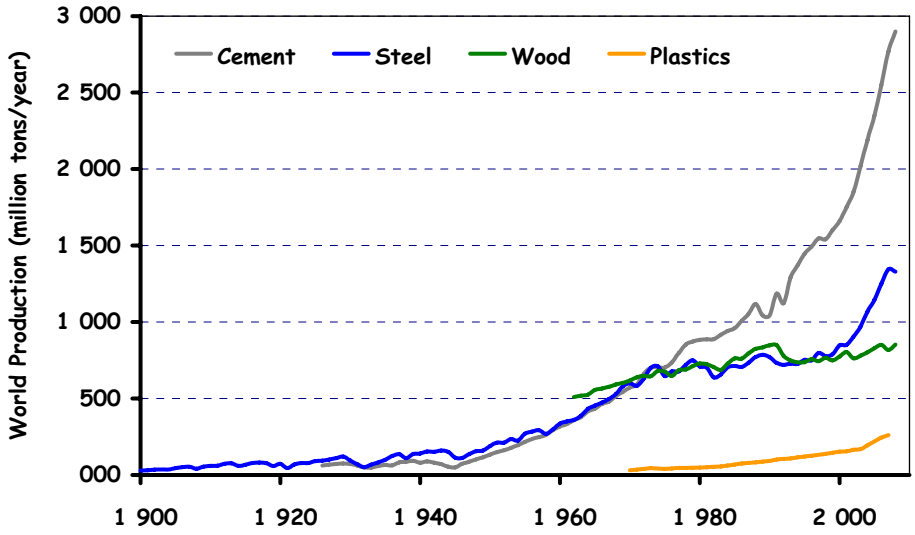


Fig. 1. Evolution of the annual production of some structural material plus plastics over 100 years [12].

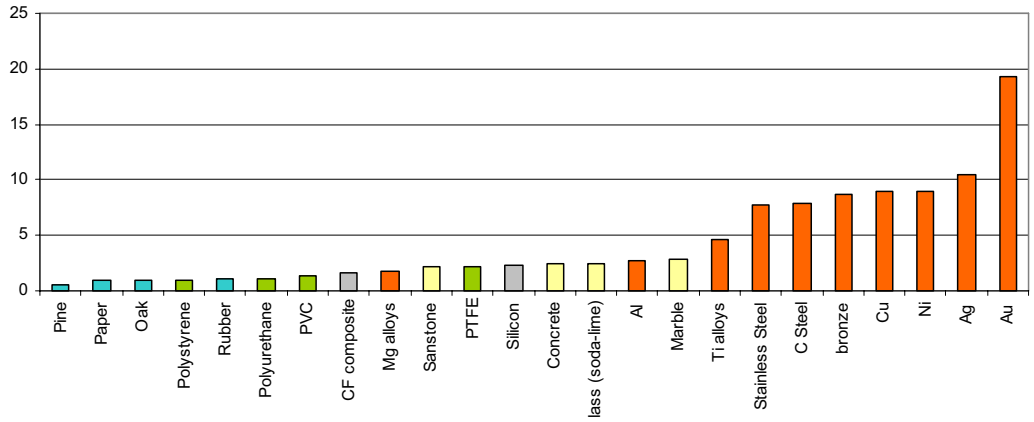


Fig. 2. Density of various materials [13].

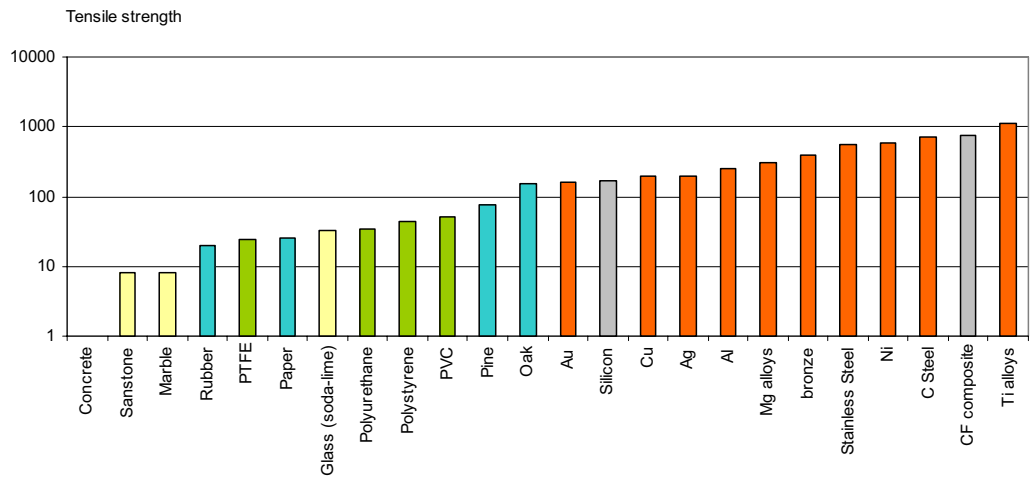


Fig. 3. Tensile strength of various materials [13].

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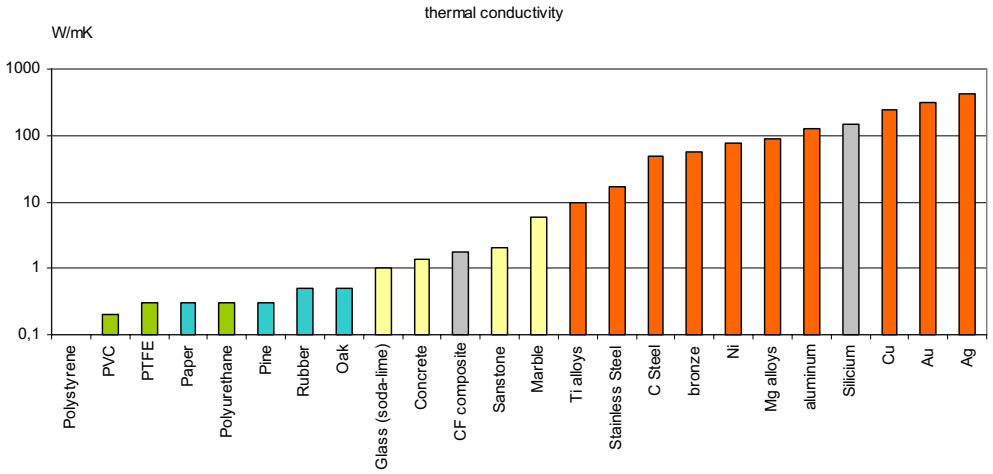


Fig. 4. Thermal conductivity of various material [13].

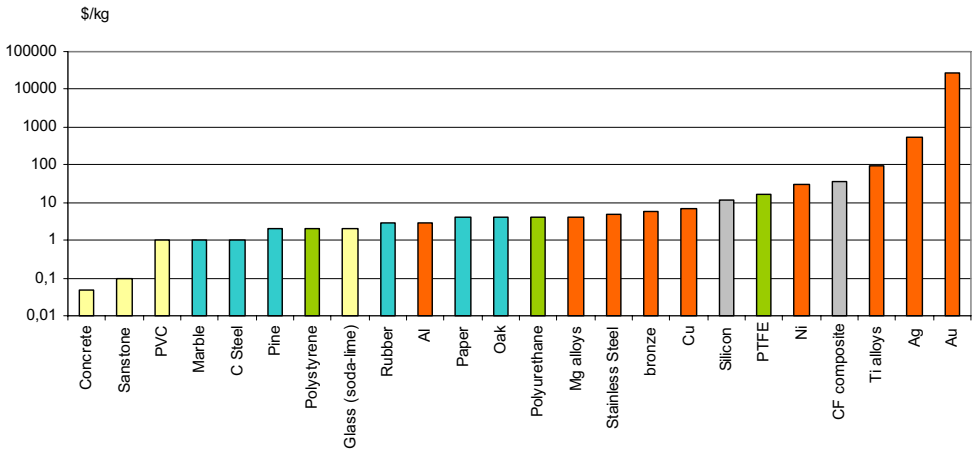


Fig. 5. Market price of various materials [13].

connection with energy issues and greenhouse gases (GHG) emissions.

The "lithic" family's main feature is that they are also close to nature, in as far as relatively little effort needs to be done to produce them – compared to metal extraction or plastics production. They are also among the cheapest materials available. Their strength is high in compression, but almost nil in other directions.

Of course, these trends are contradicted by sophisticated new materials: composites make lithic materials much stronger, in bending and even under tension (prestressed concrete, high strength concrete), while chemistry has developed plastics which are stronger than many steels (e.g. Kevlar, KEEP).

Last, the empirical and pragmatic development of materials through a historical process not dissimilar to evolution shows in the comparative prices of various materials: the ordinary, most commonly used materials are priced within an order of magnitude of each other, while high-performance ones exhibit prices that shoot upward; the economic value integrates a large number of parameters (embedded work, scarcity, capital investment, bonus for innovation), which may be the reason why it had to be deconvoluted into separate concepts such as the three pillars of sustainability to make analysis and policy making more to the point.

3 Iron and steel

Steel will be analyzed from a foresight perspective (2050 vs. 2010) in terms of production volume, recycling, energy and carbon

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Table 1. Comparison between the various projections for steel production in 2050 (crude steel) [16–19].

Source of estimates	Annual production (Mt/yr)	Comments
ULCOS-LEPII	2450/2550	POLES estimates
RITE	2200	Markal model
Tokyo University	1800 (2011 Mt/yr crude steel)	MFA model
IEA Blue Map (low/high)	2350/2700	

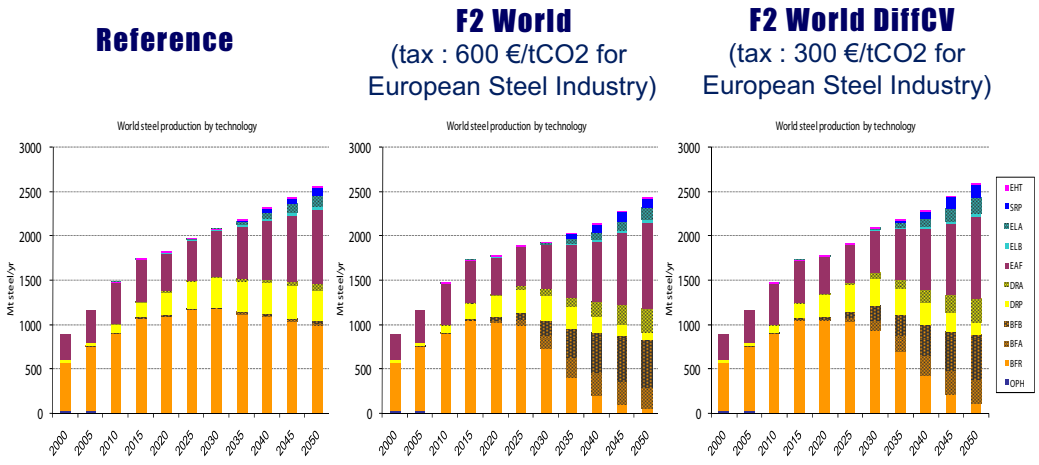


Fig. 6. Evolution of steel production according to the scenarios of LEPII (ULCOS [16]).

footprints. The same template will be used for other materials.

The authors are close to the Steel industry, which means that they are conversant with its technology and its actual and detailed performance. This makes for a deeper, more detailed discussion than what can be done for the other materials.

3.1 Steel production

Steel production was 1527 Mt in the world in 2011, 1411.6 Mt in 2010 and 1224.8 Mt in 2009 [14]. Capacity in 2001 was 1979 Mt/yr and should reach up to 2126 Mt/yr in 2015 [15].

Steel production in 2050 has been estimated in independent research works, using widely differing methodologies (cf. Tab. 1 and Figs. 6 and 7) [16–19]. Three of them are based on an Intensity of Use (IOU) method, while the 4th one makes projections on an Intensity of Stock and projects demand rather than supply (a 7% gap). The background world econometric models that they use are also quite different (POLES and Markal) and the set of scenarios as well. All projections were produced prior to the 2008 crisis.

Nevertheless, the projections are fairly similar, ranging from 2011 Mt/yr in 2050 (MFA, Tokyo) to 2700 Mt/yr (IEA, Blue Map high). The two scenarios of ULCOS-LEPII and those of the IEA are comparable, although showing a smaller dependency on the carbon scenario in the first case than in the second one. Compared to 2000, production would roughly triple, while it would double compared to 2009.

This is basically saying that steel is such a key material in the world economy that its production will continue to grow and to do it faster than population, which means an increase in consumption per capita, to accompany the strong increase in standard of living that is expected everywhere, except in Western countries. Economics seem to believe that it will happen, more or less irrespective of the strength of the Climate constraint.

As will be seen later, similar projections have been generated for the other major structural materials, also announcing large increases in volume. Their production

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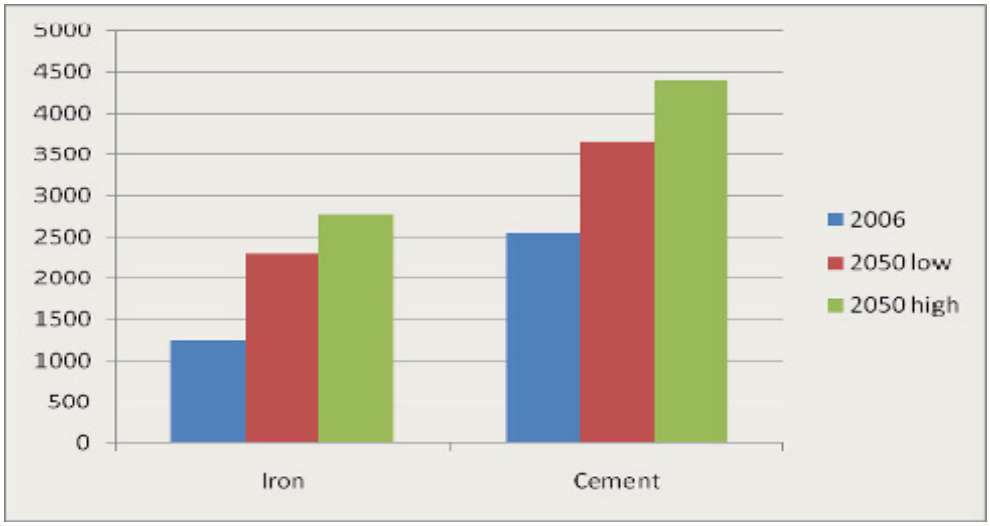


Fig. 7. Production of steel and cement 2006 and 2050 according to IEA projections [17].

should thus stay robust for as long as projections are available (2050) and probably for much longer.

At a more detailed level of analysis, the MFA model postulates a saturation of production by 2020, which the other models do not foresee. This illustrates the somewhat arbitrary pile up of assumptions that is required to produce these projections, which we have called educated guesses, earlier.

3.2 Energy consumption [20]

To analyze energy consumption and CO_2 emissions in terms of process technologies on a specific (per ton) basis, an elegant solution consists in calculating them relative to a model steel mill, where all plants are specified in order to avoid the statistical spread brought by the diversity of actual situations so that all input is normalized: a model integrated steel mill (IM) was thus defined in [20], which stems from [21], and includes coke batteries, oxygen plant, lime plant, all conventional plants from ironmaking, steelmaking to rolling on a hot strip mill, as well as a power plant to transform all excess gas into steam and electricity; the amount of scrap melted in the steel shop is also specified (190 kg/t_{HM} or ton of hot metal).

Such a steel mill, using a coherent set of Best Available Technologies, would consume 18.5 GJ/t of hot rolled coil, 16 of which are related to coal. Best performers would be at the level of 17 GJ/t, with worst performers at 50 GJ/t and world sectoral average at 25 GJ/t.

Concerning the EAF mill, the best performers would lie at 3.5 GJ/t of hot rolled product, of which 1.6 GJ/t is related to electricity consumption in the EAF (450 kWh/t), 0.6 GJ/t to fossil energy (coal and natural gas) and 0.3 GJ/t (80 kWh/t) to energy for hot rolling plus 1 GJ/t natural gas for the reheating furnace. The sectoral EU 27 average for the EAF route is 4.5 GJ/t.

Thus the EAF secondary route uses about 20% of the energy of the integrated route.

Mixing IM and EAF routes at world level (70% IM and 30% EAF) means a best performer figure of 12.9 GJ/t_{HRC}, to be compared to an IEA figure for the world sectoral average of 21.3 GJ/t_{CS} (ton of crude steel), which is almost twice as high. The gap is coherent, however, with the spread between best and worst performers.

The figures given above are shown in Figure 8 for clarity.

The distinction between these various "performers" seems essential, given the wide spread observed among them. However, making this kind of distinction means having access to data describing the world in its entirety, or to a representative sample of it. These data do not exist for all materials or are not publicly available. This makes the treatment of steel in this paper special, as

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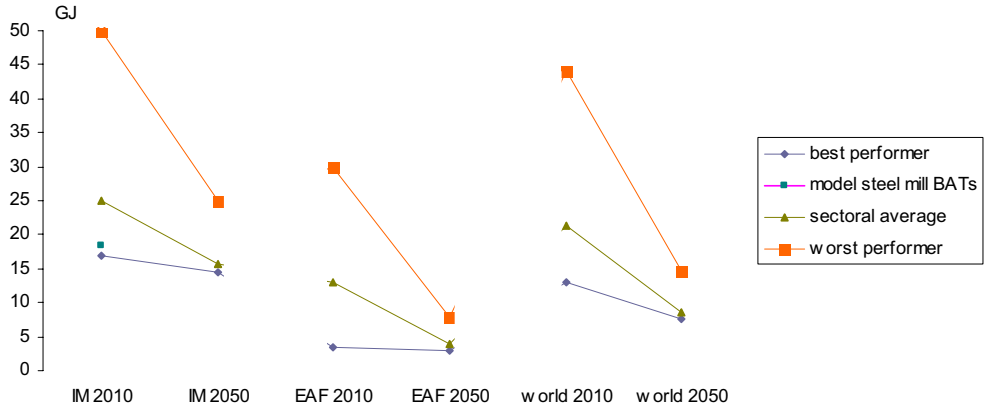


Fig. 8. Specific energy data (GJ/t, today and 2050).

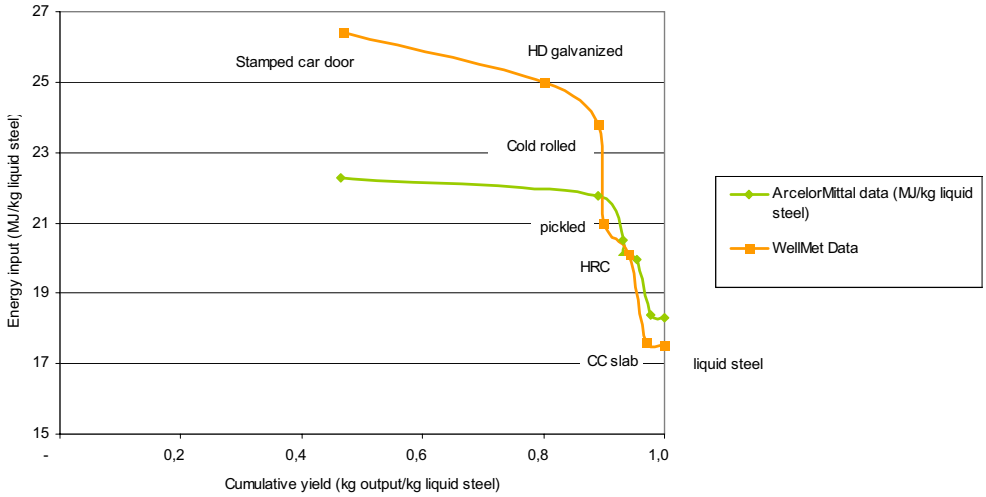


Fig. 9. Energy consumption (input) as a function of metal yield from slab to stamped automotive door [8, 23].

extending the approach to other materials will tend to be more and more difficult.

From a process metallurgy standpoint, the best performers use recent and "best" technologies, which function in effect close to thermodynamic limits, as thermodynamic equilibrium is the rule at the temperatures where steel is made. The other performers could improve their act and save energy, as well as cut operating costs, especially the worst ones. This gap is often recognized as an important way to save energy at sectoral level: it usually calls for significant changes in operating practices and often also upgrades in mill technologies, with significant investment expenditures [22].

In Figure 9, process data are segmented along production plants inside the steel mill for the example of a particular production site, where they are plotted as function of metal yield for the production of a car door, using modern technologies (beam blanks in particular). This connects energy to the final use of the material, rather than to crude tons, thus performing a kind of "functional unit" analysis. Again, the figures exemplify the broad spread of data, which critically depend on the particular steel mill represented.

Projecting these figures up to 2050, with the following assumptions:

- an IM/EAF mix of 40/60% [24];
- a best performing IM at 14.4 GJ/t and an EAF mill at 3.0 , i.e. a 15% reduction in energy consumption;

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Table 2. LCI data for various kinds of steels, WSA world database (top) and Ecoinvent database (bottom).
(BOF: Basic Oxygen Furnace, same as converter; CRC: Cold Rolled Coil).

	GJ/t	Cradle to gate	Cradle to grave
WSA	slab EAF	9.84	10.19
	slab BOF	19.32	9.59
	HRC	21.64	11.87
	section	19.63	16.39
	CRC	23.21	13.35
	finished CRC	24.91	14.79
	rebars	16.41	12.5
	Hot Dipped Galvanized	27.58	17.56
Ecoinvent	Steel low-alloy	33.32	
	Steel converter	22.36	
	steel electric	9.39	

– a worst performing IM at 25 GJ/t and an EAF mill at 7.8 , i.e. a "large" reduction in energy consumption bringing the laggards back into the main crowd.

would bring the world mix to 7.6, 8.6 and 14.7 GJ/t, respectively for the best, the average sectoral level and the worst performers.

The decrease in energy consumption from 2010 to 2050 is due to several factors: the large switch from IM to EAF mills (70/30 to 40/60) – i.e. the transformation towards a closed-loop economy, the increased energy efficiency of the best performers (15%) and the improvement of performance of the laggards (67%): on the sectoral average, specific energy consumption thus drops to 40% of the 2010 figure (as compared to 60% for the best and 33% for the worst performers). The sectoral total consumption drops by 30%.

The figures proposed until now have been *gate to gate figures* (or site process energy consumption), the ones that the Energy Community, first of all the IEA, takes on board. The LCA Community complexifies the picture by adding cradle to gate energy and end of life issues: both families of data are complementary but differ very much from each other in general, for steel as well in particular. Regarding energy, LCA reports "Primary Energy Demand" (PED), which is in general a more complex indicator, especially when different kinds of energy sources are mixed together: the difference is small for integrated mills, but is fairly large for EAF mills.

When energy issues are discussed in public debate, it is not always clear which kind of data is used, either energy consumption (process energy) or PED, and this adds to the general uncertainty and fuzziness of the data.

Life Cycle Inventories values, originating from two independent data bases, are shown in Table 2. The data are slightly different as they depend on the database used, presently by 3.3% – a fairly small difference, not significant with the level of uncertainties usually associated with LCI data.

What is more challenging is to reconcile these LCI data with the energy demand data presented earlier. Indeed, both sets of figures represent averages, which do not necessarily refer to the same sets of steel mills. For example, the difference expected between WSA and Ecoinvent data is related to a different treatment of by-product allocation, which accounts for a 3% difference [25], close to what is observed. On the other hand, upstream data related to mining operations and transport of raw materials would mean a gap of roughly + 4 GJ/t [26] between process and LCI values (21.6): this does not fit with the sectoral average presented earlier (25), but would fit better with the "model steel mill" data (18.5).

The data also show the variability related to the final steel products, such as HRC sections or CRC, but this is directly related to the energy demand of the particular plants in a steel mill, which are used for producing them, cf. Figure 10.

Table 2, exhibits a very large difference between "cradle to gate" and "cradle to grave" LCI values, up to 50%. This is due

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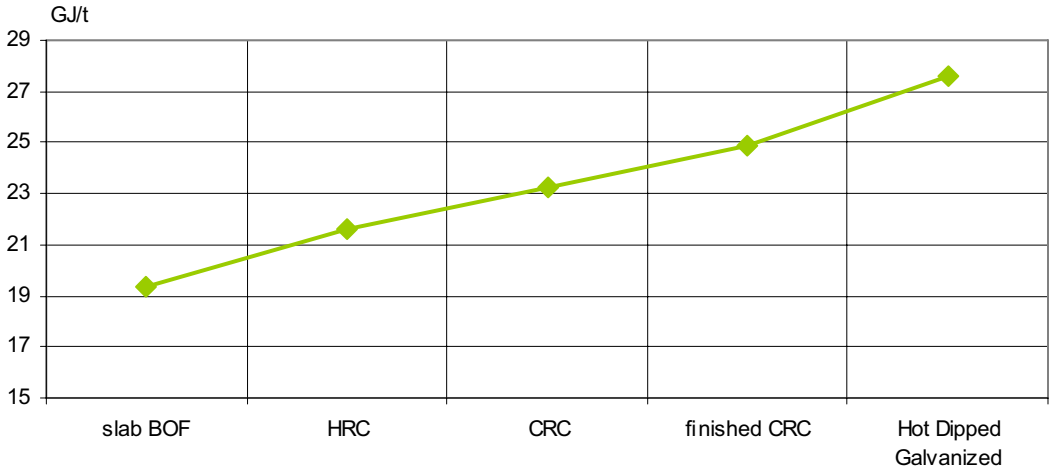


Fig. 10. Evolution of energy consumption.

to the fact that recycling is included in the WSA data base with an indefinite recycling approach [27]. This shows how important recycling is for steel, with very significant impact on its energy footprint.

Finally, it would be interesting to also project the LCA estimate in 2050. However, such *prospective LCA* is a methodology still in its infancy. A tentative answer was given in the final report of the ULCOS project [28] and more methodological developments are under way [29], but not published yet.

3.3 CO_2 emissions [20]

Estimating CO_2 emissions is even more complex than energy data: there are indeed more boundary issues and, moreover, various ways of reporting emissions, called scope I, scope II and scope III [30], all delivering fairly different figures.

Simply put, *scope I* are gate-to-gate emissions (and thus they depend on what plants lie inside the mill's gates), *scope II* adds emissions due to the production of the external energy used in the mill (mainly electricity), while *scope III* adds upstream and end of life emissions and credits or debits related to by-products. Scopes I + II + III correspond more or less to an LCA inventory "cradle to gate + end of life".

Scopes I, II and III emissions for steel production amount to the following [20]:

- the benchmark/model steelmill, already defined under the energy heading, exhibits scope I emissions of 1.81 t of CO_2 per ton of coil (t_{CO_2}/ t_{HRC}, not of crude steel, t_{CO_2}/t_{CS}); scope II, with a European electricity mix of 370 g of CO_2 per kWh, is 0.03 $t_{CO_2}$and scopes I + II, add up to 1.84–1.66 t_{CO_2}/t of crude steel;
- a benchmark steelmill based on an EAF, best performer level, has scope I emissions of 0.10 t/t of coil. Scope II emissions are 0.20 t, i.e. 0.30 in total – 0.27 t_{CO_2}/t of crude steel;
- a world mix of 70/30% IM and EAF routes has an emission factor, scope I + II, of 1.38 t_{CO_2} per ton of hot rolled product – 1.25 t_{CO_2}/t of crude steel;
- Scope I, II and III emissions together ought to be similar to LCI data, shown in Table 4. The gap due to upstream emissions is roughly 25% of gate to gate emissions, the credit due to by-products roughly 15% [31], so that the difference between 1.84 and 2.01 is accounted for. Like in the case of energy, the benchmark mill is representative of the mill sample taken on board by the WSA data.

Best performers have been estimated at 1.6 t_{CO_2}/t_{HRC} and worst ones at 5 t_{CO_2}/t_{HRC} for an Integrated Mill; 0.2 and 1.5 t_{CO_2}/t_{HRC} for en EAF Mill. Sectoral averages are at 2.3 and 0.6 t_{CO_2}/t_{HRC} respectively [20].

Foresight values for 2050 have been developed with the same rationale as the energy projections [20]. They are reported in Table 3 and Figure 11.

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Table 3. CO_2 emissions of IM, EAF and world mix steel mills, in 2010 and 2050.

	IM 2010	IM 2050	EAF 2010	EAF 2050	world 2010	world 2050	LCA 2010
Best performer	1.6	0.53	0.2	0.07	1.180	0.392	
Model mill	1.840		0.300		1.378	0.000	2.01
Sectoral average	2.3	0.77	0.6	0.2	1.790	0.599	
Worst performer	5	1.67	1.5	0.4	3.950	1.289	

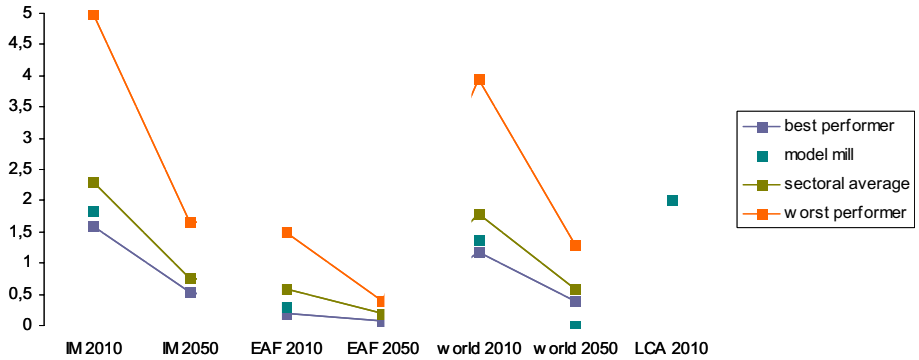


Fig. 11. CO_2 emissions of various steel mills, today (2010) and in the future (2050).

Table 4. LCI GWP data for various kinds of steels, WSA world database (top) and Ecoinvent database (bottom).

	tCO_2/tHRC	Cradle to gate	cradle to grave
WSA	slab EAF	0.757	0.797
	slab BOF	1.871	0.766
	HRC	2.009	0.908
	section	1.563	1.197
	CRC	2.186	2.359
	finished CRC	2.312	1.17
	rebars	1.244	0.803
	Hot Dipped Galva	2.474	1.344
Ecoinvent	Steel low-alloy		
	Steel converter		
	Steel electric		

The foresight projections for 2050 assume the following:

- low-carbon solutions for making steel, based on ULCOS portfolio of technologies [32], have been implemented all over the world;
- *factor 4* policies and practices are in place, thus generating electricity with a specific factor reduction of emissions;
- worst performers have invested heavily to clean up their emissions or have gone out of the market;
- the recycled content of the world steel mix has increased.

This leads to projections which cut specific CO_2 emissions by 66%, between 2010 and 2050.

Now what does this projection exactly mean?

- First that CO_2 cuts are large, because the changes projected for process and energy are large, although the exact figure is somewhat arbitrary: indeed the figures taken on board are those that are published about the capability of ULCOS processes, which are on the lower side as they have been forged in the last ten years to match the standard that was imagined to be coming up then; it would be fairly easy to imagine larger cuts to accommodate lower targets.
- Second that these projections are not simply a trend projection from a forward looking roadmap, based on progress that

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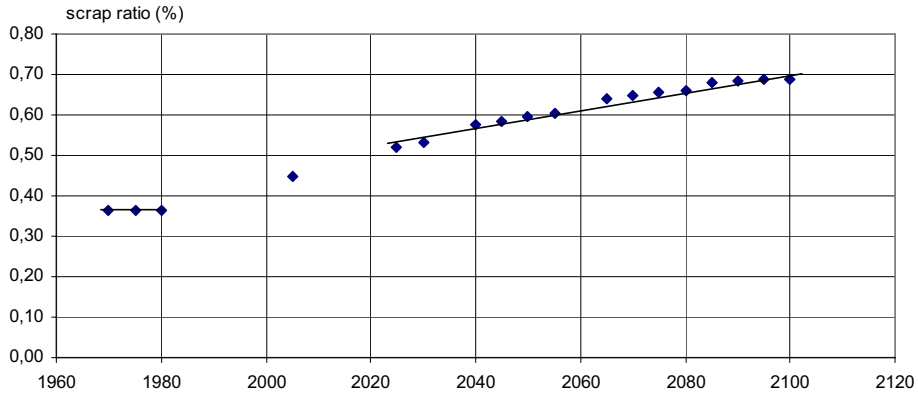


Fig. 12. Simulation of scrap ratio (recycled content) in steel production during the 21st century [24].

ought to materialize within the next 40 years, but they are based on a series of technologies that have been developed with success up until pilot scale in a large research program which has now moved into demonstrator size. These are the steps which would lead to the availability of the technologies and to their implementation. Of course, other conditions than the availability of a robust technology/process route are necessary to warranty implementation, like that of a business model to internalize the climate change externality.

3.4 Conclusions on steel as a material

Steel has a continuing role to play as one of the structural materials of the 21st century and beyond, because it is abundant, exhibits a broad array of properties and maintains a reasonable price. No other material, invented in the last 100 years, has shown that it can replace steel, except at the margin.

One of the most interesting features of steel is that it is easy to recycle, because most of its alloys are virtually identical to pure iron and because it is ferromagnetic and thus easy to sort with a magnet. Steel is indefinitely recyclable, mainly because most of the alloying elements that give it its properties are present in low composition and mostly oxidize when scrap is remelted (carbon, silicon, manganese, etc.). Steel claims to be the most recycled material in the world [33], both in terms of volume and of recycling ratio, and this is indeed one of its major strength compared to non-metals and to other metals with which it is competing. Of course this leaves toxic metals like lead or precious ones like gold or platinum outside of the discussion, as they are almost entirely recycled.

Steel has indeed already entered into a close-loop economy, meaning that recycling is privileged compared to production from primary raw materials whenever this is possible. In a somewhat stricter way (hard definition of close-loop economy), close-loop is taken as meaning that all connection with iron ore is severed, i.e. that recycling alone is capable of providing the steel industry with raw material. This extreme case is unlikely to take place quickly or even ever in the case of steel. A simulation based on projections of steel production and residence time of steel (life) in the economy until 2100 is shown in Figure 12 [24]: relying 100% on scrap is not reached by the end of the century in this particular simulation. 100% would only be reached after steel production has peaked, something that will most likely not happen before either world population or the standard of living across the world have peaked, both events that cannot be expected to happen until the 22nd century. Note also that the recycled content of steel will not be uniform across the world, something that is already true today: older industrial economies have a larger scrap resource than younger economies, for example 60% today in the US against 30% on the average in the world. By 2100, the older industrial base might

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Table 5. Aluminum production 2010 in primary and secondary Aluminum.

Aluminum production current situation	2010 production (Mt/year)
Primary Aluminum production Mt	38
Secondary Aluminum production Mt	18
Total	56
Recycled content	32%

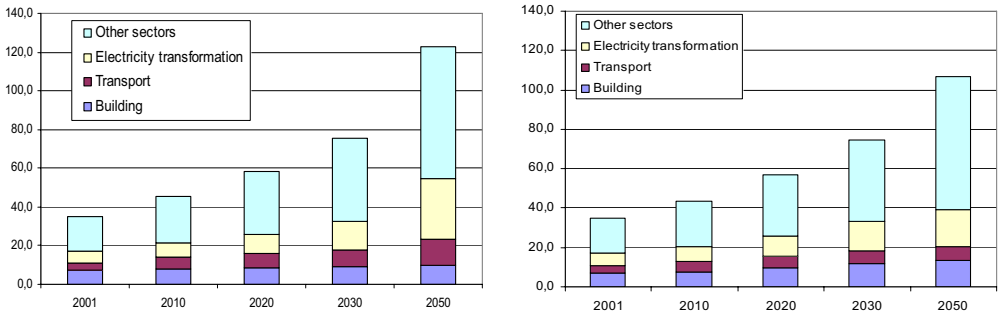


Fig. 13. Evolution of aluminum production until 2050 (reference BAU and 450 scenarios). Production in kt/y.

thus have already entered a full closed-loop economy.

In the meantime, i.e. in the next 100 years, steel will be produced in part by carbon-lean processes. Because these are breakthrough processes, the steel sector has pioneered research in this field and come up with solutions, rather than simple concepts of solutions. This should ensure quicker implementation kinetics than in other sectors, where this kind of RD&D still has to be decided, carried out and succeed. This is different from what other sectors have been doing,

4 Aluminum

Aluminum will be analyzed with the same pattern as steel.

The distinction is made traditionally between primary aluminum, which is produced from ore, i.e. bauxite, through the Bayer process (transformation of bauxite into alumina) and electrolysis, and secondary aluminum, which transforms the primary ingots plus some aluminum scrap into final products.

4.1 Aluminum production

Aluminum annual production level is shown in Table 5 for 2011: it represents roughly 1/30th of the production of steel in mass, but actually 1/10th in monetary value. The recycled content, i.e. the amount of aluminum scrap which is recycled to produce new aluminum metal, is 32%.

Foresight projections from [16, 18] are given in Figures 13 and 14. They cover the fairly broad range of 105 (strongly carbon constrained scenario, LEPII) to 170 Mt/yr (IEA 2008, Blue Map high), depending on the source: production is expected to double or triple compared to 2010, thus identifying aluminum as a key material for economic growth, the extension of wealth and of a higher standard of living across the world. More recent estimates by the IEA [34] show a range of 142–190 Mt/yr.

4.2 Aluminum energy demand

The energy data for aluminum production (cf. Tab. 6) have been collected from the literature, i.e. mainly from industry trade organizations and international agencies [4]: the data have been arranged to show best, average and worst performers, in order to mirror what was made for steel. Note that much of the energy is provided as electricity and that process energy is shown, not the primary energy, which would have introduced the yield of the power plant into the figures. Specific energy is roughly 4 times as large as steel's.

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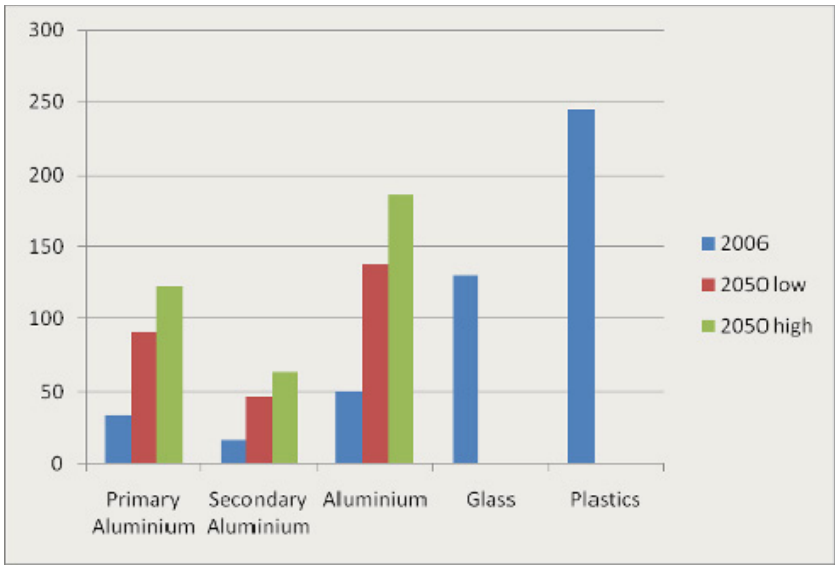


Fig. 14. Production of aluminum, glass and plastics 2050 according to IEA predictions.

Table 6. Energy consumption 2010 in primary and secondary aluminum production.

	2010		
Aluminum energy consumption current situation	Bayer process + H.H. Cell energy consumption GJ/t Al		
Process unit	Best	Average	Worst
Alumina refining	20	24	34
Anode production	1.2	2.2	5.0
Aluminum smelting	49	55	57
Other	0.8	1.9	3.7
Total primary aluminum energy GJ/t Al	71	83	100
Total secondary aluminum energy GJ/t Al	2	5	9
Weighted world average GJ/t Al	50	58	67
Total aluminum TJ/y	2638	3247	3828
Total process related energy demand Mtoe	63	79	91

It is fair to say, however, that the data sources are not of the same nature as those used for steel and thus that critical comments cannot be as detailed.

Data from LCI are given in Table 7. The LCI energy (PED) figures for primary production of aluminum are about 3 times as large as the process figures mentioned before, because LCI shows Primary Energy Demand, which takes on board a yield for the production of electricity around 1/3. Comparing the numbers at a more detailed level would probably point out a spread of published data, quite similar to what was discussed at length in the case of steel.

Projections for 2050 are given in Tables 8 and 9.

In 2050, it is assumed that for primary production of alumina will stem entirely from the Bayer process and that the Hall-Héroult cell will use inert cathodes and wetted anodes, both technologies which are not fully developed today but have been explored at research level up to the scale of pilots. The IEA assumes that they will be available – and then used extensively – from 2030 on, a level of positive technology optimism similar to that surrounding the development and use of ULCOS technologies in the Steel sector. This means a 15% improvement on today's best performers. The difference shown between the best and worst case scenarios is related to the level of recycling rate, 33 to 39% – this a different definition from the one used for the steel sector.

The energy data for aluminum are aggregated in Figure 15. Like the projections for steel, the 2050 vision is based on a

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Table 7. LCI for aluminum (Primary Energy Demand and GWP); source: Ecoinvent.

	Source	Unit	GWP ($kgCO_2eq$)	Primary energy Demand (MJ)	Comments
Aluminum					
Aluminum primary at plant	Ecoinvent 2.01	1 kg	12.2	204	European data
Aluminum secondary from old scrap	Ecoinvent 2.01	1 kg	1.4	24	European data
Aluminum secondary from new scrap	Ecoinvent 2.01	1 kg	0.4	8	European data

Table 8. Energy consumption 2050 in production of primary and secondary aluminum.

	2050		
Aluminum energy consumption future scenario	BAT Bayer process + Inert Anode + Wetted Cathode GJ/t Al		
Process unit	Best	Average	Worst
Alumina refining	16.5	18.1	19.4
Anode production	2.5	2.7	2.8
Aluminum smelting	39	43	47
Other	0.7	0.8	0.8
Total primary aluminum energy GJ/t Al	59	64	70
Total secondary aluminum energy GJ/t Al	1	2	2
Weighted world average GJ/t Al	36	42	48
Total aluminum TJ/y	5096	6687	9041
Total process related energy demand Mtoe	122	160	216

Table 9. Aluminum production 2050 in primary and secondary aluminum with different recycling rate scenarios.

Aluminum production future scenario	2050 Mt/year		
	Low	Average	High
Primary aluminum production Mt	86	102	127
Secondary aluminum production Mt	56	57	63
Total Mt	142	159	190
Recycling rate	39%	36%	33%

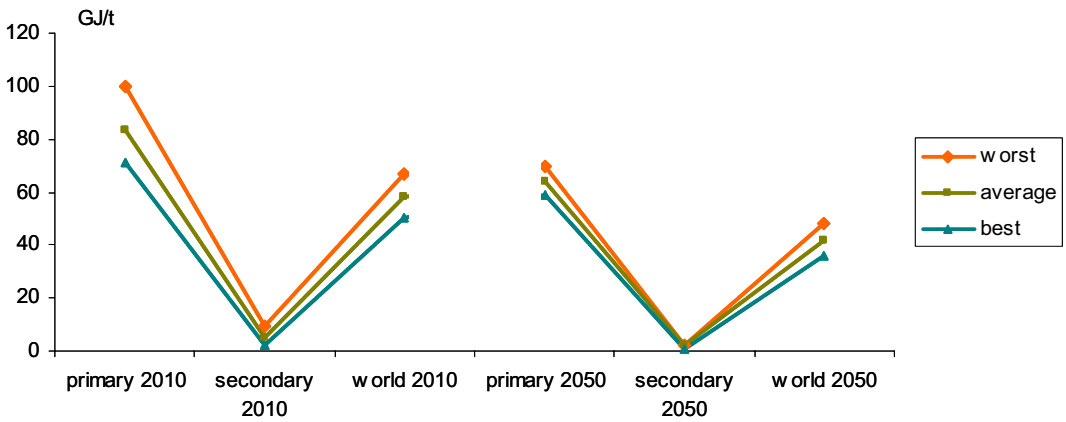


Fig. 15. Energy demand (process energy in GJ/t) for aluminum production in 2010 and 2050.

technology optimistic view of the future centered on mitigating Climate Change and on increasing energy efficiency. This assumption would double the total sectoral energy demand in 2050, compared to 2010. This is the opposite of the projection for steel, which would decrease it: this is due to the projection of the level of recycling, which is less than steel's; the difference in the amount of production which could thus be produced from scrap between the two materials may be a difference in the recycling features of the two materials but also a different vision for 2050 and for its "needs".

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Table 10. Scope I emissions 2010 in primary and secondary aluminum production.

Scope I	2010		
Aluminum CO_2 emissions	Bayer process + H.H. cell t CO_2/t Al		
Process unit	Best	Average	Worst
Alumina refining/fuel/lime production	1.5	1.8	2.0
Anode production	0.2	0.2	0.2
Anode consumption	1.4	1.5	1.7
PFC	0.2	0.2	0.3
Other	0.2	0.2	0.3
Total Emissions from primary production t CO_2/t Al	3.6	3.9	4.5
Secondary production t CO_2/t Al (Fuel NG)	0.1	0.3	0.5
Total direct emissions t CO_2/ tAl	3.7	4.1	4.9

Table 11. Scope I emissions 2050 in primary and secondary aluminum production.

Scope I	2050		
Aluminum CO_2 emissions	Bayer process + H.H. cell t CO_2/t Al		
Process unit	Best	Average	Worst
Alumina refining/fuel/lime production	1.5	1.6	1.7
Anode production	0.2	0.3	0.3
Anode consumption	0	0	0
PFC	0	0	0
Other	0.1	0.2	0.3
Total Emissions from primary production t CO_2/t Al	1.8	2.1	2.3
Secondary production t CO_2/t Al (Fuel NG)	0.1	0.1	0.1
Total direct emissions t CO_2/ tAl	1.9	2.2	2.4

Table 12. Scope II emissions 2010 in primary aluminum production.

Scope II	2010		
Aluminum Electricity	Bayer process + H.H. cell t CO_2/t Al		
Process unit	Best	Average	Worst
Alumina refining, kwh/t Al	200	300	389
Anode production, kwh/t Al	56	100	120
Electrolysis, kwh/t Al	12 900	14 000	15 400
Total electricity kWh/t Al	13 156	14 400	15 909
Total indirect emissions t CO_2/t Al	4.9	5.3	5.9

4.3 Aluminum greenhouse gas emissions

GHG emission data for aluminum production in 2010 and in 2050 are shown in Table 10–13 and Figure 16.

Note that, while GHG emissions could be assimilated to CO_2 only in the case of steel, this is no longer true for aluminum, which generates perfluorocarbons (PFC) in the Hall-Héroult cell due to the decomposition of cryolite. This has been taken on board in the following analysis: assumptions made for the evolution of electrolysis technologies in 2050 assume that PCF emissions disappear as well as the CO_2 emissions due to the oxidation of the graphite anode, which has been replaced by an inert anode.

Recycling aluminum brings an even more spectacular improvement in greenhouse gas emissions than was the case for steel, mainly because the melting point of aluminum is much lower than iron's. This gives a strong incentive to getting the recycling rate as high as possible. However, this does not necessarily translate into a very high recycled content (predicted to increase from 32 to 39% in a best case scenario), probably because aluminum alloys are more alloyed than steel, because the industry is much younger and cannot yet capitalize on a huge stock of old metal, like steel can, or because analysis has not been completed on this matter.

Aluminum, like steel, has developed a roadmap for cutting its greenhouse gas emissions significantly, thus being

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Table 13. Scope II emissions 2050 in primary and secondary aluminum production.

Scope II	2050		
Aluminum electricity	Bayer process + H.H. cell t CO_2/t Al		
Process unit	Best	Average	Worst
Alumina refining, kwh/t Al	200	230	260
Anode production, kwh/t Al	56	100	120
Electrolysis, kwh/t Al	13 000	14 000	15 000
Total electricity kWh/t Al	13 256	14 330	15 380
Total indirect emissions t CO_2/t Al Case 1	1.2	1.3	1.4
Total indirect emissions t CO_2/t Al Case 2	2.1	2.3	2.5

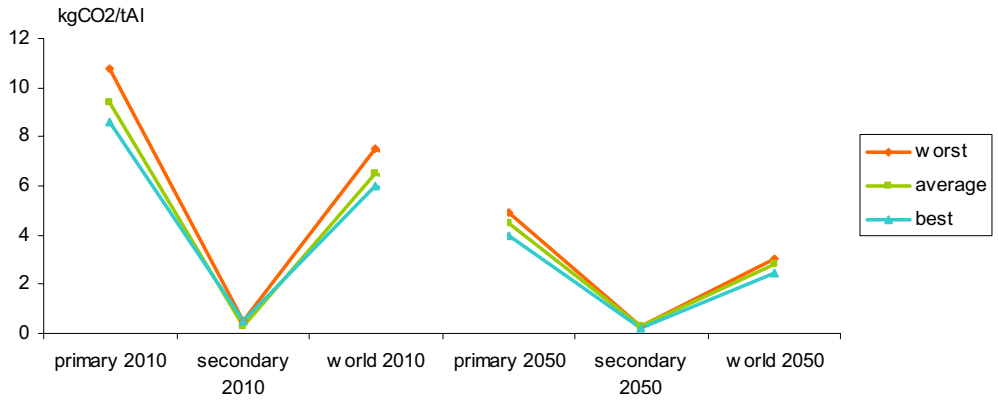


Fig. 16. GHG emissions in the case of aluminum production (case 2 for 2050).

responsive to the climate Change challenge. This is a 60% decrease on specific emissions and, at sectoral level, which would or increase emissions slightly. As was analyzed in the case of energy, this is different from the steel picture and is due to the recycled content estimates for 2050, which are lower.

4.4 Conclusions on aluminum as a material

At a qualitative level, aluminum behaves like steel: the large footprint due to primary production can be alleviated by recycling. Differences between the two metals are due to the higher footprint of primary aluminum per ton, which is due to the larger electronegativity of the element, a very basic physico-chemical property and to the lower recycling level predicted by 2050. The two metals can keep competing briskly as the difference in density compensates part of the gap and makes for interesting comparisons at the functional level of a full LCA.

As a common conclusion that holds for all metals, their recycling ability gives them an important leverage on their ecological footprint. They share this feature with paper and glass.

5 Cement and concrete [4]

Cement is produced today from raw materials in a cement kiln to produce clinker, which is then mixed with other materials, usually secondary raw materials (blast furnace slag, fly ash), i.e. residues from other industries, but also gypsum, to produce cement per se. The amount of each varies, depending on the quality of cement.

5.1 Cement production

Cement is the largest structural material in terms of production volume in the world and, as cement is used to make concrete (typically, 300 kg of cement per m^3 of concrete), concrete is several times more ubiquous than steel or wood.

Cement production ought to continue to increase, as shown in Figures 7 and 17. Various models make slightly different projections, like was discussed in the sections on

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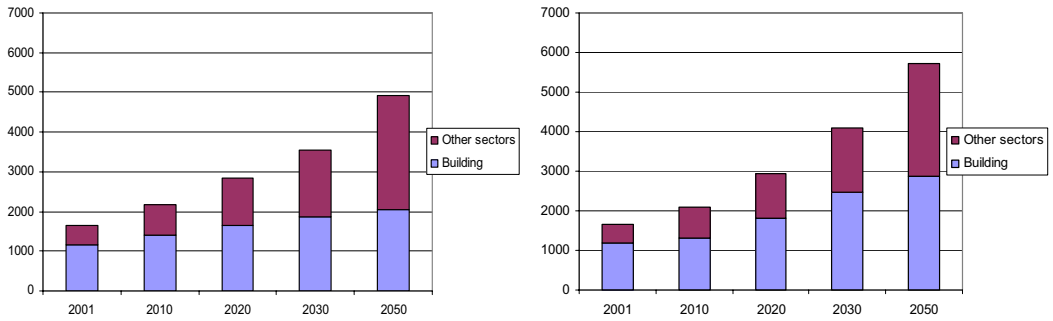


Fig. 17. Evolution of cement production until 2050 (reference BAU and 450 scenarios). Production in Mt/y.

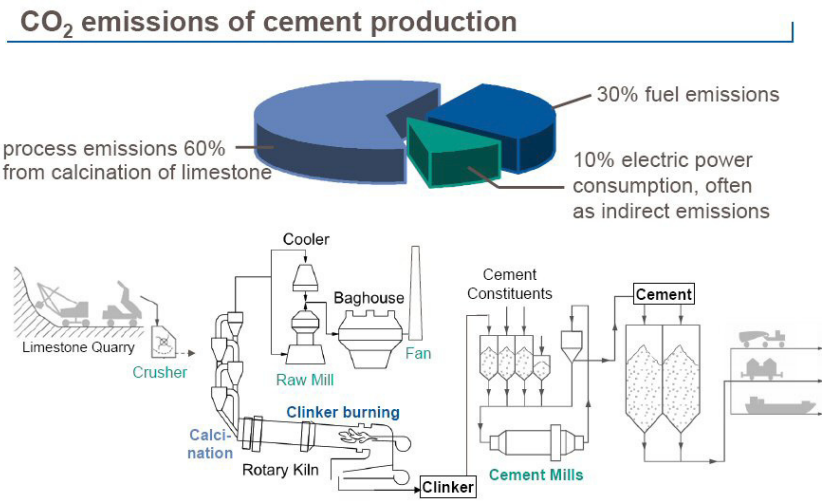


Fig. 18. Scheme of cement production and pie chart of CO_2 emissions categories.

metals, but the trends are the same: a large increase in production is forecast, which is fairly unrelated to the climate scenarios and to the methodology used to model the world economy. Cement, like steel comes out as a core material in our modern world and the growth of the world economy has a strong need for it.

The reference will always be to Portland cement in the following sections. The information analyzed here originates from [7,35,36].

5.2 Energy consumption

Energy in the cement kiln is used to calcinate calcium carbonate at 950 °C (i.e. decompose it into CaO) and then to "burn" the clinker at 1450 °C to generate its hydraulic properties; in addition, electrical energy is needed to run the equipment: 3.7 GJ/$t_{clinker}$ on the one hand, and 110 kWh/t_{cement}. According to the IEA, this translates in 2010 into 3.9 GJ/$t_{clinker}$. This should be viewed as a sectoral average value, at the level of 3.1 GJ/t_{cement}.

This is the figure for "dry" kilns, the standard technology today; "humid" kilns need 50% more energy. Some of the energy burnt in the kiln also often consists of secondary carbon-bearing raw materials, such as old tires or animal feed (up to 54% of the fossil energy needs).

IEA projection for 2050 are at the level of 3.2–3.3 GJ/$t_{clinker}$.

5.3 CO_2 emissions – cement

Direct CO_2 emissions today, i.e. scope I emissions, (cf. Fig. 18) are at the level of 0.8, 0.6 and 0.2 t_{CO_2} per ton of clinker, cement

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and concrete, respectively. These include 0.53 $t_{CO_2}/t_{clinker}$, which come from the decarbonizing of limestone. The emissions due to electricity (scope II) would add 40 kg of CO_2 with the present average EU electricity mix (370 g/kWh), i.e. add up to scope I and II emissions of 0.640 t_{CO_2}/t_{cement}. These figures include 50% of alternative fuels and biomass: if one were to reintroduce the avoided emissions in the total, this would add another 0.18 $t_{CO_2}/t_{clinker}$, i.e. a global figure of 0.96 $t_{CO_2}/t_{clinker}$.

Whether these emissions ought to be included in the emissions or not is a matter of controversy: indeed, they are based on two strong assumptions, on the one hand that these alternative sources avoid the use of fossil fuel (a consequential LCA analysis would be needed to establish that), and on the other hand that biomass is carbon-neutral (this avoids discussing Land-Use Change or LCU). Both are conventions rather than established results that can be safely included in an LCA approach. Moreover, they belong to scope III and LCI approaches even though they are included in a scope I analysis.

In the long term, the IEA roadmap projects emissions for the world sector at 2.34 Gt for the baseline scenario and 1.55 Gt for the "Blue" scenario (cement to clinker ratio of 71%), i.e. 0.42 $t_{CO_2}/t_{clinker}$ and 0.64 $t_{CO_2}/t_{clinker}$, depending on the assumption regarding alternative fuels.

This lower scenario would include reductions due to:

- 10% increase in energy efficiency;
- 24% switch to alternative fuels and other fuels;
- 10% of clinker substitution;
- 56% due to CCS implementation, i.e. 220 to 430 kilns equipped by 2050.

There are a lot of ad hoc assumptions in this scenario, related mainly to the effect of clinker and fuel substitution. One of them, for instance, is that blast furnace slag is sold to the cement industry without any CO_2 allocation, which the Steel sector is not necessarily willing to do.

On the other hand, the roadmap projections do not include some possible breakthrough products for the cement sector, which would decrease CO_2 emissions dramatically, such as:

- *NOVACEM cement*, made from MgO (ex silicates) rather than CaO (ex carbonates)-based cement, would reduce significantly CO_2 needs and the product would harden by picking up CO_2 from the atmosphere, thus opening up the prospect that this cement would be carbon-negative [37].
- *CALERA* proposes to mix calcium and magnesium carbonates and hydroxides, to add brine, sea water or brackish water and to use the waste heat from a power station's flue gas and its CO_2 content to precipitate carbonates and decrease overall carbon footprint compared to Portland cement [38].
- *CALIX's cement* is produced by calcinizing dolomite rocks in superheated steam, the resulting CO_2 being highly concentrated and easier to capture and further store [39].
- *Geopolymer cements* use residues from other industries and concrete waste and activates the hydraulic properties using alkalis (NaOH or KOH) [40].

The potential of these solutions to cut emissions is real but the market share that they can grab by 2050 is very uncertain.

LCI data are given in Table 14 for reference. Available information on these materials does not make it possible to analyze the differences versus process data as closely as was done for steel or aluminum.

5.4 Conclusions on cement as a material

Cement is a material which is very different from a metal at a fundamental level and, thus, its levers for accommodating more energy efficiency and lower CO_2 emissions are different, mainly exogenous compared to what the metal industries can do. On the other hand, it is cheap and will remain cheaper than metals and thus keep being used at a level that is several times that of steel, the most used metal.

Cement cannot be recycled as a similar material: its hydraulic properties can only be used once. However, it can be reused as aggregate added to new cement to make

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Table 14. LCI data for glass, concrete and cement (source: EcoInvent).

	Source	Unité	GWP (kg CO_2eq)	Primary energy Demand (MJ)	Comments
Glass					
flat glass coated at plant	Ecoinvent 2.01	1 kg	0.67	14.8	European data
packaging glass white at plant	Ecoinvent 2.01	1 kg	0.83	15.2	European data
Concrete					
concrete normal at plant	Ecoinvent 2.01	1 kg	0.11	0.7	density: 2.38; Swiss data
concrete exacting at plant	Ecoinvent 2.01	1 kg	0.14	0.8	density: 2.44; Swiss data
Concrete C30/37 PE	PE	1 kg	0.11	0.6	density 2.3; Swiss & German data
Cement					
cement unspecified at plant	Ecoinvent 2.01	1 kg	0.77	3.8	Swiss data
cement portland class Z42-5	Ecoinvent 2.01	1 kg	0.84	4.04	Swiss data
Blast furnace slag cement	Ecoinvent 2.01	1 kg	0.45	3	Swiss data

concrete and thus displace quarry material: the move can be significant in terms of use of natural resources but is not very large in terms of energy demand and GWP.

What it can do, and has been doing for a long time, is use waste from other sectors, as fuel or as clinker substitutes. The driver until now has been economic and has indeed managed to keep the price of cement low, because the cement kiln has in effect been used as an industrial incinerator, for a fee.

This does not cut energy demand nor reduce GHG emissions at process level. One can argue that this may displace other energy uses or GHG emissions if a proper case to support the claim is made in the framework of a consequential LCA and thus help the cement do its bit in fighting climate change.

The cement sector is also investigating the use of CCS as a way to deal with its CO_2 emissions directly, as metals do or are planning to do – and thus not through a burden-shifting mechanism. This would cut emissions unambiguously but also add cost, which would probably be at the same level as the present price of cement: the industry is searching for an adequate business model to take this on board, like steel, but with an even stronger incentive.

6 Glass [4]

80% of glass production is used in containers, in windows of buildings or vehicles and in glass wool (fiberglass) for insulating purposes. It is therefore a structural material providing transparency to light, structural strength in packaging and curbing heat transfer.

The global glass production in 2010 is in the order of 140 Mt/yr (extrapolated IEA data) [4]. Foresights for the total global glass manufacturing volume in 2050 are uncertain (cf. Fig. 19 for flat glass used in construction), but can be assumed (in analogy with other materials) to be between two to three times the current production, that is in the range of 280 to 420 Mt/yr.

Energy consumption is mostly due to heating and melting, where enthalpies amount to 2.5 GJ/t (+/–0.2, depending on composition) and are much lower than metal's but slightly higher than cement's. The sector qualifies as energy intensive, especially since actual consumption is several times higher than this thermodynamic need. Annealing uses up about 25% of total energy consumption.

Recycled glass is in principle an easy-to-use raw material and, indeed, glass is recycled to a high level (e.g. 62% in France) [42].

Actual figures of energy consumption for melting glass are shown in Table 15 as reported for the US. There are large differences in the efficiency of the various technologies used in the industry, a 1 to 4 factor.

Energy consumption and GHG emissions, in this case overwhelmingly CO_2, are given in Tables 16–18. They have been

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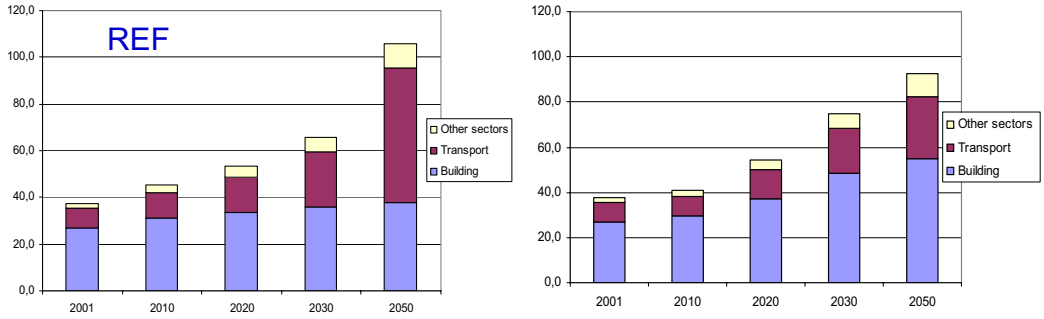


Fig. 19. Evolution of flat glass production until 2050 (reference BAU and 450 scenarios). Production in Mt/y [41].

Table 15. Estimated specific energy consumption of glass melting furnace in the US [43].

Subsector/ Furnace type	Estimated share	Average specific energy (GJ/ton)			
		Nat gas	Electricity	Electricity losses	Primary energy
Container glass					
Regenerative	70%	5–11	0.1–0.5	0.6	8.9
Oxy-fuel	30%	3.9–4.6	0.6–0.8	1.6	6.5
Electric boost	15%	3.5–6.3	0.6–1.2	1.8	7.6
Electric melter	n.a.	–	2.6–3.2	6.1	9.1
Flat glass					
Regenerative	80%	6.5–12.5	0.1–0.6	0.6	9.9
Oxy-fuel	20%	5.0	0.7	1.6	7.3
Electric boost	n.a.	5.3–6.6	0.6–1.2	1.8	8.6
Fiberglass insulation					
Electric melter	55%	–	3.2–12.6	16.5	24.4
Recuperative	10%	6.3–8.5	–	–	7.4

Table 16. Energy intensities for the production of glass today, and predictions for 2050.

	GJ/t_{glass}	Soda-lime (cullet $\bar{x}$ = 5%)	Soda-lime (cullet $\bar{x}$ = 45%)	Boro-silicate (cullet $\bar{x}$ = 55%)
2010	Best performers	7	4.7	7
	Sector average	9	7	8
	Worst performers	10.5	8.5	20
2050	Sector average	5–7	4–5	5–6

Table 17. Estimated CO_2 emission intensities of Soda-Lime glass today, and predictions for 2050.

	t_{CO_2}/t_{glass}	Soda-lime (low cullet 0–5%)			Soda-lime (medium-high cullet 45–50%)		
		Scope I	Scope II*	Scope I+II	Scope I	Scope II*	Scope I+II
2010	Sector average	0.75	0.12	0.87	0.50	0.11	0.61
2050	Sector alt I	0.50	0.04	0.54	0.32	0.03	0.35
	Sector alt II	0.50	0.02	0.52	0.32	0.02	0.34

* Emission factors for Scope II calculations: 2010 = 370 g/kWh, 2050 alt I = 160 g/kWh, 2050 alt II = 92 g/kWh.

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Table 18. Estimated CO_2 emission intensities of Boro-Silicate glass today, and predictions for 2050.

	t_{CO_2}/t_{glass}	Boro-silicate (cullet 40%)			Boro-silicate (cullet 70%)		
		Scope I	Scope II*	Scope I+II	Scope I	Scope II*	Scope I+II
2010	Sector average	1.35	0.42	1.77	1.05	0.32	1.37
2050	Sector alt I	1.05	0.14	1.19	0.75	0.10	0.85
	Sector alt II	1.05	0.08	1.13	0.75	0.06	0.81

* Emission factors for Scope II calculations: 2010 = 370 g/kWh, 2050 alt I = 160 g/kWh, 2050 alt II = 92 g/kWh.

Table 19. Energy consumption (process energy) and CO_2 emissions due to the manufacture and end of life of plastics.

2010	Feedstock	Process chain	transport	cradle to gate + EoL
GJ/t	45.6	23.9	9.6	79.1
tCO_2/t	0.74	0.99	0.96	2.69

2050	Feedstock	Process chain	transport	cradle to gate + EoL
GJ/t	40.7	21.4	8.6	70.7
tCO_2/t	0.5	0.67	0.64	1.81

compiled from various sources, as the industry does not publish aggregated data. Similarly, projections for 2050 are rare and a process roadmap for saving energy and reducing its carbon footprint has not been found: thus only incremental progress related to energy efficiency has been taken on board, contrary to what was done for metals and cement.

This translates into an improvement in energy consumption of 25 to 45%, which is paradoxically more than what was forecast for the previously analyzed materials; indeed, as the process for glass seems less optimized today, there is more room for improvement. Improvements in CO_2 specific emissions (scopes I and II) are very close to the energy cuts, which is fully consistent with the assumptions that were made to project them.

The Glass sector is less integrated, more diversified in terms of products and less intensive in turnover and volume of production that either the cement or steel sectors, and thus has produced less long-term projections of its energy and carbon footprint than the more production-intensive materials. This does not mean, however, that visions for a post-carbon future are not under formalization in the Glass community, as Figure 20 shows [42].

LCI data are given in Table 14 for reference.

7 Polymers and plastics

Plastics production was 230 Mt in 2009 and 265 in 2010. Its uses are in packaging (40%), furniture and small domestic goods (26%), building and construction (20%) and automotive applications (7%) [44]. 75% of plastics belong to 5 families: polyethylene (PE), polypropylene (PP), polyvinyl chloride PVC), polystyrene (PS), and polyethylene tetraphtalate (PET).

Sector figures, which are not consolidated in publications, have been aggregated in [4] and they are shown in Table 19.

The data are split into 4 categories:

– *feedstock data* account for the energy content of the whole plastic stock and for CO_2 emissions generated when plastics are incinerated at end of life. The feedstock energy is quite large and accounts for about twice as much as process chain energy. Including the energy feedstock in the plastics energy footprint is one of several possible methodological choices: another choice would consist in ignoring this feedstock energy as it stays trapped inside the material until it is eventually returned to its basic constituents, by combustion or degradation; taking it on board means that the removal of the petrochemical from nature (the oil field for example) removes its chemical and energy contents at the same time, which

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Fig. 20. Vision of a glass plant in 2030 (Saint Gobain).

is then no longer available for other uses. There is some analogy with coal for iron-making, which is counted as part of the raw material needed for making steel. In the present data selected for plastics, GHG emissions, on the other hand, are accounted to the level to which incineration takes place – which does not overestimate the CO_2 burden;

- from a practical standpoint, this is a simplified model of end of life, which does not represent what really happens: plastics are not overwhelmingly incinerated, so that the energy generated in practice is less – and the part which is actually burned does not produce usable energy at the level of the LCV of plastics;
- *process chain* data account for scope I and scope II emissions, in the various processes that follow each other from the oil well to the refinery and to the chemical plants that transform it into polymers and plastics;
- *transport data* take on board the emissions related to transportation at various steps of the value chain;
- *cradle to grave + end of life data* add up all these elements to account for the material footprint all along the value chain, except during the use phase.

2050 projections have been extrapolated by assuming a general use of present best practices, as there are no long-term forecasts publicly available in the literature. This amounts to a 10% drop in specific energy needs and a 33% drop in CO_2 emissions.

To reduce the energy and CO_2 footprints, in a Life-Cycle Analysis context:

- reuse is a way forward;
- recycling is another way forward, although not always easy to put in practice due to the nature of the material, as only thermoplastics can be recycled; recycling can be carried out directly like what metals do (i.e. material to identical material) or as "feedstock recycling", where old plastic is broken back into monomers from which new plastic is produced. It amounts to 30% in Europe today and 8% in the world [4];
- energy recovery is another way forward, which should be analyzed in the context of a consequential LCA (thus taken on board if and only if the energy displaces the use of fossil fuel, for example): this

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Table 20. Typical energy intensities for the production of wood products, and predictions for 2050.

	GJ/t_p	Framing lumber	Glued-laminated timber
2010	Typical total	7.0	9.0
	– fossil + indirect	2–5	4–7
	– internal (biogenic)	2–5	2–5
2050	Estimate	5.0	6.0

Table 21. Typical CO_2 intensities for the production of wood products, and predictions for 2050.

	t_{CO_2}/t_p	Framing lumber	Glued-laminated timber
2010	Typical total	0.18–0.35	0.22–0.44
	– fossil + indirect	0.05–0.08	0.10–0.15
	– internal (biogenic)	0.10–0.30	0.10–0.30
2050	Estimate	0.12	0.15

is an end of life that somehow fits the nature of plastics better. Incineration, not exactly energy recovery, represents 30% in Europe today and 25% in the world [4];
– bio-plastics constitute another solution, which could cut emissions significantly, assuming that the feedstock is certified as exhibiting a low-CO_2 footprint.

Note that these solutions have not been included explicitely in the analysis, like what was done in the case of metals, because of a lack of references on the issue. The various recycling and recovery processes are supposed to have been included in the industry data that were used, at their present level.

LCI data are given in Table 14 for reference.

8 Wood

Wood is at the same time a raw material for making paper, a fuel used directly or after carbonization into charcoal and also a structural material, which is the main focus here.

Wood is a renewable material, the first of this kind in the list of structural materials examined previously in this paper, and thus requires a specific methodology for analyzing its energy and CO_2 footprints. Renewable means that the material is in part generated by "natural", biological processes, which collect the elements from atmosphere and soil and energy from the sun – as plants are involved. What is renewable is actually the raw materials from which wood is made (timber), a process that takes place within the biosphere, while their transformation into materials used by the economy like construction wood takes place in a processing plant fully immerged in the anthroposphere.

The complexity of the biological process is not usually analyzed in terms of energy and mass balances, although this is starting to happen [45, 46], but still needs a lot more work: for example, the "yield" of photosynthesis (energy stored in the wood over incident solar energy), which is of the order of 0.85% [47] a small figure for anyone used to discussing energy efficiency, is rarely discussed nor compared to artificial processes like photovoltaics, which is an order of magnitude more efficient[2].

Process figures for construction wood are given in Tables 20 and 21.

The energy figures in Table 20 do not include the energy involved in the natural process, nor any end of life energy recovery: energy consumption is thus gate to gate, in the wood factory (saw mill and wood processing plant) and includes fossil fuel and electricity (*fossil + indirect*) plus the use of wood residues, chips, saw dust or mulch, called (*internal, biogenic*).

The CO_2 emissions figures in Table 21 in effect take on board gate to gate process emissions, both scope I and scope II. The emissions from wood residues are taken at face value, i.e. without any credit or claim at

[2] This, incidentally, points out that natural or biological processes do not operate on the basis of best energy efficiency. Natural selection and survival of the species call on many more optimization criteria and it is not clear if they could actually be described by an optimization function.

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Table 22. LCI data of wood, from EcoInvent and Gabi databases.

	Ecoinvent	GaBi
	RER: sawn timber, softwood, raw, kiln dried, u = 10%, at plant	DE: Solid construction timber (softwood) PE
CML2001 – Dec. 07, Global Warming Potential (GWP 100 years) [kg CO_2-Equiv.]	–1.41	–1.27
Primary energy demand from ren. and non ren. resources (net cal. value) [MJ]	21.89	27.02

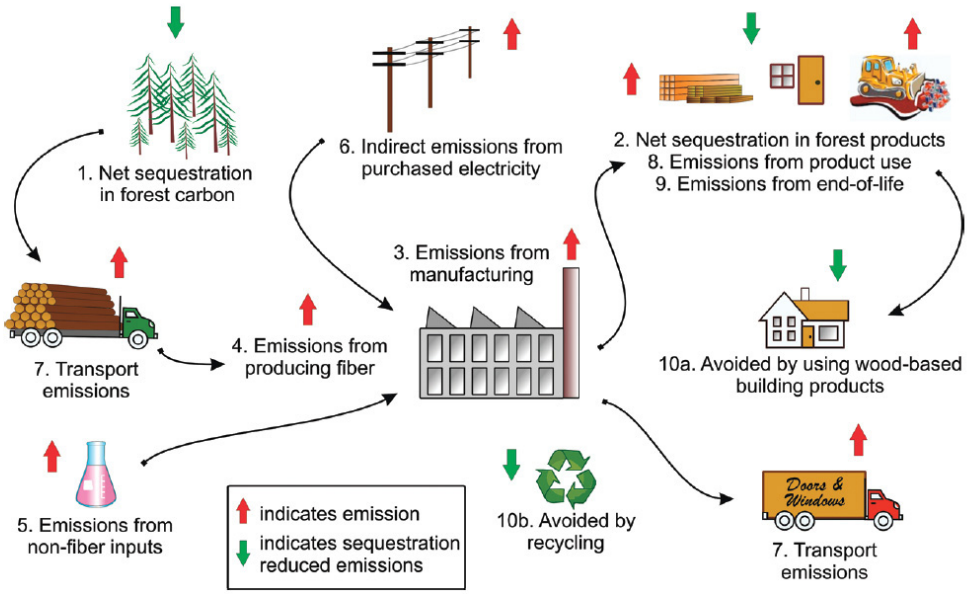


Fig. 21. Elements of the forest products industry related to its greenhouse gas profile (1).

their carbon-neutrality. No end of life is assumed either, nor any feedstock energy content; this is therefore different from what was presented in the case of plastics.

For the sake of completeness, the LCI data of wood are given in Table 22 and the physiological chemistry of wood generation explained in Figure 21 from a CO_2 balance standpoint. The connection with the process data of the previous tables is not fully clear. Figure 21 illustrates why: wood is such a different case from the other structural materials that many new input/output have to be taken into account and the options for doing so are numerous and not explicitely stated. We will therefore accept the present status of work on progress in this area and renounce telling a better story. Wood will also be left out of the comparisons made in the next section.

In Scandinavia, experts in the field of using wood in construction have designed a special methodology to compare wood with other materials, which bypasses a detailed LCA description. They have introduced a displacement factor expressing the efficiency of using biomass to reduce greenhouse gas emissions, by quantifying the amount of emission reduction achieved per unit of wood used. Usually this is exemplified by comparing the use of wood products with that of a cement-based product. The rationale is to avoid CO_2 emissions from cement manufacturing and to take advantage

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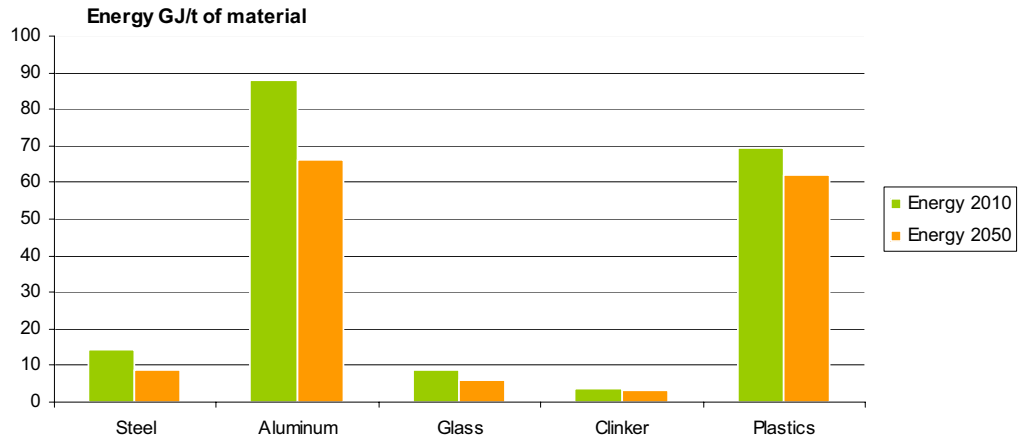


Fig. 22. Energy consumption for producing one ton of structural materials in 2010 and projected in 2050.

of the mitigation possibilities from forest to end-of-life recovery. This is a kind of life cycle analysis/life cycle inventory approach.

The displacement factors can be defined as tonnes of carbon, t_C, of emission reduction per t_C in wood product [4]. In case of negative displacement factors, the GHG emissions of wood products are greater than that of alternatives. In case studies on buildings, the use of wood instead of cement/concrete usually leads to displacement factors in the range of 1.0 to 3.0 [4]. The use of wood instead of steel leads to lower displacement factors, in some cases in favor of steel [4]. The concept of wood substitution to replace other products in order to reduce greenhouse gas emissions requires that forests are sustainably managed and that wood residues are used responsibly.

9 Comparisons between materials

In this section, the data presented for each structural material regarding energy demand and CO_2 emissions, are brought together and their levels compared. This should make it possible to attempt a comparison between materials and to give the premises of a discussion on materials competition and on their possible substitution but also to compare how they seem able to evolve by 2050 in the face of expected constraints on energy consumption and GHG emissions.

Figure 22 shows specific energy consumption for each of the materials surveyed. Clinker (cement) is the less intensive in energy (per unit of mass), followed by glass, then steel and plastics. The order of merit and the relative levels stem directly from the major features of these materials reviewed under the Materials 101 section. In the case of plastics, feedstock energy is added to cradle to gate emissions and thus positions them at a very high level of energy intensity: as pointed out before, this is due to their dual nature of material and fuel and, to some extend, it is a methodological convention. Metals require more work to scavenge the metal from ores, often oxides, by chemical reduction, than the mineral (lithic) materials where separation of minerals from raw materials can be carried out with limited chemical transformations. Among metals, the most electronegative ones, i.e. those of which the oxides are the most stable, need more energy.

Comparing energy intensity of materials per ton is not necessarily very meaningful, as materials are used and selected for a combination of properties, like energy, density, strength or rigidity, weighted according to a particular design criterion, which leads to some optimization function. It is the purpose of LCA to carry out this kind of comparison on a well specified "functional unit" and there are no simple ways to establish an order of merit among them, as each case is different. It is also the objective of design

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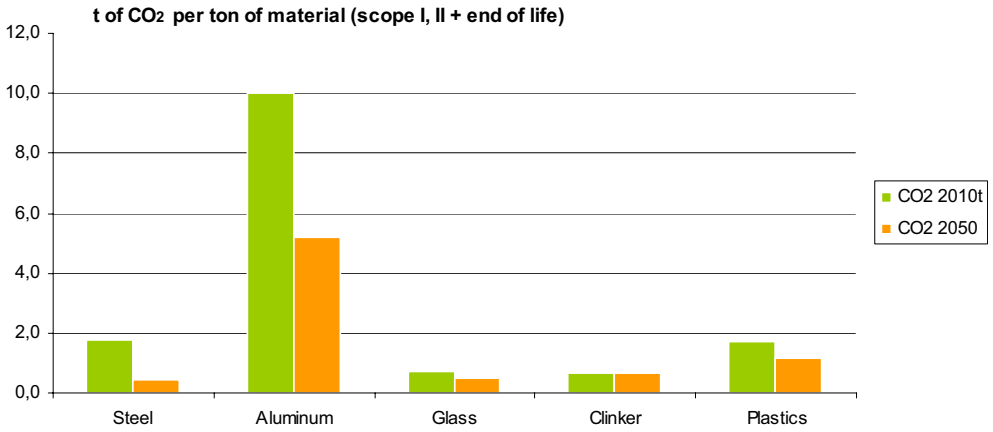


Fig. 23. Specific CO_2 (equivalent) emissions related to structural materials for producing and disposing (end of life) of them. Energy-related emissions (scope II) are also included.

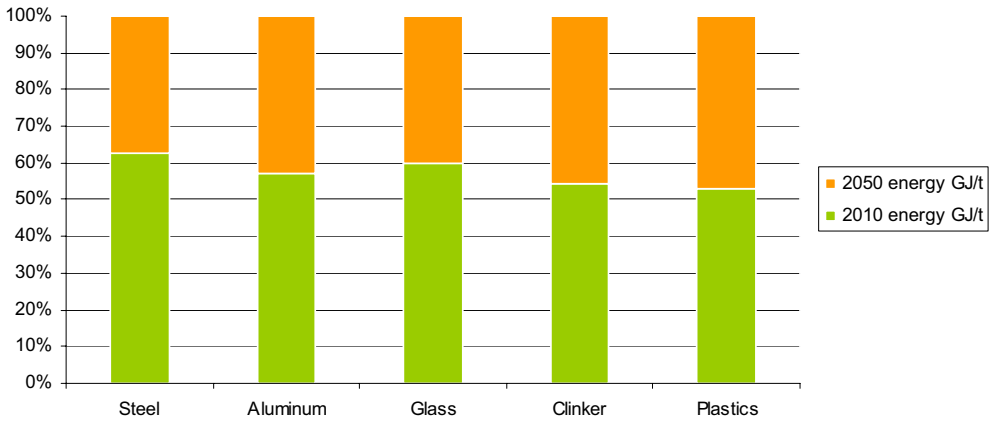


Fig. 24. Comparison between specific energy consumption in 2010 and 2050 of major structural materials.

and eco-design, at an earlier creative stage to combine these various properties to achieve a design purpose [10].

The CO_2 emission factor (Fig. 25) of structural materials is a fairly direct mirror image of energy intensity, with slight differences related to the energy mix that is used to make each material and to specific material features like the decarbonatation in a cement kiln. Plastics behave in a different way, because all of the feedstock energy is included in Figure 22, while only the part of plastics that end up being incinerated is shown in Figure 25.

The evolution between today and 2050 is also interesting to analyze and the presentations of Figures 24 and 25 may be helpful in that respect.

In terms of energy intensity, the largest transition is accomplished by steel, then by glass and aluminum: this is due to efficiency gains but also to the progression of recycling. Cement and plastics seem to accomplish less, because they are only relying on efficiency gains in the image we have collected from the literature. As a matter of fact, efficiency gains are fairly limited for the best performers in the manufacture of most materials, especially those produced through pyrometallurgical processes, and they rely mostly in applying best technologies and best practices to technology-laggard plants.

The evolution regarding CO_2 emissions can be much larger than energy's, because some of the CO_2 mitigating solutions are decoupled from energy reducing ones, foremost among which is CCS.

These conclusions should be mitigated by the fact that 2050 projections rely on scenarios which are not fully coherent

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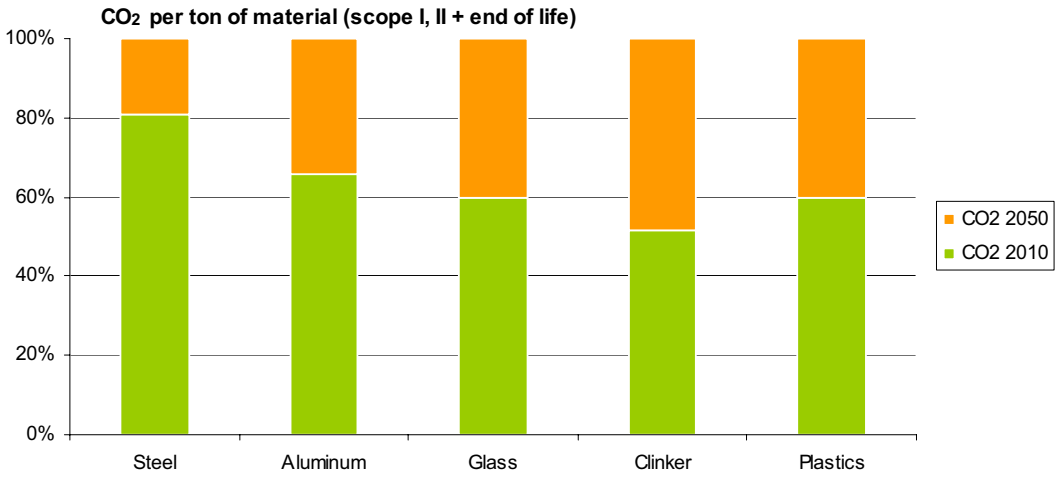


Fig. 25. Comparison between specific CO_2 emissions in 2010 and 2050 of major structural materials.

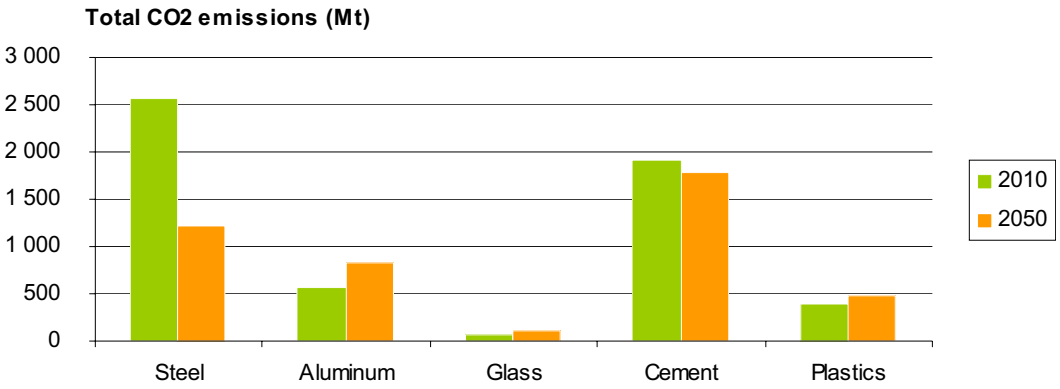


Fig. 26. Sectoral total CO_2 emissions.

among the various materials, which is compounding the fact that future projections are also by nature educated guesses or guestimates.

Figure 26 shows the evolution of global sectoral CO_2 emissions for each of the major materials in 2010 and 2050.

While all materials increase production by a factor of 2 or 3, some decrease their emissions and others increase them. This is very much related to the projection chosen for the evolution of recycled content and for the introduction of breakthrough technologies for mitigating GHG emissions: these projections, in turn, reflect how each material community projects its future (communication, roadmaps) and has been preparing it (research, pilots, demonstrators, etc.). Moreover, one should point out again that all future projections do not contain the same amount of "guess work": when a breakthrough technology has reached the scale of a large pilot or a demonstrator, then it is more likely to happen than when only a roadmap has been produced or when no special technical studies have been carried out yet, beyond communication exercises.

Anyway, steel reduces its global emissions, under the present set of assumptions and so does cement to a lower level. The other materials increase them. The special position of steel, as already pointed out before, is due to the large move towards a closed-loop economy taken on board in the foresight vision and to the assumption that CO_2-lean technologies, such as ULCOS' [6], will be broadly implemented by 2050. The other materials perform differently, because

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recycling is either less massive or does not play a large role due to the core nature of the material.

This does not necessarily gives a true or entirely believable picture of the post-carbon society that ought to be with us in 2050, but of how each material community projects itself and communicates about it.

10 Conclusions

Interesting as the exercise carried ou in this paper may be, it is risky for several reasons:

- the seemingly simple task of collecting present data on energy efficiency and GHG emissions by material sector is anything but simple;
- 2050 projections today are heavily bent towards foresight exercises dealing with energy and GHG emissions, mostly and rather exclusively. Each material has responded in different ways to the Climate Change challenge and to the political pressures that this has created. The various scenarios and forecasts publicly available paint a global landscape that is not fully coherent among materials. Thus, they belong to the real world, not to an academic platonic vision of the future.

Regarding data first, it is quite obvious from this paper that the data available in the "data sphere" are not fully coherent, do not all represent the same things, or cannot even be found. Consumed energy and Primary Energy Demand, for example, are two very different things. So is the distinction between renewable and non-renewable energy, which we did not bring into the present discussion. So is the distinction between best practice, worst practice and sectoral average. All plants or mills are not identical in terms of which technology they include inside or outside their boundaries. Some sectors use fairly well identified processes, which economic competitions brings to comparable levels of operational performance, while others do not, and this questions the real meaning of a sectoral averages and specific intensity factors. Figures collected by economists, LCA database providers or process engineers are not identical and not always easy to reconcile, etc.

This does not prevent international organizations from doing their perceived duty and to publish data. These data are often fuzzy, fraught with uncertainties, sometimes contain errors, etc, but make a fair attempt at describing reality. We did the exercise of analyzing these issues in this paper, when we could, and then had to stop doing it as we reviewed materials more and more different from steel, because the information necessary for a critical approach was not available. The data sphere is a communication universe, not yet as a scientific one as it is striving to become.

At an almost philosophical level, this means that it is practically not possible to access any kind of "vital" statistical information, as it does not always exist and as it might not be possible to make it exist, even with infinite resources! We are confronted with a wall of "unknowableness" of the kind that physics (Heisenberg and quantum mechanics) or mathematics (Gödel and formal logics) have pinpointed in more rigorous contexts. This raises serious issues with policy making, as decision makers need data and turn to experts to provide them.

The other epistemological point is that vital statistics of the kind that we have been trying to compile here are not "pure numbers" but are deeply connected to the issues that they are meant to illustrate: they are thus contingent. The data sphere is not a platonic world [48] but one that belongs to the real world.

Regarding foresight exercises second, the future will be determined by factors that prospective studies do not all take on board. Beyond energy and GHG considerations, access to water, water quality, biodiversity along with population growth and urbanization are some of the world grand challenges, which will deeply determine the shape of things to come.

It is rather fascinating to observe that materials have been very responsive to the dialectics of climate change and of resource efficiency and have developed sophisticated visions of the future that echo these issues. Some materials have done it to a greater extend that others.

We did not deal here at all with the caveats that industrial sectors have

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expressed regarding whether these visions can be implemented in the economic world, i.e. whether a business model can be formulated for example for implementing CCS.

Coming back to the conclusions of this paper, it is clear that most materials have developed a strong sensitivity to energy consumption and have erected energy efficiency as a guiding business principle: the dual drivers of economics and environment have been pulling this trend. GHG mitigation has also been widely discussed, although the economic driver is not yet fully clear, as this kind of environmental externality has not been fully internalized in the economy yet, in spite of ETS schemes and such instruments.

Steel is probably more advanced in this respect than the other materials. It benefits both from its indefinite recyclability, its already high level of recycling and from the advanced work carried out early on CO_2 breakthrough technologies.

The other materials are following suit with a time lag.

Other materials than metals and glass (and paper) have also developed other strategies to adapt to energy and GHG constraints:

- mineral materials have been relying on residues from other industries, for raw materials and energy (synergetic industrial ecology), and may eventually use CCS, if the price of the technology is right;
- plastics use their energy content (feedstock energy) to generate energy at the end of life, through energy recovery schemes that need to be made more systematic and efficient that they are yet today;
- bio-based materials, wood in particular, collects renewable energy from the sun which reduces their consumption of fossil fuels and their greenhouse gas emissions, if proper sustainable husbandry rules for forests and plantations are followed. CCS can also be used at the end of life of wood and thus create a virtuous system through which CO_2 would be pumped out of the atmosphere.

Recycling, which is an intrinsic property of some special materials, foremost of which are metals, is not a completely universal solution for dealing with the world of diminishing resources and climate change that the future is painted to become: forcing recycling on materials that have other ways to deal with the challenges through regulation may not be the best policy and may lead to rebound effects. Even in the case of metals situations come up once in a while when recycling is not the best solution in terms of energy and CO_2 footprints [49].

On the other hand, the tree should not mask the forest. Structural materials have played such an important role in the economy and the historical path that society is following, that they will not be judged solely on their ability to respond to climate change, for example.

This raises also the issue of competition among materials. It would be tempting to use the previous predictions for 2050 as a tool to judge how one material will displace or even replace another one, therefore to analyze the future as a cut-throat competitive world that will be determined by climate change responsiveness.

However, if one looks at inter-material competition, a different picture comes to mind. Not that of an all-out war, with no prisoners taken, but rather of skirmishes between large powers, which invade neighboring borderland or loose some of their own, but stay geographically stable in their own strongholds. Another metaphor is that of a trophic chain, where predators eat smaller ones and are devoured by larger ones but keep occupying their ecological niche. Steel, or concrete or aluminum have their own domain of excellence, related to their chemical nature and physical properties, and they will keep competing briskly but without overwhelming the other, except possibly in some niche market.

This would be better described as inter-material cooperation, at the level of the full technological episteme, rather than as inter-material competition.

Inter-material cooperation might actually also end up being a better way to increase resource efficiency, decrease the dependency on natural resources and ensure more safety of supply, and, eventually, the most pragmatic way to dematerialize the economy.

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In the day-to-day routine of product design, inter-material competition will remain brisk and alert, but it will in effect lead to the cooperative scheme that prevails today.

It should be stressed again that the authors are convinced that, by 2050, none of the structural materials discussed in this paper will be replaced massively by other materials, including some that might not be known or invented today. This is based on the historical analysis of the present status of structural materials and on that of the market share that "new" materials that appeared in the last 50 years have grabbed in the long run – a discussion that was only alluded to in the paper but was discussed more in [4].

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