Post-Fossil Fuel Building Construction and Materials

Short Report to AECB

David Olivier

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Summary

The UK has a policy of reaching 'net zero' greenhouse gas emissions (GHGs) by 2050. This document briefly outlines moving towards a future in which buildings would be constructed, and materials manufactured, with 'net zero' GHG emissions.

The report excludes production of renewable materials, e.g. timber, bamboo, but describes how most other major material-producing industries operate and need to change to approach net zero. Examples include cement and concrete; fired clay bricks, paviors and tiles; calcium silicate; steel and aluminium.

As the report explains, given the chemistry involved in producing most materials, residual GHG emissions are unavoidable. To reach net zero, the report sets out a modest role for Negative Emissions Technologies (NETs) as an essential part of an urgent climate protection policy.

1) Boundary Definitions and Correct CO_2 Accounting

These are likely to cause many errors and misinterpretations regarding CO_2 emissions. It is essential to be clear on the differences between the UK net zero target, a supposed net zero target for UK construction and international climate change targets.

Under current UK policy, if we close down our steel, cement or brick industries and import these materials from less energy-efficient plants abroad, it has a positive impact on meeting our net zero target. But there is clearly a negative impact on the planet. So this is best described as a perverse incentive.

Boundary definitions are also relevant to timber growth and biosequestration. Unless we have very clear accounting rules, it is likely that incorrect claims will be made, perverse incentives will appear and intended targets will not be met.

Thus, as an example, the government does not distinguish clearly between

1. 'biofuels' from organic wastes which would decay anyway and emit GHGs
2. biomass sources which could otherwise be left standing and which would not then emit CO_2
   and
3. biological wastes which might have a higher-value or less CO_2-intensive use than burning them.

If fuel type 1) is used for energy, it is likely to give zero CO_2 emissions, i.e. when the outcome is compared to the emissions if it is not utilised. Therefore, such fuels are potentially useful in moving towards 'net zero'.

An example of fuel type 2) is harvesting and burning forest trees in combustion plants such as Drax power station. [1] The use of this fuel risks being a case of 'emissions now, absorption later'. Wood's combustion emissions can be 5-10% higher than those from coal, i.e. in kg per kWh.

Examples of fuel type 3) are a) untreated timber sent to landfill b) timber waste burned by factories to heat buildings. 3 a) might reduce net CO_2 emissions more effectively if it is shredded and the resulting woodchip used on gardens or farmland as mulch. If this happens, much of it can be turned into new topsoil. 3 b) could potentially be composted, shredded for mulch or even anaerobically digested. These approaches lead to sequestration and/or clean energy production. They also avoid the air pollution associated with small-scale wood-fired boilers.

To avoid future errors, it seems essential to account for CO_2 on a cash-flow basis, i.e. list all positive and negative terms in that country, for that year and add them up. This will indicate either an overall credit or debit. [2] Summing up the totals for all 197 countries [3] gives the planet's total GHG emissions that year. One then repeats for the following year, and so on.

2) Materials-Producing Industries

2.1) Steel

The iron and steel industry emits 5% of global CO_2 at a rate of some 1.9 tonnes per tonne of raw steel. 1.8 billion tonnes of 'new' steel were made in 2018, i.e. from iron ore.

World Steel gives for 'average steels' a range from 2.28 to 3.06 tonnes per tonne, depending on steel type. The above 1.9 tonnes/tonne figure is presumably for raw pig iron, not steel.

Steel products for use in construction, e.g. reinforcing mesh or bar, have variable impacts and some figures provided by reviewers during this work are inconsistent with past Steel Construction Institute figures. Work is needed to reconcile this.

Iron is one of the most abundant elements in the earth's crust. [4] But it normally occurs in nature as iron oxides, e.g. hematite, Fe_2O_3. These oxides must be reduced, i.e. the oxygen atoms removed, to give metallic iron. This takes energy.

The chemical process from iron ore to molten iron in a blast furnace can be summed up:

$$2\,C + O_2 \rightarrow 2\,CO$$

$$Fe_2O_3 + 3\,CO \rightarrow 2\,Fe + 3\,CO_2$$

where C is coke or charcoal, Fe_2O_3 is iron ore. [5]

Preheated blast air is blown into the furnace and reacts with carbon in the form of coke - or charcoal - to produce carbon monoxide and heat. The carbon monoxide reduces the iron ore to molten iron. The molten iron is subsequently processed into steel, a step which involves removing some of the carbon content of the raw pig iron.

Charcoal was used to make all steel before the fossil fuel age. But given the chemical processes involved, CO_2 emissions are part of the reduction of iron ore to steel, regardless of which carbonaceous fuel is used.

The UK manufactures less steel than it consumes. It imports large amounts. Many of the CO_2 emissions attributable to UK steel consumption are therefore recorded as occurring abroad, sometimes in developed countries with large steel industries, e.g. Germany, Italy, Japan and South Korea. [6] This is relevant to section 1).

Modern steelmaking is apparently having to be more selective in its use of ores. Almost all modern steel scrap contains alloying elements, to a greater or lesser extent. These impurities can interfere with the increasingly tight specifications for steel products.

Sweden is developing iron ore reduction by electrolytic hydrogen. It may be 2035 before it is fully developed. Success is uncertain [7] and on recent estimates it is set to cost 20-30% more than normal new steel. In the view of an experienced UK metallurgist, Dr. Fred Starr:

> '... hydrogen is not particularly good at producing iron from iron ore. The iron has to be quite pure to be of any use. A major issue is that the process cannot be done with iron in the molten state. Unlike carbon, hydrogen becomes less effective as a reducing agent as the temperature increases.' [8]

Molten oxide electrolysis is more speculative still than hydrogen steelmaking. If developed, it too would sidestep the CO_2 emissions in making steel from ore. [9]

By contrast to new steel, steel recycling is already an electrical process. It does not need carbonaceous fuels. But CO_2 is still emitted, owing to the methods used to purify the molten steel in the arc furnace.

2.2) Aluminium

Aluminium is among the most abundant elements on earth but in nature it is tightly bound as aluminium oxide. It takes considerably more energy to remove the oxygen from bauxite ore and make 1 kg aluminium than to make 1 kg of steel.

Aluminium smelting consumes 4% of world electricity. [10] The basic process is:

$$2\ Al_2O_3 + 3\ C \rightarrow 4\ Al + 3\ CO_2$$

where Al_2O_3 is bauxite ore, C is the carbon anode.

This 4% may be comparable to the energy consumption of the world's steel industry. Aluminium smelters are often said to operate 'entirely on hydropower', but this is overoptimistic. All consumers connected to a country's grid at any one time, including aluminium smelters, receive virtually the same mix of fossil, nuclear and renewable electricity.

The world's aluminium smelters consume 14.1 kWh of electricity per kg of metal on average. A recent plant in Norway consumes 11.6 kWh/kg, i.e. 18% less. [11] So there is a fair way to go towards 'best practice'. The theoretical minimum consumption is around 7 kWh/kg.

The carbon anodes used in smelting emit CO_2 at a rate of 1.5 tonnes per tonne of aluminium. Inert anodes could reduce energy consumption by 20-25%, and GHG emissions more than that, but the work has been ongoing for decades and progress is slow. [12] There were recent predictions that inert anodes will be in use by 2024. [13]

2.3) Copper, Zinc, Manganese, Cobalt, Chromium

Copper plumbing systems are widespread. Zinc is used for flashings and roofing, especially in eastern Europe. Manganese, cobalt and chromium are essential ingredients of stainless steel, a fairly non-toxic metal that provides great durability vs. alternatives such as copper and lead.

They are probably essential post-fossil fuel building materials. The fuller report will consider an appropriate policy.

2.4) Cement and Concrete

Worldwide, four billion tonnes per year of cement are produced. Assuming a cement content of 14% by volume, world concrete output is 28 billion tonnes per year, i.e. 15 times the weight of the steel output.

On some estimates, the world will construct as many more buildings by 2060 as it has created in recorded history. Developing countries are urbanising fast, even if developed countries have reached a more steady state. Concrete is ubiquitous. It has been called 'liquid stone'.

Cement is the fired component of concrete and the chemical processes in making it are not dissimilar to quicklime production. See 2.6. The other ~85% of its volume is unfired sand and gravel, which can be produced without fossil fuels. Blasting at quarries might still need to use chemical energy to dislodge blocks of stone, but drilling and wedges can be an alternative. In GHG terms, we need to focus on the 15% cement content.

The use of pulverised fuel ash, i.e. from coal burning (PFA), plus granulated ground blast furnace slag from steelmaking (GGBFS), are widely quoted methods to reduce concrete's CO_2 intensity. They both substitute for Portland cement content. But PFA may disappear as coal is phased out. Some PFA samples are too radioactive for use in buildings. [14] Blast furnace slag can be high in toxic metals and, if less new steel is made, its production would drop. So these are *not* really sustainable methods to 'de-carbonise' cement as may be claimed. [15]

The industry rarely invests in energy efficiency improvements, i.e. leading to lower fuel usage in the kiln, unless they give at least a 35-50%/y return on investment. By contrast, the UK public sector assesses projects at a 3.5%/y real rate of return. Many decades ago, a report cited the scope for the UK to save energy by moving rapidly to 100% dry kilns. [16] As the 2015 review pointed out, however, one semi-wet and two semi-dry plants are still in use. [17] In practice, the industry modified its fuels and kept some old kilns.

Worldwide, 90% of cement kilns are still fired by coal or petroleum coke, i.e. carbon-rich fuels with high GHG emissions. A 2015 review of the cement industry gave the 2012 UK fuel mix as approximately:

- 60% coal
- 18% solid biofuels [18]
- 22% wastes. [19]

The cement industry and government still focus relatively unselectively on 'biomass'. [20] If kilns burn one carbon-rich fuel or another, it does not usually materially affect CO_2 emissions. One cement company is selling a 'net zero' cement based on offsetting. [21] If we want to move to materials with lower GHG emissions, it is unclear why this is allowed. It risks disincentivising further improvement.

Unless there is outside intervention, many of the cement kilns that will be in use in 2050 already exist. 'Genuine' advances in kiln energy efficiency might it seems cut the energy and CO_2 intensity of cement manufacture up to another 20-25% by 2050, i.e. without changing fuel. Moving from solid carbonaceous fuels to natural gas now, or biomethane from wastes later would in theory cut CO_2 emissions, i.e. at the kiln, about 50% 'overnight'. [22] This and improved kilns might reduce it 60%.

There is scope to substitute inert fines for up to 50% of cement volume without affecting concrete compressive strength. [23] [24] 50% inert fines might get us to 75-80% less CO_2.

New electrochemical routes to cement have been proposed. [25] It seems unlikely that electrical techniques can account for most production by 2050. But the proposal is sound in theory. If successfully developed, it might enter use widely before 2050.

Concrete re-carbonates over time as it reabsorbs CO_2 from the air. The process is welcome and, as the cement industry stresses, it is usually omitted when calculating in net GHG emissions. But it is too slow to be of much help in meeting urgent targets.

Geopolymer concretes also offer lower CO_2 emissions. [26] A product on the market may attain similar CO_2 intensity to improved Portland cement concretes. [27] If we take the geopolymer route, iron-rich raw materials may offer a means to make concrete red bricks whose appearance is indistinguishable from red clay bricks. [28] This might be useful, given the difficulty in reducing fired clay CO_2 emissions to the level of concrete products; see 2.5.

2.5) Fired Clay Products

Clay bricks are fired at around 1050°C, which is lower than the 1,350°C for cement kilns. But all the material is fired, as opposed to only about 15% for concrete. Today's main fuel is natural gas.

Past UK brickmaking relied heavily on the Lower Oxford Clay. Not only can this clay be forced into moulds straight from the pit, but it contains around 5% lignite. So 75% of the firing energy is 'free'. This is akin to coal firing of the kilns, though. So it emits more GHGs and other air pollutants than normal clay bricks with natural gas firing. In 2010, only 10% of UK bricks came from this source. [29]

Clays now in use probably average 1% carbon. This places a lower limit on CO_2 emissions. Even if kilns convert to hydrogen or genuine biofuels from waste, emissions are still equivalent to roughly 15% coal firing.

Issues also arise with ceramic tiles, clay paviors, clay roof tiles and fired clay blocks. [30] Some porous clay blocks in the past were made by mixing the clay with particles of carbonaceous fuel. This disappears after combustion, leaving behind empty pores to reduce the thermal conductivity but also discharging CO_2 to the atmosphere.

2.6) Calcium Silicate

Producing quicklime, blending with well-graded sand and autoclaving produces a dense white solid material suited to utilisation in load-bearing wall construction. It is widely-used in Germany and the Low Countries.

The chemical equations for quicklime and calcium silicate production are:

$CaCO_3 \rightarrow CaO + CO_2$

$2\ CaO + SiO_2 \rightarrow Ca_2SiO_4$

where $CaCO_3$ is limestone, CaO is quicklime, SiO_2 is sand.

Calcium silicate is less energy-intensive, i.e. in kWh/kg, than concrete or dense aggregate blocks and can be made to tighter tolerances than precast or *in situ* concrete. If buildings need thermal capacity, it achieves similar density to dense blocks. Being airtight, it only needs sealing at joints, i.e. like precast concrete.

The sand-lime mix can be autoclaved with low-pressure steam, i.e. fairly low-grade heat. In sunny climates, it could be from CSP. But quicklime production needs a temperature of 900°C. Admittedly, this is lower than 1,150°C for fired clay or 1,350°C for cement.

90% or more of a calcium silicate mix can be sand. That makes it less energy-intensive than today's concrete. But given that one ingredient of concrete is calcium silicate, the two materials are closer to each other than they are to fired clay products.

In the past, calcium silicate bricks tended to cost less than clay bricks. Calcium silicate is softer than concrete or fired clay, with a similar thermal expansion coefficient to concrete. So buildings of it need to use correct movement joints, lime mortar, etc. The result should be at least as durable as clay brick. [31]

2.7) Timber

Timber, bamboo, etc are renewable materials. Today their cultivation, harvesting, transport and processing may consume fossil energy and emit CO_2. Because of its scope to displace more CO_2-intensive materials, a shift to timber is important. But it would have to be processed with renewable energy, e.g. the kiln-drying.

Careful treatment is needed of timber's combustion energy and CO_2 emissions. Although timber structures are a way to lock up CO_2, accidents can happen. [32]

It is important not to allocate negative emissions to wood utilised in the UK if the forestry industry that produced it, perhaps in Sweden, Finland or Canada, has already claimed CO_2 sequestration. This could amount to double counting. See section 1).

2.8) Plastic Foams, Pipes, Membranes

If necessary, we can turn plants into any desired polymer. Oil and natural gas took over from plants and became the dominant sources of chemical feedstocks for a simple reason. They were cheaper, i.e. when one excluded the 'externalities'.

Wood is still used, however, to make some packaging membranes and fabrics, e.g. 'Cellophane', 'Rayon', 'Viscose'. These biodegradeable materials have been produced for the past 50-100 years.

If needed, plants could probably be utilised to make non-biodegradeable polymers, e.g. polyethylene, polystyrene, ABS, etc. For damp-proof membranes (DPMs), one might wish to continue with polyethylene. Foundations, i.e. with the DPM in place, can outlast the superstructure.

Above-ground thermal insulation is less clear-cut. Building superstructures can last less long than the foundations and DPM. What does one do, say, if some EWI has to be removed and new insulation fitted?

The 2015 discovery that the enzymes in some microbes can digest what were considered non-biodegradeable plastics could change our view. In theory, it allows us to produce non-biodegradeable polymers from plants and dispose of them safely at the end of their life. But reality is harder. [33] For the moment, to avoid plastic pollution, there may only be a few safe routes at the end of a material's life.

As with construction timber, bio-polymers produced abroad need correct accounting for GHG emissions.

3) Future of the Materials-Producing Industries

It is likely that materials substitutions, energy efficiency improvements and fuel substitutions could get us a huge way towards net zero, but not all the way there. We briefly deal with the materials covered in section 2). This short section focuses on each main part of a building in turn rather than on each material.

3.1) Foundations

We need comparisons of steel and radically improved concrete. If steel is 96% recycled, the energy and CO_2 intensity falls compared to new steel. However, if concrete moves to a) polymer cements, b) finer grinding, c) inert fines and d) ends all coal firing, its energy and CO_2 intensity greatly drop.

Does steel have the lifespan of reinforced or mass concrete? The latter seems to endure for millennia in dry climates, given obvious examples from Rome and South America. Steel and possibly concrete [34] will be less durable below ground. Further work is needed.

Canada has experience of *wooden* foundations in dry climates, [35] i.e. wood replaces the normal poured concrete basement below a one- to three-storey timber-frame superstructure. However, wood below ground is associated with preservative use. Are there any acceptable ones?

3.2) Superstructures

In the USA, concrete and wood are often seen as lower-embodied energy than clay bricks or steel. The UK figures appear to support this.

However, UK figures for reinforced concrete (RC) versus steel-frame are ambiguous. Given the author's experience on his own house and of structural engineers' practice on large buildings, RC with near-minimum steel volumes and short spans does not seem very energy- or CO_2-intensive. By contrast though, RC might become more of a GHG emitter than structural steel if it is deliberately overdesigned and/or uses very long spans.

We therefore need comparisons of steel and concrete for buildings which, for various reasons, cannot be of timber-frame construction. Some worked calculations could be helpful in the longer successor to this report. They need to take into account on the one hand, the lower embodied CO_2 of concrete, i.e. in kg per tonne or m^3; but on the other hand, the fact that concrete cannot be recycled as fully as steel sections. Concrete may be crushed to decorative gravel; steel may go to a recycling plant.

In low-rise buildings, a clay brick-clad timber-frame wall apparently has higher embodied energy (EE) and CO_2 than a concrete or block wall with EWI and render. A calcium silicate wall might be somewhat lower-EE than concrete. But note the need to check the figures for improved concrete; see 2.4.

Past US energy-efficient 'custom architecture' emphasised *selective* use of thermal capacity, possibly a single concrete wall and ground floor/raft in otherwise low-thermal capacity timber buildings. Sometimes this allowed more passive solar to displace winter space heating, i.e. the large south windows utilised would overheat a wooden house [36] but in a higher-thermal capacity house they *reduced* space heating energy use. [37]

There are diminishing returns. To simplify, adding 20% of the potential maximum capacity might yield 80% of the potential benefit. Changes like an internal 'veneer' of ceramic or natural stone tile, denser boarding or, in single-storey timber structures, a concrete ground floor, can make a timber building easier to cool in summer and/or allow designers to be more liberal with the glass area.

One suspects that calcium silicate used on a conventional UK site would be in the form of blocks. They are less labour-intensive than brick-sized units, subject to H&S rules.

In a mechanised world, though, i.e. across the English Channel, it is easier to crane large units into place than lay small units by hand. In typical German projects, no stocks are kept. The designer or contractor submits a list of element sizes and the factory supplies them to order.

The USA, Canada and northern Scandinavian countries widely use timber-frame at under 3-4 storeys but do not routinely use preservative. [38] Timber treatment can stop waste timber from being safely reused.

Ending the UK's default use of preservatives, only allowing it in special cases, seems a high priority. If, by law, treated construction timber had to be permanently stamped and labelled, including timber windows, this could greatly help when buildings are dismantled.

Treated timber could go to safe incineration or other processing. Sound untreated timber could be re-used or composted, depending on its condition.

3.3) Claddings

Most new UK pitched roofs are clad by concrete tiles, lesser numbers by fired clay. Could natural slate replace them? Slate needs no firing, only extraction of the bulk rock, splitting and cutting.

Welsh slate was the standard late 19th.C 'industrial' roofing material. Numerous slates have passed the test of time and last 150 years or more. But some are shorter-lived.

Past wastage rates with all slate were very high, leading to mountains of waste. Some quarries producing the most durable slate may be running low. It needs checking.

With clays having an average 1% carbon content, bricks are problematic. Can brick slips be used? They have not become common, despite their availability. If they are produced by just slicing a normal brick, do they offer a net benefit? Or can clays of much lower carbon content be utilised to make normal size bricks? Or if cement can become up to 75-80% lower-CO_2, i.e. in kg per kg, can a concrete brick replicate the appearance of a clay one?

External lime render seems to give a useful blend of modest embodied energy and long life. But on EWI systems, acrylic render is a more proven finish. This needs more consideration. In the long run, the latter would be produced using bio-polymers.

Softwood boarding of most genera/species is short-lived and maintenance-intensive. Assuming that say tens of percent of future walls are wood-clad, is there enough FSC/PEFC durable temperate hardwood, red cedar and/or imported tropical hardwood?

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4) Negative Emission Technologies

4.1.) The Need

It is quite widely thought that government plans for dealing with climate change rely too much on 'negative emissions' technologies (NETs). That is, NETs are being used as an excuse to delay urgent emissions cuts.

Some governments see emissions cuts as politically awkward even if they may look more straightforward to others familiar with the field. Examples include building insulation, combined heat and power, electric heat pumps, more energy-efficient lights, motors, fans and appliances; more fuel-efficient cars, vans, HGVs; more fuel-efficient commercial aviation.

But in some sectors, including building materials, there is probably no alternative to NETs. CO_2 is inevitably emitted when we smelt iron, aluminium, copper, etc from ores or produce fired clay, concrete or calcium silicate. Without a corresponding CO_2 sink, we cannot reach 'net zero'.

Examples of sectors of the economy apparently needing NETs include:

- 'mass load-bearing materials', i.e. concrete, calcium silicate, clay brick
- 'new' metals manufacture
- recycling industries that emit CO_2, e.g. steel
- residual air travel, e.g. commercial and military, plus leisure use of light aircraft.

Air travel is outside the scope of this document.

4.2) The Options

Perhaps we should entitle this section 'safe, less safe and unsafe options'. International organisations have restricted 'geo-engineering' technologies, for fear that they might harm the planet more than the problem they aim to tackle.

But in time, an obviously very urgent situation may force us to implement the 'less risky' geo-engineering options, e.g. enhanced fertilisation of the oceans, adding particles to the upper atmosphere. Their omission for now leaves us with three 'safe' options:

- 'Conventional' CCS
- Biosequestration
- Enhanced weathering

One of the hardest parts of 'conventional' CCS is access to pipelines and disused wellheads to send the CO_2 back. There are other issues. [39] It seems prudent to proceed on the basis that it will not become significant. If so, we need other techniques to meet the target.

Bio-sequestration, on land at least, means more storage in the biosphere, i.e. the soil and standing biomass. The terms can be confusing. Out of 'tree planting', 'regenerative farming', 'agroforestry' and 'forest gardening', most lay people probably only understand the first. The second at least seems to be equally important, given the area of farmland used to feed 7.5 billion people.

Many 'regenerative farming' projects are apparently sequestering CO_2, producing higher average yields and more net profit than conventional farms, i.e. a 'win-win' situation. They are even having success with arable agriculture. Until now, arable has been seen as a particular problem, given the effects on GHG emissions of the bare soil and the regular ploughing.

Regenerative farmers are utilising a wide range of techniques including cover crops, multiple cropping, livestock grazing of crop residues and 'no-till'. However, the number of approaches may be as large as the number of individual farmers, i.e. because it is spreading mainly by individuals 'tweaking' someone else's successful approach, not following central government guidance. The US food company General Mills, Inc. reportedly agrees that the case for such farming now 'stacks up'.

Enhanced weathering relates to faster breakdown of the silicate minerals found in the earth's crust. The rocks need to be crushed to accelerate this natural process, e.g. presumably using the gravel-sized output in landscaping or horticulture and the fine output as rock flour, possibly on grassland as well as on arable farms. [40]

The processes which lead these materials to absorb atmospheric CO_2 are analogous to the slow recarbonation of concrete over time. If rock dust increases crop yields, it could be another 'win-win' process, with higher yields lowering the cost below the reported £60-150 per tonne CO_2.

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Appendices

1) Construction Waste

In the early 2010s, the EU produced 450 Mt/y of construction waste. [41] Much was apparently inert material but went to landfill and was not reused.

The UK accounted for 100 Mt/y of this, i.e. 22%. [42] This is apparently a higher proportion than its share of EU population, i.e. around 13%. It is likely that most of the inert waste could be utilised as aggregate, or for higher-grade uses, were it not mixed up with other waste.

To minimise environmental impact, the standard advice is 'reduce, reuse, recycle'. So on a building site, the likely priority with an item like concrete blocks, in descending order of preference, would be:

1) do not handle blocks so carelessly that 20-25% are broken or trodden into the ground
2) having reduced the need for ordering blocks do not order excess pallets
3) find a local use for leftover part-pallets, e.g. on the next job
4) send genuine waste, e.g. block offcuts, to a location where they are crushed and utilised.

Ideally, one might separate inert waste into fired and unfired streams. Fired waste may continue to sequester CO_2 if it is crushed and used for landscaping, i.e. gravel drives and paths, instead of the usual crushed stone or river gravel. This makes it a NET. But if it has pozzolanic activity, it might reduce cement usage if it substitutes for part of the cement in concrete. Optimum policies need more study.

UK household waste sites used by the author clearly designate one or two containers for 'inert waste', e.g. building stone, ceramic tile, blocks and bricks. From anecdotal observations, the public use them carefully and rarely contaminate them with the wrong materials.[43]

By contrast, most construction sites seem to mix up inert waste with other waste at random until a container is full. After empty cement and lime bags, set plaster, insulation scraps and used foam cans are mixed with bricks and ceramic tile offcuts, one cannot easily separate them. But the 'recycling' industry tries to do so. [44] Could the difficulty be reduced by using containers labelled:

5) 'inert waste'
6) 'metals'
7) 'other'?

1) & 2) are easy and safe to deal with. 3) is less so. But the volume of 3) should be lower once 1) and 2) are removed.

2) Metal Recycling Rates

UK rates are reportedly as follows:

- Steel 96%
- Aluminium 96%
- Copper 65%

96% seems to be close to feasible upper limits. 65% is disappointing, considering copper's high scrap value. Also, these figures have been questioned; are they for construction or for the UK economy as a whole? In the longer report, they will be checked and if applicable suggestions will be made how to raise rates.

References and Notes

[1] https://theecologist.org/2018/apr/16/hardwood-forests-cut-down-feed-drax-power-plant-channel-4-dispatches-claims

[2] https://www.aecb.net/download/less-is-more-energy-security-after-oil/ . But unfortunately, at present most countries will have a debit, i.e. they produce net positive GHG emissions.

[3] There are disagreements about the total number of countries in the world but most sources suggest between 195 and 197.

[4] https://en.wikipedia.org/wiki/Abundance_of_elements_in_Earth%27s_crust#/media/File:Elemental_abundances.svg

[5] https://en.wikipedia.org/wiki/Blast_furnace

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[10] https://www.ctc-n.org/technologies/inert-anode-technology-aluminium-smelters

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[12] Ref. 7, *op cit*.

[13] https://www.imeche.org/news/news-article/feature-carbon-re-engineered-5-genius-engineering-tricks-cutting-emissions

[14] Polish paper to BRE conference on Buildings and the Environment 1994.

[15] https://www.scientificamerican.com/article/cement-producers-are-developing-a-plan-to-reduce-co2-emissions/

[16] Olivier, D et al, *Energy-Efficient Futures: Opening the Solar Option.* Earth Resources Research Ltd., London 1983.

[17] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/416674/Cement_Report.pdf

[18] The ambiguous term 'biomass' is used. If used correctly, this usually refers to all biological material. We assume that the authors meant solid biofuels, e.g. wood.

[19] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/416674/Cement_Report.pdf

[20] To be less ambiguous, the term itself should apparently be altered to 'solid biofuels'.

[21] https://www.lafargeholcim.com/ecopact-the-green-concrete

[22] https://www.cemnet.com/News/story/166997/keystone-cement-to-switch-to-natural-gas.html

[23] https://en.wikipedia.org/wiki/Cement#cite_note-Justnes-42

[24] https://link.springer.com/article/10.1007/s11595-010-2328-5

[25] http://news.mit.edu/2019/carbon-dioxide-emissions-free-cement-0916

[26] https://www.geopolymer.org/conference/gpcamp/gpcamp-2020/

[27] https://www.brett.co.uk/news/capital-concrete-debuts-low-carbon-concrete-for-london-development/

[28] https://www.geopolymer.org/news/red-geopolymer-cement-could-become-the-standard/

[29] https://en.wikipedia.org/wiki/London_Brick_Company

[30] Fired clay blocks are widely used in some continental European countries, e.g. as load-bearing walls in Germany, infill between concrete frames in Spain. They are also imported to the UK.

[31] http://buildingdefectanalysis.co.uk/masonry-defects/an-introduction-to-calcium-silicate-bricks/

[32] https://www.bbc.co.uk/news/uk-england-london-10645700

[33] https://cen.acs.org/environment/sustainability/Plastics-recycling-microbes-worms-further/96/i25

[34] Concrete may deteriorate faster in acidic soils than above ground.

[35] Typically in the prairies with rainfall of around 500-600 mm/y.

[36] That is, in winter in a sunnier climate, e.g. most of the USA. See Mazria, Edward, *The Passive Solar Energy Book* 1979.

[37] Work at University of Saskatchewan.

[38] Individual states may require treated timber in termite-prone areas, i.e. analogous to the UK house longhorn beetle regulations.

[39] https://physicsworld.com/a/whatever-happened-to-carbon-capture/

[40] https://www.nature.com/articles/s41586-020-2448-9

[41] https://www.sciencedirect.com/topics/earth-and-planetary-sciences/construction-waste

[42] http://www.wrap.org.uk/sites/files/wrap/Reducing%20your%20construction%20waste%20-%20a%20pocket%20guide%20for%20SME%20contractors.pdf

[43] They sometimes contain soil and plant roots. No separate bin is provided for those.

[44] https://www.paprec.com/en/understanding-recycling/recycling-construction-waste/building-site-waste-sorting

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