Decarbonising the Built Environment

A Global Overview

By Tom Ackers

From peoplenature.org

Decarbonising the Built Environment: a Global Overview

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Foreword

This series of articles by Tom Ackers presents an outline of the challenge of decarbonising the built environment – the buildings and infrastructure we use – as part of tackling global heating.

In contrast to all the valuable analysis and discussion material focused on this problem at local and national scales, Tom concentrates on the global picture. It is a comprehensive survey, covering the history of construction techniques and how the stock of buildings and infrastructure expanded together with the capitalist economy in the late 20th century, how China overtook the rich industrialised countries, and the scale of the challenge in front. Tom writes about the potential for "contraction and convergence" between the richest countries and the rest; assesses the pros and cons of approaches to fossil-free construction and fossil-free heating and cooling of buildings; and discusses the politics of change.

All this is necessary context for working on the local and national problems. The local is global. Action locally can and must address this global crisis.

I am delighted to publish this work on People & Nature: like everything on the site, it is offered for discussion, to underpin action towards superceding fossil capital and tackling global heating.

Simon Pirani

Part 1: Introduction

A critical mass of worker-led environmental activism is emerging in the built environment professions of architecture, construction, engineering, and urban design. Campaigners are seeking to remake the built environment – buildings and infrastructure – so that existing and future development is compatible with a liveable future on the planet.

In the UK, examples include the groups Architects Climate Action Network (ACAN), Low Energy Transformation Initiative (LETI) and Architects Declare (AD).

These new groups are building on longstanding efforts by organisations such as the Centre for Alternative Technology (CAT), and The Green Register. The Royal Institute of British Architects (RIBA), and the Architects' Journal (AJ), are also now very active on this front.

Collaborative initiatives like these are doing a great job in building knowledge about green transition in the built environment sector – and recasting models of professional "best practice" when faced with environmental emergency.

Indeed, this conversation is happening globally.

The built environment – in some form – is a crucial part of people's lives almost everywhere.

In late 2021, Insulate Britain took this professional and workplace-based activism to the streets, and succeeded in pushing what is essentially an engineering problem – how well buildings retain heat – up the political agenda in the UK.

This is all hugely welcome – because the ways that we design, build and reproduce our built environments globally impose a very large proportion of societies' environment burdens.

In the UK, the focus on insulation was also incredibly timely, as the costs of home heating leapt up during 2022, acutely sharpening a broad-based cost of living crisis.

It seems ever more urgent that practical engineering knowledge about the built environment is transmitted out into society at large. This would be an important step on the way to collectively managing decent standards of living for everyone in society and to meet multiple environmental emergencies.

Moreover, *decarbonising* the different aspects of the built environment is bound to interact with various forms of economic struggle – most notably, the international class struggle, and demands for *economic development*.

In my view, the politics of decarbonising the built environment therefore demands an internationalist approach. And in this series, I consider the built environment in relation to variant forms, directions, and distributions of economic development.

The necessary course for the future is "contraction and convergence" – with the global rich contracting their material consumption very substantially, and the global poor in many cases expanding theirs, in order to *converge upwards* on western living standards.

This is the case with all forms of consumption. Certainly it is the case with the construction and maintenance of buildings and infrastructure.

Contraction and convergence is specifically *not* about establishing universal access to current rich country norms of consumption, and prevailing norms of the built environment, that were established in the period of fossil capital.

To the contrary, contraction and convergence means a radical *recomposition* of global production, circulation and consumption, and a massive *redistribution* of useful things, globally. The existing forms of the built environment have to be overhauled, and re-oriented on need, material efficiency, a future with zero anthropogenic (i.e. human-made) greenhouse gas emissions, and a future built on social and ecological restoration.

One way there is a broad, worker-led coalition – pushing for decarbonisation of the built environment, in the context of providing for real needs. Such a movement needs to overcome the divisions within the working class between intellectual and manual work, and between different sectors of employment.

The aim of this series of ten articles is to relay something of what is at stake. I will draw from the work of ACAN, LETI and Insulate Britain, but also try to set that work in a broader historical and international perspective: the built environment as a crucial aspect of the history of capitalism.[1]

In part 2, I outline some core concepts.

In part 3, I offer a brief global history of the built environment in the context of the fossil-fueled economy. Part 4 focuses on China, now the largest single emitter of greenhouse gases.

In part 5, I focus on the materials – concrete, cement, steel, glass – deposited through this history into the world's buildings and infrastructure, and the corresponding mass of greenhouse gas emissions.

In part 6, I relate decarbonising the built environment to the project of "contraction and convergence". I look at forecasts for the scale of urbanisation worldwide, and the expansion in global building floor area through 2050; and I survey some low-carbon approaches to urban planning.

After that, in part 7, I focus on the embodied emissions (that is, the greenhouse gases emitted in the course of making things like buildings and infrastructure), and, in part 8, on what the reduction of these implies for economic development.

In part 9, I turn to "operational emissions" (that is, the greenhouse gases emitted while buildings are being used e.g. to provide heat, cooking fuel and electricity). There I focus on building design and thermal performance.

In part 10, I look specifically at the issues around decarbonising heating and cooling in buildings.

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[1] With thanks to Peter Somerville, who read and commented on a draft of the articles

The parts can each be read individually, or as part of the whole. My aim has been to gather salient information in one place, and map a terrain of struggle.

I am not a climate scientist, engineer or architect. For environmental science and data on materials consumption and emissions, I look to organisations like the Intergovernmental Panel on Climate Change (IPCC), the UN Environment Programme (UNEP), and the International Energy Agency (IEA), alongside peer-reviewed journal articles by academic researchers, and the work of charities and NGOs.

In some places, I have focused on, or provided examples from, the UK. Part of that is about coming across these groups like ACAN and AD, and because I have lived most of my life in the UK. However, the UK is also important for this topic on its own terms: it is where the fossil economy was born, and it remains a key centre for the financial marshalling of capital today.

Moreover, for similar historical reasons, the UK remains a centre for engineering and architectural expertise. It is also a locus internationally for financing and commissioning construction, and (arguably) a prime example of a dysfunctional "over-accumulation" of the built environment.

From the perspective of reforming the industries of the built environment, it is therefore good – and politically hopeful – that there is both theoretical *and* practical talk about decarbonisation in the UK, amongst workers of the built environment.

However, this needs to be a global conversation across societies as a whole, and across the working class. It concerns fundamental issues about how societies provision and distribute resources, and might do so in future in an ecologically viable way. This cannot simply be a conversation between technical specialists.

I welcome feedback. I hope people will tell me how my analysis can be developed and my proposals improved upon. And if you think I have got something wrong, please let me know by email. You can contact me at: tomackers.peopleandnature@gmail.com.

November 2023

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Part 2: Concepts & measures

In this part, I will define some ideas that will be used throughout the series: first, what I mean by the built environment and other key terms; and then flows and stocks (section 2.1); material footprint and carbon footprint (section 2.2); embodied emissions and operational emissions (section 2.3); Life Cycle Analysis (section 2.4); and varieties of footprint (section 2.5). In a final section 2.6, I comment on the politics inherent in the idea of footprints and the way they are calculated.

Researchers who study greenhouse gas emissions and other environmental impacts, conventionally understand the **built environment** to include all elements of human-made infrastructure and buildings: large, durable products that sit in one place and (usually, ideally) provide a long lifetime of use, from homes to office buildings, roads to reservoirs.

In order for the built environment to function well, it needs to be appropriate to its environmental context; durable, resilient to changes in the environment, and *actively maintained*.

The category of the built environment tends to exclude agricultural land-use, except for the buildings and infrastructure that make farming possible.

Also, the built environment is conventionally distinguished both from transport and from energy transmission.[1]

Nevertheless, the *kinds* of transport and energy infrastructures that get commissioned and built – roads, railways, wind farms, pipelines – bear very strongly not only on the end-use footprints of the transport and energy sectors, but also on the operational use of buildings and of non-energy and -transport infrastructure.

Throughout this series I will use the term "use-value" to describe the physical aspect of something – the side of it that has a some physical or otherwise "sensuous" use. The use-value of something is distinct from its monetary value ("exchange-value") – and use-values need to be described and quantified in non-monetary terms.[2]

I also use the terms "fossil capitalism" and "fossil capital". These are intended to highlight the way in which capitalism *in general*, and capital in particular, are presently – and overwhelmingly – built on the use of fossil fuels.[3]

2.1. Flows and stocks

We can look at all societies and economies as consisting in the movement of physical matter. Those movements can be quantified – as with value accounting – by looking at various **flows** and **stocks** of materials.

In broad terms, we can think of material stocks and flows as providing various "services".

For example, clay is extracted from the ground, shaped and fired into bricks, and assembled with mortar to build walls and a home. This dwelling is a building "stock" as long as it stands, and it provides the "service" of shelter.

Living space may need heat and light: both of these are flows of energy derived from some fuel stock. People require some flow of water, a supply of food, and some means of discharging effluents and waste.

And different services require different combinations of material stocks and material flows.

The built environment comprises a variety of such stocks of materials, constructed together out of material flows. Built stocks are placed in relation to one another according to the social relations that form the context for construction. And the useful life of a built stock then involves it as a site for channelling various other subsequent flows.

Stocks and flows can address social needs directly. However, in the context of capitalism, stocks and flows tend to dispense social benefits only insofar as they benefit the proprietors of capital.

Beyond that, material stocks and flows are bound to be directed to benefit some people and not others – they may *even dispense deliberate harms to others*, as is obviously the case with the activities of a military installation.

Moreover, in the contexts of the long history of capitalism and colonialism, material stock accumulation and material flows have occurred for the benefit of some and to the wholesale detriment of others, generating wave after wave of social and environmental violence.

2.2. Material footprints and carbon footprints

Material footprint **(MF)** is a consumption-based indicator of resource use that seeks to capture the mass of material flows along a supply chain, or across the breadth of an economy.

The concept of **carbon footprint** **(CF)** has been used in different ways, but nowadays usually refers to the mass of atmospheric emissions – measured as CO_2 equivalent (CO_2e) – that can be attributed to an activity or process. It is an indicator for global warming potential.[4]

These concepts are just some of the means available to quantify material use and/or environmental impacts – for example, those of a country, a company, a supply chain, a

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[1] This way, the material and environmental costs embodied in the *construction* of transport and energy infrastructure are usually allotted by analysts to the construction industry. But the material and environmental costs of the subsequent operational *use* of transport and of energy infrastructure – e.g. of burning coal in a power station or petrol in a car's engine – are categorised separately, as arising directly from the energy and transport sectors

[2] In Marx, exchange-value is the rate of exchange of between any two commodities. One of those commodities is usually money

[3] *Fossil Capital* is a book by Andreas Malm

[4] Carbon footprints reflect the different global warming potential of different greenhouse gases, usually over 100 years. So for example, a tonne of carbon dioxide emissions is 1 tonne of CO_2e, but a tonne of methane emissions over 100 years is said to have the same effects as 25 tonnes of CO_2e – it has a GWP of 25; a tonne of nitrous oxide is equivalent to 290 tonnes of CO_2e, so the GWP of nitrous oxide is 290 when calculated on a 100-year basis

household, or an individual. They are "material accounts" data, as opposed to economic data based on monetary value.

When you look at material or carbon (or any other) footprints, you can also choose to look at things from the perspective of either production or consumption.

A *production*-based approach looks at the sum of materials consumed, or the emissions produced, in the course of the normal activities of a company or region – it is focused on economic inputs and processes. In the case of countries, a production-based perspective is also referred to as a domestic-based, or a territorial-based perspective.

A *consumption*-based approach looks instead from the point of view of end-consumers, and seeks to quantify what they consume, and then allot an appropriate material or emissions footprint to that consumption, based on the share of consumption. However, end-consumption is not always easy to define.

At the global level, the sum of all production footprints equals the sum of all consumption footprints, setting aside loss and wastage. For example, global consumption- and production-based emissions are identical – and become skewed one way or the other at the local level, according to the balance of international trade.

Rich countries import emissions-intensive goods from elsewhere, and this shows up in comparisons of production- and consumption-based emissions, such as one by Our World in Data.

You can also choose to refer only to the *direct* ("on-site") impacts of the final stage of material use, or you can take a more holistic approach, and consider as well all of the *indirect* ("off-site") materials and environmental impacts upstream in a supply chain that are effectively contained ("embodied") in the product consumed.

For example, when you look at the total domestic consumption-based emissions of a region, and include indirect emissions, that will include all of the emissions due to production abroad, and effectively embodied within imports. It will also *exclude* the emissions of domestic production that are effectively embodied in exported goods.

2.3. Embodied emissions and operational emissions

Just as with any other commodity, so with the built environment: it is useful to distinguish between the materials and emissions associated with the production of something, and with its use.

The materials, emissions, and anything else that go into producing something are said to be *embodied* in the end product. Everything associated with a product's end-use is said to be *operational*.

As outlined above, a comprehensive accounting will include all of the direct and indirect materials and impacts that feed into the provision of some material thing or "service".

In the case of the stock of buildings and infrastructure, the *embodied* materials and emissions comprise everything that goes into construction.

This encompasses production of all the physical inputs that go into the bricks and mortar. But it also includes everything that goes into, or comes out of, construction, alongside the bricks and mortar: labour processes, upstream supply chains, transport, energy, disposal of waste streams, installations of plant and machinery, and a lifetime of maintenance after the initial construction has ended. Plus any deconstruction, demolition or disposal at the end of a building's or piece of infrastructure's lifetime of use.

These things are often mis-allocated in consumption-based footprint data – a point I will come back to.

Meanwhile, *operational* footprints are all the material flows and waste streams associated with a normal lifetime of use *after* production or construction. Again, this should include indirect as well as direct material use and impacts.

In the case of a building, this mostly comprises utilities: electricity, heating, water.

As above, operational footprints conventionally do not include aspects of maintenance and replacement that are carried forward as part of the embodied footprint.

The embodied and operational footprints of the built environment, when assessed on a consumption basis, will end up distributed across the end consumption categories of the economy. Much of that is via the "intermediate consumption" of corporations.

But all elements of the built environment are constructed to provide some "service". And every such structure therefore has its own stock-flow / embodied-operational material profile. Depending on how it is designed and made, this will be reflected in a balance of standard operational costs, in both material and monetary terms.

As for the climate burdens associated with the built environment, we are usually concerned primarily with identifying and minimising **embodied emissions** (or "embodied carbon") and **operational emissions** (or "operational carbon"). These are the atmospheric emissions, measured as amounts of CO_2e, embodied in the production and disposal of a building or piece of infrastructure, and those emissions spent while using it during its lifetime of use.

These are the main targets of decarbonisation in the built environment.

2.4 Life Cycle Analysis

We can also consider how material flows and environmental impacts vary across the whole *life cycle* of a product – from production to consumption, through to end-of-life disposal. A nose-to-tail, cradle-to-grave analysis of this sort is a **Life Cycle Analysis / Assessment (LCA)**, or a Whole Life Cycle Analysis / Assessment (WLCA).

However, there are truncated LCAs, such as so-called cradle-to-gate (i.e. cradle-to-use) analysis. These refer to the material footprint or carbon footprint of a product of manufacture as it leaves the factory gate or showroom, pending whatever happens to it thereafter.

Life cycle analysis is an evolving science. It is not always *scientifically* clear where the boundary of a life cycle should be drawn, and how far up the materials supply chain you need to go. Such decisions usually involve some form of *political* judgement. In the case of a building or piece of infrastructure, all the embodied emissions, plus all the operational emissions, comprise the **whole life cycle emissions.**

As climate issues move to the centre of politics, WLCAs are becoming standard. And with them has come great pressure from the construction industry to turn them on their heads: to use them for greenwashing, instead of for making the carbon load of buildings transparent.

Buildings represent a significant investment of capital – and unlike with infrastructure, buildings construction is usually undertaken on the initiative and expense of private businesses. Those businesses have a keen interest in seeing a return on their investment.

And yet, in jurisdictions where environmental factors have become an important *political* consideration, a WLCA can now help determine whether, and in what form, a building gets made. Can a new building be justified, especially where it depends on demolishing an already existing one?

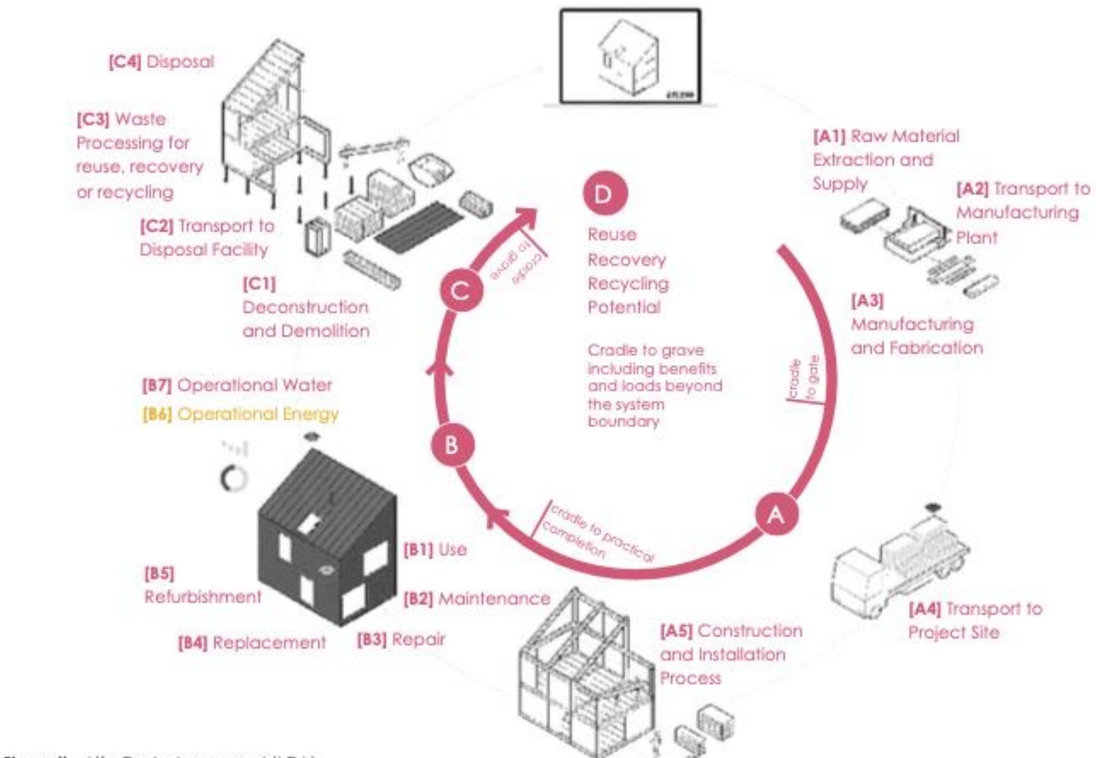


Figure ii - Life Cycle Assessment (LCA)
Diagram adapted from Hawkins\Brown using illustrations from Open Systems Lab 2018 licensed under Creative Commons CC-BY-ND

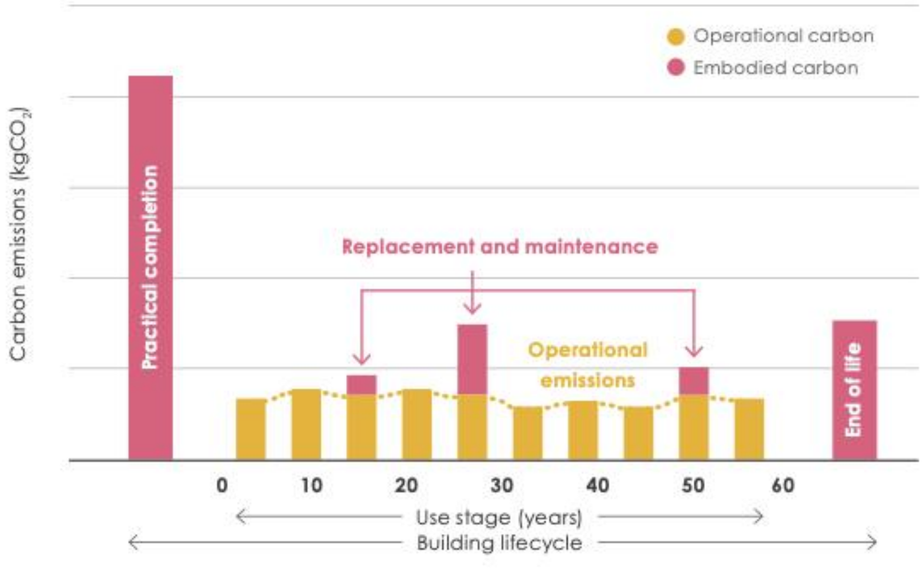


Figure iii - Emission breakdown of a building's life cycle

How architects visualise Life Cycle Assessment of a building's carbon emissions. Source: LETI Climate Emergency Design Guide, 2020, and LETI Embodied Carbon Primer, 2020

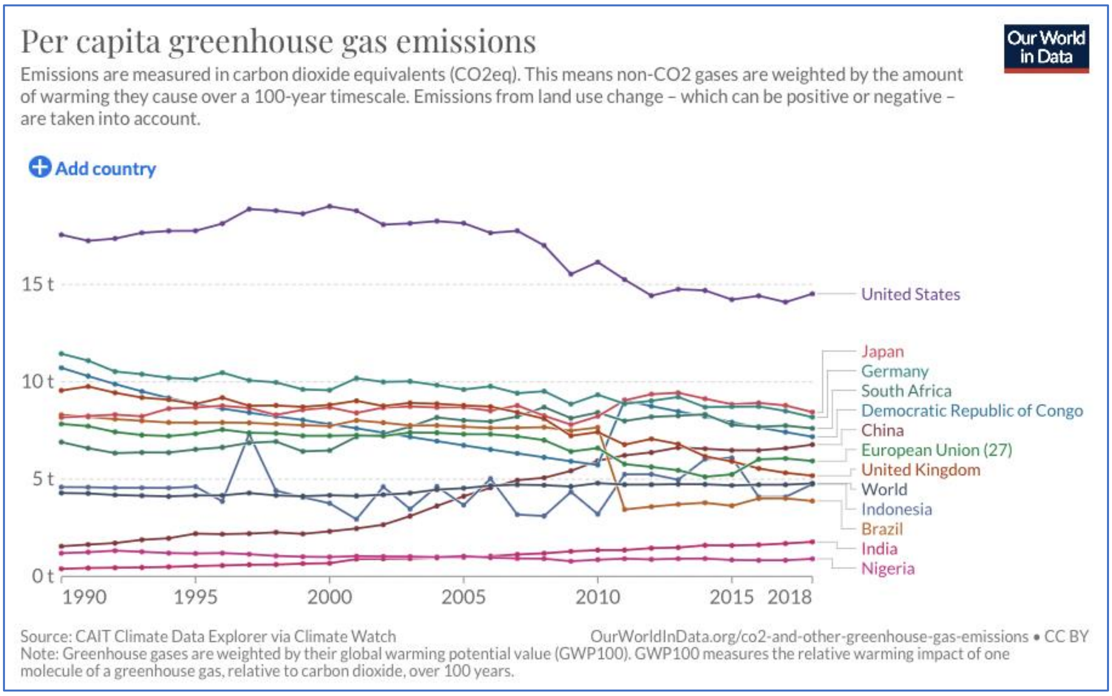
In London, for example, WLCAs are all the rage with new developments, and they are part of most new planning applications. However, as Will Ing, the specialist construction journalist, notes, *it is the developers that pay consultants to carry out those assessments*. There is now "widespread concern that he who pays the piper calls the tune".

Henrietta Billings, director of SAVE Britain's Heritage, told Ing: "Few planning departments have the expertise or resources to scrutinise WLCAs with the rigour required."

Simon Sturgis, an expert on WLCAs, has found that consultants working for developers might set up a straw man: they overstate the operational inefficiencies and embodied costs of simply refurbishing an existing building, and talk up the gains and downplay the drawbacks of demolition and replacement.

That seems to have been done, for example, with plans to redevelop sites around the Barbican. However, Sturgis says that while the data in an WLCA can contain errors, the qualitative analysis in the accompanying report is more likely to be misleading.

Ing quotes another expert, Charlie Baxter: “It’s clear that planning officers and GLA [Greater London Authority] officials rely on [planning] applicants being open and honest.” He thinks there should be independent audits – as with tax returns – and that, if a planning applicant’s WLCA contains errors, there should be legal and financial penalties. In my view, these forms of analysis will continue to be essential for constructing a politics to decarbonise the global economy, and for engineering a genuinely restorative approach for all forms of environmental harm.[5]


Per capita greenhouse gas emissions

Emissions are measured in carbon dioxide equivalents (CO2eq). This means non-CO2 gases are weighted by the amount of warming they cause over a 100-year timescale. Emissions from land use change – which can be positive or negative – are taken into account.

Source: CAIT Climate Data Explorer via Climate Watch OurWorldInData.org/co2-and-other-greenhouse-gas-emissions • CC BY
Note: Greenhouse gases are weighted by their global warming potential value (GWP100). GWP100 measures the relative warming impact of one molecule of a greenhouse gas, relative to carbon dioxide, over 100 years.

Consumption-based greenhouse gas emissions data, measured per head of population. Source: Hannah Ritchie, Pablo Rosado & Max Roser / Our World in Data

But to be effective, footprint analysis and whole life assessments need to be autonomised from the interests of capital – and from the political economy of capitalist development.

2.5 Varieties of footprint

So how does the built environment fit into broader trends of material consumption and emissions?

The International Energy Agency (IEA), working with the UN Environment Programme (UNEP), has for a number of years compiled carbon footprint data for the built environment. These will be discussed more in later parts of this series.

However, it is easy to get blinded by sectoral numbers, in the absence of other information to give a sense of scale.

Here is a brief survey of the main conventions and findings of consumption- and production-based footprints, which should give a better sense of how the built environment’s footprints fit into the larger picture.

a. Country-based footprints

The most familiar, and commonly-used material footprint and carbon footprint indices are country-based. The dominant convention is for the *total* quantities of material use or emissions to be attributed to a country as a whole – or to the population as a whole, on a per-capita basis.

The convention is widespread, because it fits with the agenda of *national* policy responses to climate change. International treaties on emissions, such as the 2015 Paris Agreement, are all production- (territorially-)based.

However, a disadvantage *analytically* of doing things by country is that it lumps everyone and everything in each country together, abstracting away internal differentiation within countries, according to social class, geography, wealth and income; and according to different areas of the economy.

b. Footprints measured by economic sector

Another more economistic convention is for emissions to be attributed to different categories of “end-consumption”, the same way economic indices of consumption are partitioned in national accounts data.

This gives five mutually-exclusive end-consumption categories: consumption by households, consumption by “nonprofit organisations serving households” (NPISH), consumption by government, consumption for “gross capital formation”, and consumption for changes in inventories and valuables.

These statistics – like all statistics! – do not provide a full picture. By focusing on end uses, they leave out of account the process by which the consumed goods came to be made.

For example: as you can see in the second of the next two graphs, four-fifths of the category “household emissions” are “indirect emissions”. This includes emissions from concrete and steel production that go into building people’s homes, electricity generation that supplies households with light and heat, and farming that provides their food – processes over which they have little or no control.

Some researchers have designated consumption of these goods and services, produced by systems the end consumer cannot control, as “non-discretionary”, in contrast to “discretionary” consumption associated with the end consumer’s own decisions. (See also point (c) below.)

Nevertheless, these five categories provide more information about the materials economy of a given country,

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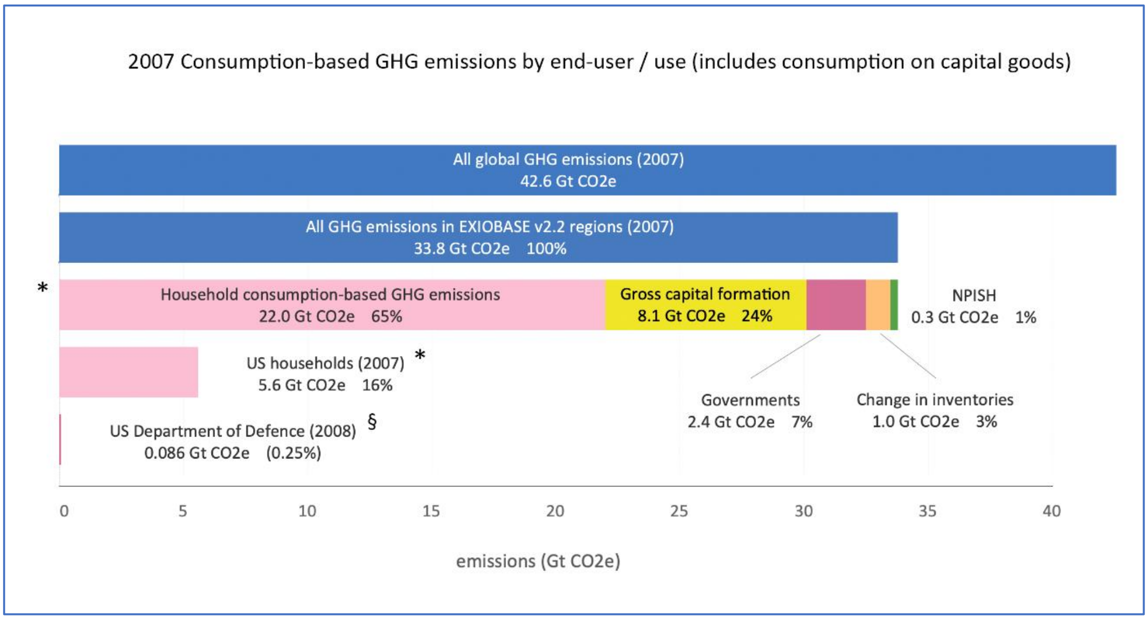
[5] See here for Simon Sturgis’s own criticisms of London’s councils

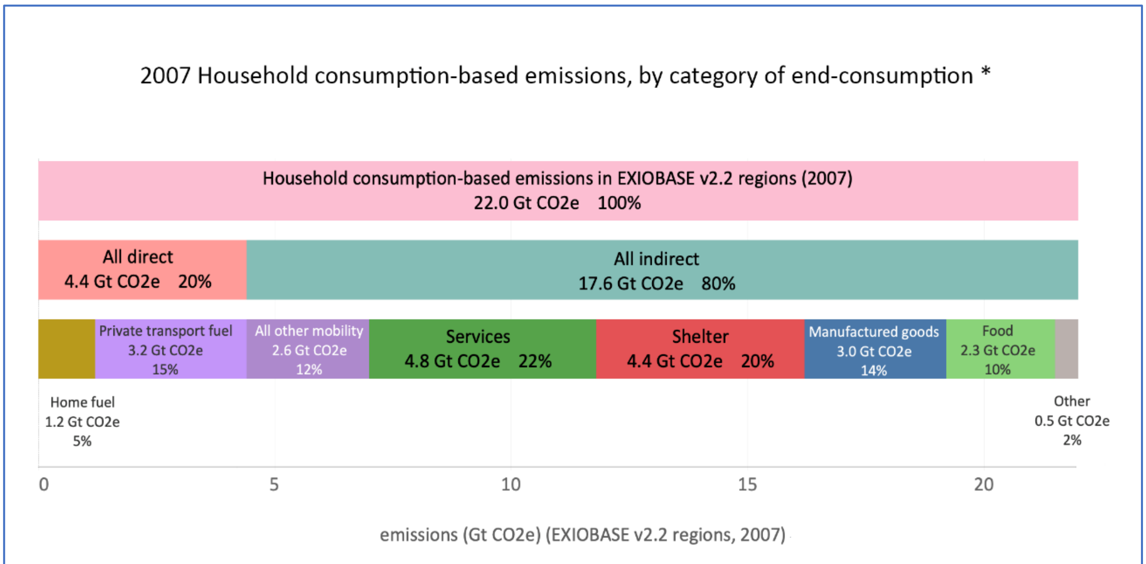
and the consumption drivers of emissions, than we get when simply lumping everything together into one country index.

You can also add together all those separate country-based end-consumption carbon footprints, to get a picture of how *global* end-consumption drives emissions. On this basis, a good estimate (based on 2007 data) is that demand from global household consumption drives around 65% of the global carbon footprint; “gross capital formation” drives around 24%; and government expenditure about 7%.

Those results come from a materials database called EXIOBASE, which covers the economies of 43 countries, and about 90% of global GDP. The data are illustrated here.



The consumption-based carbon footprint of 43 big economies. Sources: * Diana Ivanova et al. (2015); US Department of Energy



Source: * Diana Ivanova et al. (2015)

In the top graph on this page, the first three rows show different breakdowns of (i.e. different ways of looking at) the same emissions. The last two rows are included for comparison. The carbon footprint of all US households comprised 16% of all global emissions.

The US military is notoriously polluting, with a notoriously outsized carbon footprint. So I have also included the carbon footprint of the US Department of Defense (USDoD), according to data from the US Department of Energy. 2008 is the earliest year for which USDoD carbon footprint data is available, and it was 0.086 gigatonnes of carbon dioxide equivalent (Gt CO_2e) (0.25% of 2007’s global emissions).

If we attribute the carbon footprint of the USDoD in 2008 to the US population, it was about 0.28 tonnes CO_2e per person. The per capita carbon footprint (production-based, CO_2 only) *of the whole economy of Afghanistan* in 2008 was 0.15 tonnes CO_2 per person – in 2011 it had risen to 0.40 tonnes, but by 2018 had declined back down to 0.22 tonnes CO_2 per person. (Consumption-based data for Afghanistan seem to be unavailable.)

In any case, looking into the global household data a little more, you can see how global household consumption-based emissions were weighted in 2007. In the graph above, the three rows show different breakdowns of the same emissions.

This graph also shows that the world’s direct household emissions arise about 25% from home fuel – such as for heating, cooling, and cooking. The other 75% is for private transport. Most indirect emissions are associated with home life, however, not cars.

c. Income groups’ footprints

There are very large *distributional* skews in the economy, between states and within them, reflecting society’s vast inequalities. Global consumption-based emissions are

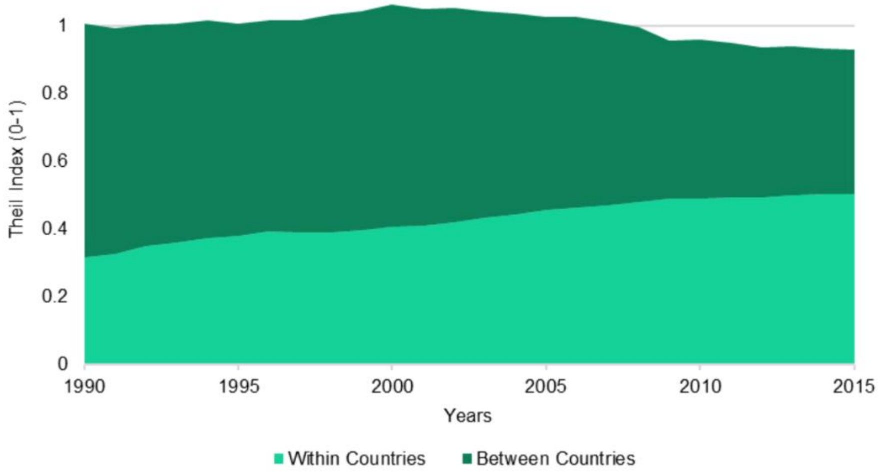
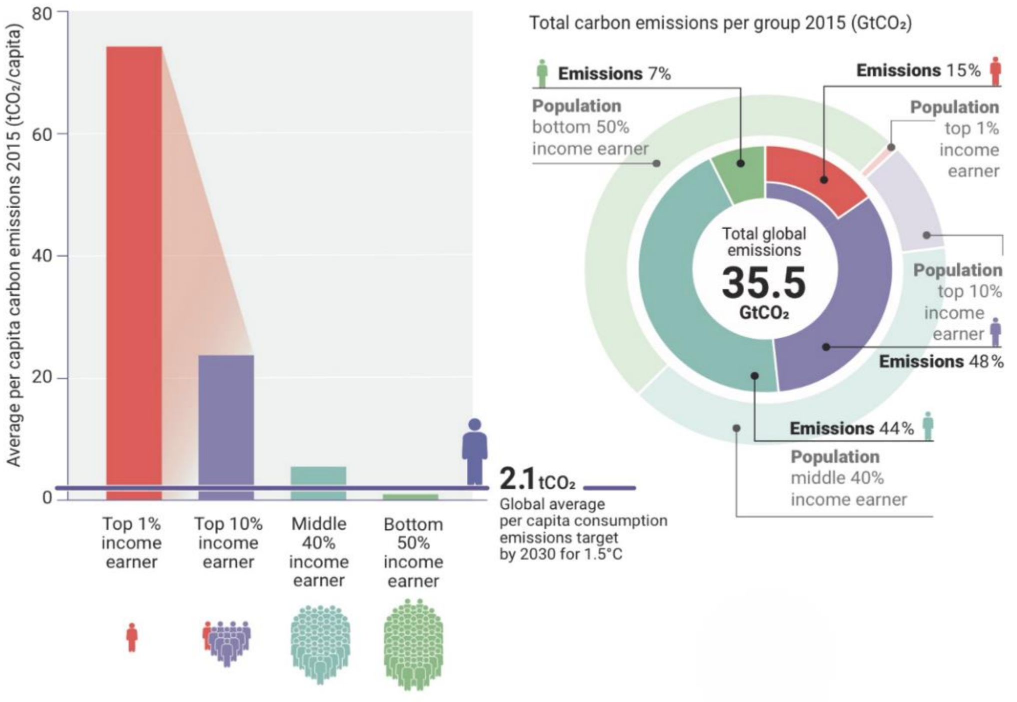


Figure 6: Emissions-weighted Theil index, showing within-country inequality rising and between-country inequality falling.

Source: Oxfam/SEI (2020) Note: the Theil Index is a statistical measure of inequality that can be applied (as here) to income data. See also here in the Oxfam/SEI report.

Figure 6.1. Per capita and absolute CO_2 consumption emissions by four global income groups in 2015



Note: Per capita CO_2 consumption emissions, and absolute CO_2 consumption emissions by four global income groups in 2015, compared with emissions reduction targets for 2030 for limiting warming to 1.5°C. Income thresholds in 2015 are according to US$ purchasing power parity in 2011: 1 per cent > US$109,000; 10 per cent > US$38,000; middle 40 per cent > US$6,000; poorest 50 per cent < US$6,000.

Source: UNEP (2020), based on Oxfam/SEI (2020)

dominated by higher-consumption societies and individuals – as the large total for US household emissions makes clear.

In particular, when a person has greater wealth or income, they also tend to consume and emit more, wherever they live. Discretionary individual and household consumption are said on the whole to expand in proportion to income, once "non-primary" needs are met: this trend has been researched, both within and between countries.

But, crucially, this is subject to local conditions. The strong relationship between income and emissions varies significantly between countries and regions, according to different consumption norms.[6]

Those norms, in turn, are determined by numerous political, economic and cultural factors – *for which the form of the built environment is a crucial mediating factor*. For example, compare the car-centric US to the bicycle- and pedestrian-centric Netherlands – each of which were the product of concrete struggles (see below).

Beyond that, as a general trend, economic inequality *between* countries – in terms of income and wealth – has been declining in recent years, as economic inequality *within* countries has increased. These shifts have in turn produced a general recomposition of the balance of global material consumption and consumption-based emissions.

One influential way that these phenomena have been captured is in a series of studies by Oxfam and the Stockholm Environment Institute (SEI).

Based on the observed correlation between household income and household consumption, they argue that people are "responsible" for *all* forms of national end-consumption (not just "household" consumption), in proportion to their individual income and consumption. This method is simplifying; however, in my view it does offer a helpful snapshot of the uneven "responsibilities" for global warming, internationally.

In their 2020 study, Oxfam/SEI partitioned the national CO_2 emissions of 117 countries according to the spread of

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[6] Examples here and here

individual income within those countries, for the years 1990-2015. (These studies exclude non-CO_2 emissions.) On that basis, their data signal the skew of CO_2 emissions responsibility at the world level, among "global citizens", and how this has changed over time.

In 2015, the top 1% of the world's population by income were those earning over US$109,000 a year – about 60 million people – and according to this study they were responsible on average for 74 tonnes of CO_2 emissions per person per year, around 15% of world CO_2 emissions. The top 10% were those earning over US$38,000 – about 770 million people, responsible for around 23.5 tonnes of CO_2 per person, around 49% of world CO_2 emissions.

For comparison, the per-capita *national, consumption-based* CO_2 emissions of the US in 2018 were 17.51 tonnes CO_2 per person. The EU-27's were 8.08 tonnes CO_2, the UK's a few grammes lower. For China, it was 6.50 tonnes CO_2; India, 1.75 tonnes CO_2; Nigeria, 0.65 tonnes CO_2.

The second graph on page 10 also shows how large the computed carbon footprints are, compared with where the global average would need to be to meet the Paris goal of constraining global warming to 1.5C above pre-industrial temperatures: 2.1 tonnes CO_2 per person.

Most acutely, the top 0.1% of the world's population by income are responsible, by the Oxfam/SEI model, for a ginormous 216.7 tonnes of CO_2 emissions per person per year on average. Whereas the whole of the bottom 50% of the world's population by income account for, on average, 0.69 tonnes CO2 emissions per person per year.

A similar study, by the World Inequality Lab, written up in Bloomberg, makes the stark point that the top 1% by income are responsible for half the world's aviation emissions – and that 10% of the flights that left France in 2019 were via private jet.

2.6. Capital's hidden footprints

The level of emissions worldwide is unsustainable, and the emissions attributable to individuals with higher wealth and income are appalling. Nevertheless, it is *not* true that all material use and emissions can be pegged to individual consumption. Individual consumer choice is important, but it is not the only factor – nor perhaps the most politically salient.

For starters, companies and states use materials and energy, often only *notionally* on behalf of their customers and populations – in order to develop stocks of fixed capital, infrastructure, housing, welfare systems and militaries.

As far as the built environment is concerned, few people have any immediate choice about how they "consume" infrastructure, or the buildings they use, such as homes. Those are political and commercial decisions, in which the average person does not have much agency.

Also, the material economy is not just about the movement of physical materials. It is about the application of labour and technology to change the *form* of physical materials. It is about the production of economic value on that basis, exploitation, the exercise of *political* power, ownership and dispossession, the distribution of profit, and the exchange of commodities: goods for money. These are the *social* factors that determine the overall shape of material consumption – and much of the built environment. So when we look at production or consumption aggregated according to national *populations*, or divided into disembodied industrial or manufacturing or service *sectors*, the social conditions that drive the economy in the first place can be obscured.

What drives the economy are *capital*, *states*, and – this brings us back to the 1% and the 0.1% – individuals with directive power over them, subject to laws of competition, and more often than not engaged in rivalrous consumption of the earth's resources.

Those who consume a lot tend also to be the same people who govern societies and direct capital investments – so they have a "double responsibility".

For example, companies and company bosses *gain economically from production and consumption, even though that gain is not captured by physical accounts data.* Moreover, it is the prerogative of "business" – and states in hoc to capital – to *direct and shape* economic activity to make profit. They determine *on that basis* the possibilities for individual consumption.

A specific example is capital goods, which much consumption-based accounting treats as a form of final consumption, obscuring the role of capital and its power. (See Appendix 1.)

Households and individuals, in turn, can only consume things that businesses find it profitable to produce, or that states provide outside of market competition – and in ways that states legislate to allow.

Business gains, in turn, are based on a fundamentally antagonistic relationship between capital and labour, and between capital and the wider community – notwithstanding strategic truces at times. Capital's relationship with the environment is neglectful at best, but more usually systematically extractive and destructive. And as skews in individual material footprints and carbon footprints are driven by disparities in income and wealth, so those skews themselves are *the product of class relations*: of the fact that some people derive income from their labour alone, while others derive income from capital and other forms of property, over which they may have directive power.

Within the waged sector, there are also plainly sharp differentiations of seniority and reward, that place the interests of certain workers closer to the interests of capital.

Individual wealth, meanwhile, is the accumulated *stock* of capital and other forms of wealth: flows of income that are surplus to the economic necessities of daily life – and transmitted intergenerationally as inherited wealth. The top 10% by income, the top 1%, and the top 0.1%, are those with the main collective stocks of global wealth.

In any case, footprint analysis does not *have* to overlook all these social determinants – but there is a risk that it does.

And because physical accounting does not usually talk about value accounting, it can also be a tool of misdirection. Notoriously, individual carbon footprints have been promoted by corporations – most notably, BP – in an effort at greenwashing that also individualises the issue of responsibility for carbon-intensive consumption.

Meant to deflect attention away from BP's own corporate interest, it also obscured the obvious environmental culpability of those directing its operations for at least the last 50 years. These power relations, and politics, loom over footprints and emissions accounting. It is important that we do not lose sight of them.

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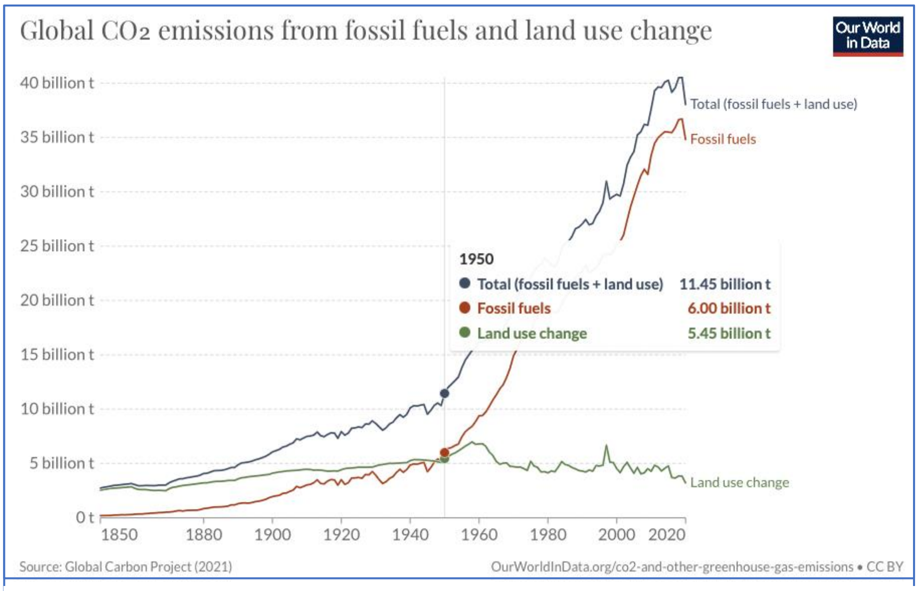
Part 3. The built environment in the fossil economy: a history

The built environment tends to reflect the form of the society of which it is a part. And so a large and growing majority of built environments reflect a world dominated and governed by capitalism – a capitalism whose energetic basis, overwhelmingly, is fossil fuels.

However, that has not always been the case – nor need it be in future.

Three characteristic features of capitalism are: the accumulation of capital; competition for profits; and a population without autonomous means of survival outside a world of waged work.

When production is organised along capitalist lines, it proceeds on a competitive basis, drawing in labour and building capital. Capitalist production is competitively *intensive* in its appropriation and recombination of labour, energy, and other materials.



Annual global CO_2 emissions from fossil fuels and land use change. Source: Hannah Ritchie, Pablo Rosado & Max Roser / Our World in Data CO_2 emissions dataset (see data sources and methods)

Ever since the origins of fossil capitalism in eighteenth-century England, coal, and later gas and oil, have acted as a "force multiplier" to industrial forms of capitalist production.

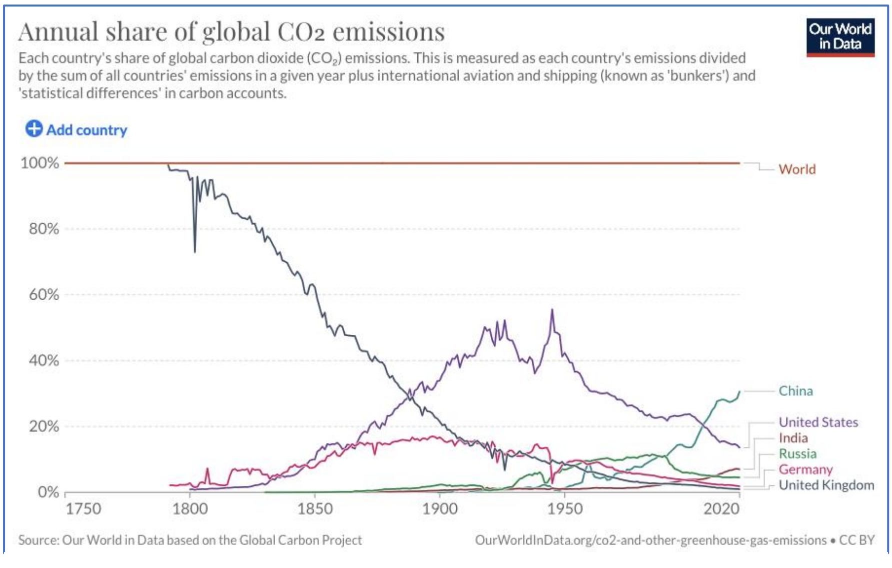
In this part, I will show how the built environment has been tied up with fossil-fuelled capitalism through history: from the emergence of a fossil capitalist economy in Britain in the 1700s (section 3.1); through the rapid economic expansion of rich countries after world war two (section 3.2) and during the economic crises from the 1970s (section 3.3).

3.1. From the 18th to the 20th century

The "at will" nature of commodified fossil energy seems first to have given fossil industrialists a competitive edge in subduing organised labour. That was its main advantage to owners of capital, before it afforded a straightforward energetic advantage over water power.

However, as capitalist production proceeded on an ever-greater energetic basis, thanks to fossil fuels, those fuels became an accelerant to economic growth and capital accumulation on an ever-wider scale. More and more physical materials were sucked into production, combined with labour, and pumped out in the form of more commodities, waste and profit.

The industrial economy, fired by coal, increasingly eclipsed the norms of an agrarian, *organic* economy, to establish a new *mineral* economy (the terms are Anthony Wrigley's) – with a basis in large, but nonetheless finite, mineral stocks mined from the earth. In industrialised countries like England, a capitalist economy in agriculture was supplemented, and overtaken in economic terms, by a capitalist economy in industrial manufacturing.



Source: Hannah Ritchie and Max Roser / Our World in Data CO_2 emissions dataset (see data sources and methods)

Already in 1750, plenty of greenhouse gas emissions were being emitted from industry and construction. Close to 100% of the world's annual greenhouse gas emissions from the burning of fossil fuels (for energy) and from cement production came from the UK – 9.35 million tonnes of CO_2 equivalent (CO_2e). Per capita – that is, averaged across all classes in society – this was 1.01 tonnes of CO_2e per head per year in the UK.

The dirty emissions sites were concentrated in the working class communities of industrial mill towns. But coal's puff of dirty smoke got the fossil capital ball rolling, and gave the UK bourgeoisie first-mover advantage in the export economy of fossil-backed industry and plunder.

Nevertheless, in 1820, still 94% of humanity's primary energy was derived from biomass – that is, from non-fossil, organically compostable materials: wood, peat, dung, straw, and other crop residues.

Meanwhile, the vast majority of effective greenhouse gas emissions globally were caused by changes in land-use – principally deforestation to clear land for farming. Much of that was tied to colonial Europe's violent expropriation of foreign lands for agricultural use: the products either consumed "domestically" by settler colonies, or exported back to Europe.[1]

For the fossil-powered industries and economies of the early fossil capitalist era, the energetic "base" was coal – but other minerals were also economically crucial: cement, sand, and metals contributed to the expansion of manufacturing capacity, through build-out in capital goods, in the shape of machinery, buildings, and infrastructure.

By volume, according to Paul Bairoch, the "developed" countries of the time were self-sufficient in most of these minerals throughout the 19th century and up until around 1950. Self-sufficiency was predominant, and imports travelled only short distances – certainly for the heaviest minerals such as iron ore, and the non-metallic minerals used mostly in construction.

Sand, gravel and crushed rock for construction are widely available across geographic regions, and are almost always used locally. Much engineering consisted in the excavation or movement of local soils and rocks. Limestone, structural clays and gypsum, the main ingredients of concrete, and concrete itself, at most tended to be traded between countries regionally.

During the 19th century, those leading capitalist economies probably extracted more than 99% of the metal ores they consumed (by weight), and out of these produced most of their own finished metal products. These were needed both to make machines and for construction. Reinforced concrete using iron or steel reinforcing bars (rebar) had emerged as a construction technique in the 18th century.

The leading capitalist economies of the time were not, however, self-sufficient in certain other economically important raw materials – for example, cotton, sugar, and gold.

Colonial profiteers and settlers had long plundered foreign lands, dominated their peoples and committed genocides, with the economic support of the European states and the ideological props of racial supremacy – all for the sake of acquiring dominance over labour, land and minerals, and cultivating natural products that were unavailable at home, – or unavailable at such volumes and prices.

Those companies and states remained so dependent as fossil industry developed – as did their beneficiaries in the governing echelons of the British Empire, European imperialism, and settler-colonial states. European consumers had also grown to depend on cheap imported goods.

The sites of colonial plunder may not have been where the *productivity gains* of fossil capitalism were realised – that was in domestic industry and in its local relations of production. But they nonetheless pumped a vital flow of raw materials into the machines and bellies of the industrial heartlands, off the backs of colonially-sourced slavery and "coolie" labour.

The products of industry – like spun cotton and textiles – could then be pumped out and sold for a healthy return. During the 19th century, moreover, Britain's industrial development was based more and more on overseas and colonial export. So too it depended on gunboat mercantilism to assert the right kind of "liberal" world economy, via forced deindustrialisation in India, coerced levies from China, and so on.

Thereafter, the revolution in profits is what made Britain's enlarging colonial empire possible: energetically, economically, technologically and militarily.[2]

And *almost all* of the raw minerals extracted in tropical regions were those exported to the industrial economies.

Yet minerals remained a tiny proportion of colonial exports. Minerals exports were massively overshadowed by the export of natural products – and *by weight* imported minerals comprised only a tiny fraction of the minerals the rich regions themselves consumed.

The point is that the construction of fixed capital, worked out of domestic raw minerals and powered by coal, was *just one of several* key determinants of growth in the industrial core – but an fundamental one.

The accumulation of the gross stock of machinery, its technological renewal, and the expansion of non-residential buildings construction, provided the direct physical means for rapid competitive increases in labour productivity and efficiency. During the 19th century, the rate of energy use multiplied approximately five times over.[3]

1820 was also an inflection point for volumes of world trade, which – on the energetic basis of fossil fuels – turned sharply upwards and accelerated for most of the next 200-odd years. Britain exerted a dominant colonial influence, but also a "diffusionist" role, driving world economic "development" on a fossil capitalist basis.

That development, in turn, drove the industrialisation of the production of building materials themselves, and (increasingly) of construction processes.

Private capital *and* states were building out infrastructure. Projects undertaken by states functioned as a socialised subsidy to capital. But states also undertook civil

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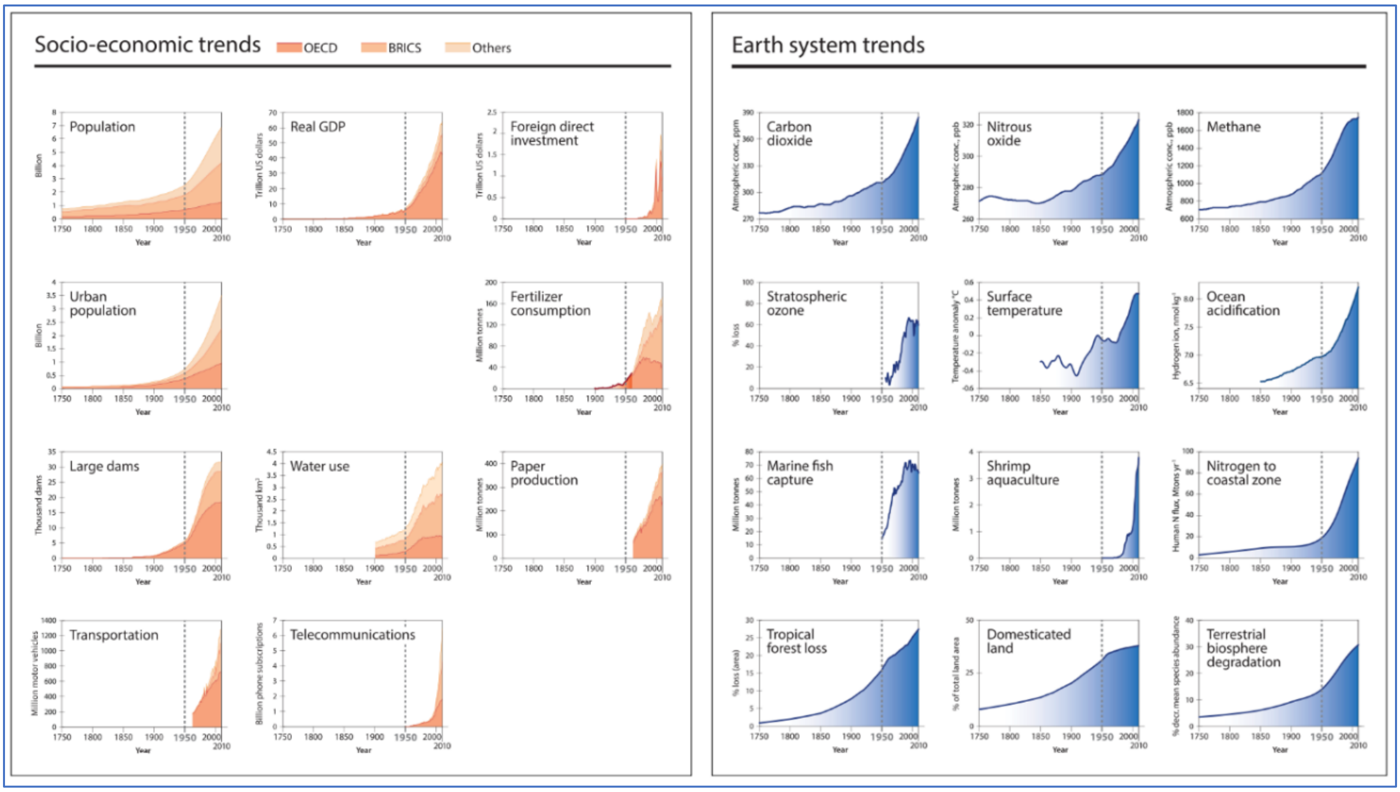
[1] In 1850, for example, effective emissions from the loss of land-based carbon sinks have been calculated at 2.54 billion tonnes of atmospheric carbon, versus 197 million tonnes from burning fossil fuels. (To be more specific, the graph line showing land use change represents a bookkeeping average from three different estimates for "net CO_2 flux", the net effect on atmospheric CO_2 of sociogenic changes in land-use, such as deforestation, forest degradation, logging, agricultural harvest and land management practices, afforestation, and forest regrowth.)

[2] See Paul Bairoch, Economics and World History: myths and paradoxes (1993), p.86

[3] In the UK, the gross stock of machinery rose from $92 per person in 1820, to $878 per person in 1913 (in 1990 US dollars). The value of non-residential structures rose from $1,074 per person to $2,509 per person. Alongside this, the average years of primary education per person rose from two years to nearly nine years.



The “great acceleration”. Source: Will Steffen et al (2015)

engineering projects according to “moral” precepts of bettering conditions for their own “native” workers and populations at large – for example through the hygienic delivery of drinking water and removal of wastes. And as the economic rewards of construction came in, so too did new rounds of capital investments in the built environment.

3.2. After the second world war

Growth in the fossil economy took off decisively after 1945, with a “great acceleration” of industrial output, material throughput, and gross domestic product (GDP). It was made possible by the “energy regime” of fossil fuels that by this time had spread world-wide. The acceleration of greenhouse gas emissions followed as a matter of course. World population also expanded rapidly.

The rate of effective CO_2 emissions from changes in land-use, such as deforestation for agriculture, had not changed dramatically since 1850. But emissions from fossil fuels now eclipsed those from land-use change.

To understand the way the built environment grew, we need to look at the political and economic mechanisms that drove patterns of industrial development and consumption.

The US had exited world war two as the dominant political and economic player, beneficiary of half a continent and its resources, looted through broken treaties and genocide. With Europe’s colonial projects thrown out or falling apart, the greater part of Europe’s own infrastructure and fixed capital were in pieces. By contrast, there had been no fundamental damage to US infrastructure and fixed capital. And US industrial and manufacturing capital had been pump-primed for expansion by the war economy. At the new core of the world economy, the US now possessed such plant, machinery, and relations of production as to place its domestic economy at the forefront of labour productivity.

Physical reconstruction in Europe, alongside technical improvements, restructuring and dollar-denominated investments, drove economic growth in a direction that gave rewards, albeit skewed by racism and gender, to both capital and labour across the “core” economies, but particularly the USA.

The Bretton Woods system of international trade (established in 1944, with the US dollar as the reserve currency) underpinned an expansion in worldwide trade and investment between 1950 and 1973, ventilated by US dollar export.

This also brought a period of wider, unparalleled – if uneven – global economic prosperity, as newly industrialising regions built out their infrastructures and their plant and machinery, cashing the gains of “late development”. Dollar exports came home to the US in the form of investment profits, export sales, and cheap imports, and a mutually-beneficial cycle emerged, of rising domestic and foreign wages, and rising consumption.

As a result, the expansion of GDP worldwide led to a significant *convergence between states* in their per capita incomes, and in their rates of labour productivity.

Meanwhile, the Soviet Union eschewed the price and demand signals of consumption via open markets, but nonetheless pursued industrial planning and development of the built environment on a competitively productivist basis – to environmentally-destructive effect.

In fact, all regions that were already industrial economies post-war developed similar profiles of material use. There

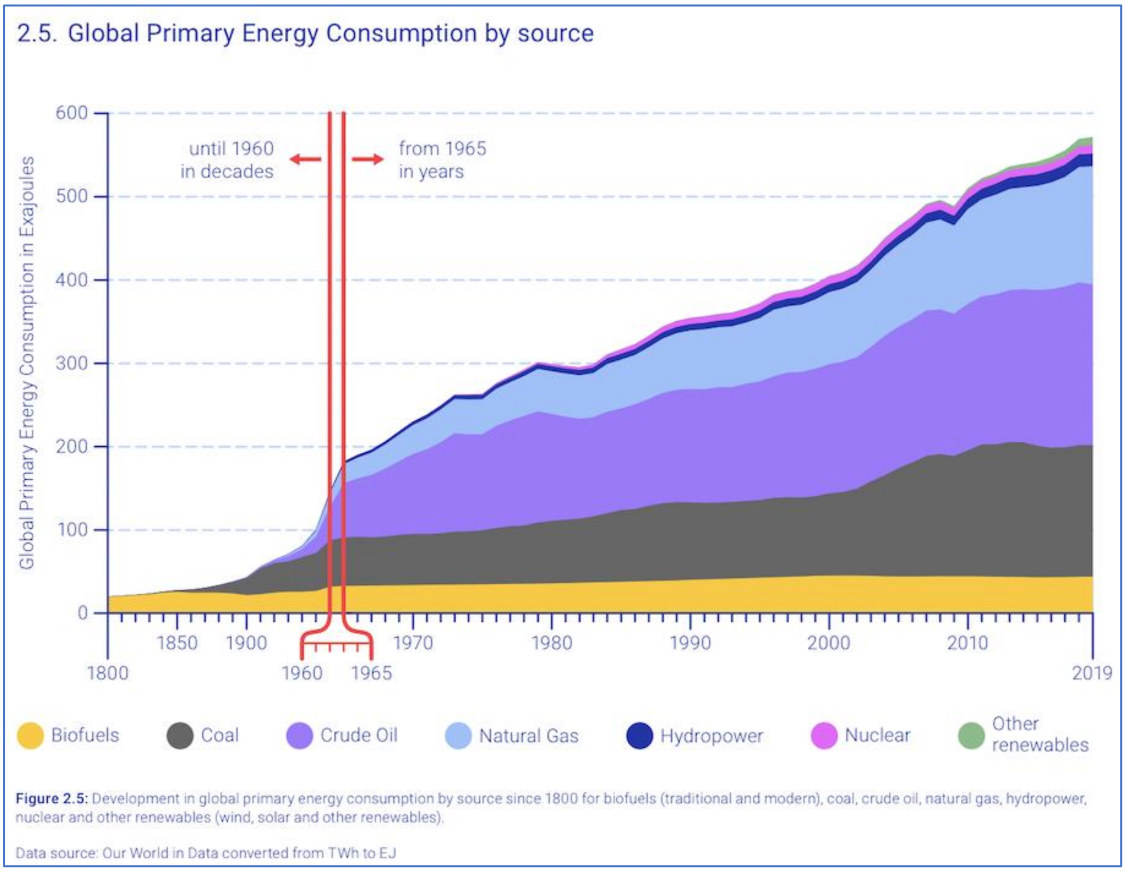


Figure 2.5: Development in global primary energy consumption by source since 1800 for biofuels (traditional and modern), coal, crude oil, natural gas, hydropower, nuclear and other renewables (wind, solar and other renewables).

Data source: Our World in Data converted from TWh to EJ

Energy consumption, measured by energy content. Source: UNEP (2021)

was “no fundamental difference in the trajectory between market and planned economies”, although most of the impetus for industrial development came from the capitalist nations, according to a recent study conducted at the Vienna Institute of Sociology.

In the global south, programmes of post-colonial state-building and “modernisation” drove large-scale civil engineering, infrastructure, and extraction projects. Again, fossil fuels were at the base of it all. One might not want to endorse all such projects, but as a whole they improved the life chances of millions of people, by furthering delivery of essential services.

Patterns of development were additionally contoured by the inter-imperial rivalries of the Cold War. For example, it was in the US’s political interests, against the perceived threat of communism and an insurgent left, to assist in a developmentalist uplift of people’s lives in Japan. To this end, the US granted Japan (and later South Korea) favourable export conditions into the US domestic market, and helped open its regional neighbours to Japanese exports.

Another example of Cold War construction is Egypt’s Aswan High Dam, across the Nile, which remains the world’s largest embankment dam – and was financed and designed by the Soviet Union.

Military installations, and years of war-readiness, also generated large material, construction, environmental and carbon footprints. The US military’s global sprawl remains notorious for its carbon intensity, as mentioned in part 2.

The graph above shows how energy consumption expanded in the post-war period. After 1945, there was a sharp upturn in total energy consumption, especially oil. By 1965, oil was the dominant fuel, but with coal remaining a major and *increased* player, alongside the emergence of natural gas.

Up through world war two, the US had been the world’s largest oil producer, but during the post-war boom production rose steadily in the Middle East (chiefly Iran and Saudi Arabia) and North Africa (Libya). This brought a commensurate acceleration in these states’ fixed capital investments, which lasted until the 1980s – when the growth of construction stocks in these countries peaked at about 10% per year, in terms of the mass of materials deposited in infrastructure.

Since oil was the basis of the most competitive elements of the post-war economy, the rich states believed – in their typically racist way – that Middle Eastern and North African oil was rightfully theirs to invest in, control, and exploit at will. Of course this conflicted with local efforts of national self-determination, although circumstances were also ripe for the cooptation of traditional elites, as with Saudi Arabia.

The built environment grew, at multiplying orders of magnitude, thanks to industrial development on a fossil fuels basis.

This meant that there was also a significant change in the composition of global material flows.

In 1900, nearly 80% of such annual flows were used “dissipatively” – that is, materials overwhelmingly passed through the various metabolisms of the world’s societies, and out the other side: food, feed and fuel became energy, excrement and emissions, along with other waste products.

In the post-war period, the absolute volumes of dissipative throughputs increased dramatically. However, the *proportion* of materials that went to dissipative use declined year-on-year. There was a dramatic accumulation of material throughputs deposited as stocks.

Indeed, stock accumulation was the main reason for increases in material throughput after 1950. This is shown in the graphic, from a specialist research paper on material flows. By weight, about 40% of those stocks comprised of concrete (see graphs C and D in the graphic on page 16).[4] Aggregates, bricks and asphalt make up most of the

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[4] For data, see this previous paper

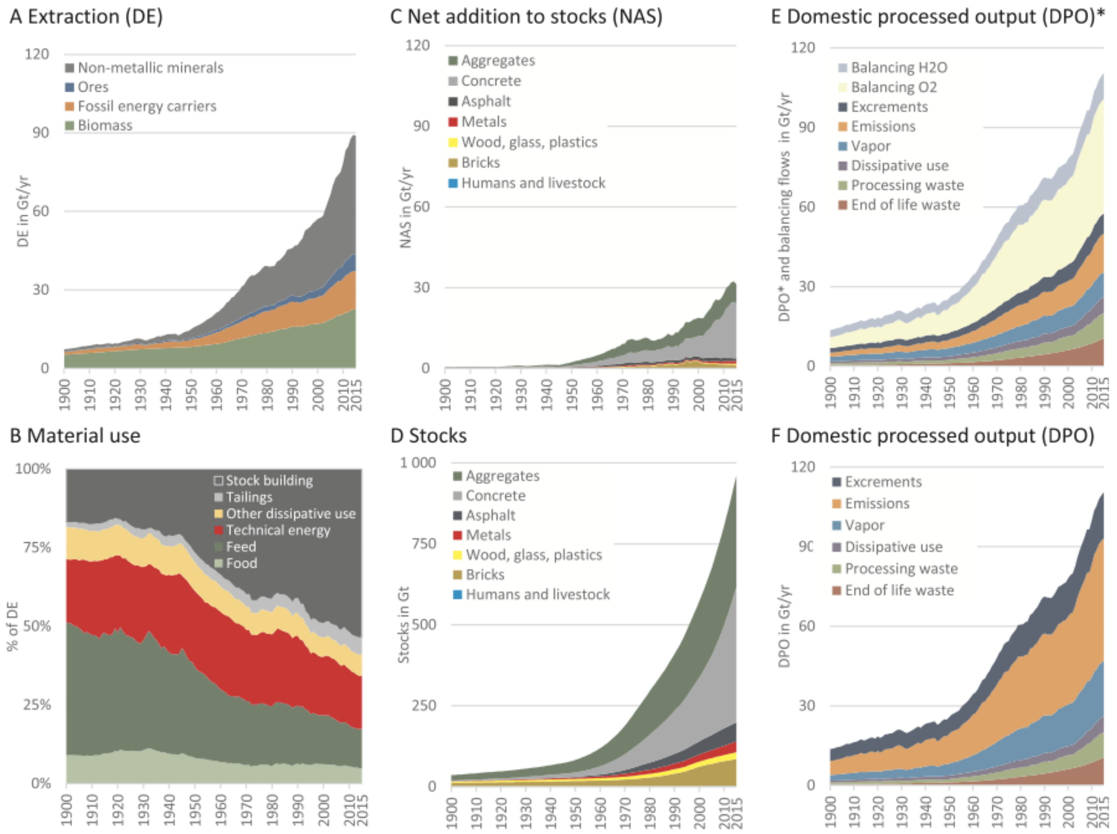

Fig. 2. Global material flows in Gt/yr and stocks in Gt from 1900 to 2015. A: material extraction by main material group; B: share of major use types in total extraction; C: yearly net additions to stock (NAS); D: stocks of humans, livestock and manufactured capital in Gt; E: the fraction of domestic processed output that actually originates from DE (DPO*) separate from balancing oxygen and water F: DPO by main type including balancing oxygen and water.

Global material flows, 1900-2015: stocks outstrip dissipative uses. Source: Fridolin Krausmann et al. (2018)

remaining stocks. These four are the main ingredients of the built environment, the products of extracted non-metallic minerals and ores. They are used for little else besides construction – so evidently the majority of stock accumulation, and the majority of material throughput post-war, went into the construction of the built environment.

Stock accumulation in the form of other materials, such as metals, wood, glass and plastics, was much smaller by weight. Those too are used in construction; however they are primarily important as ingredients for machinery and consumer durables – and clearly very economically important in *driving* the boom in construction. [5]

In terms of waste products, the increase was greatest and most dramatic from waste emissions and vapour outputs (graph F in the graphic). These are followed by processing waste and end-of-life waste – although the percentage increase in those last two was greater. The increase in end-of-life waste, in particular, is related to the growth in consumer economies post-war, built on high levels of throughput and disposability.

The growth in emissions after 1950 was undoubtedly associated with the large increase in buildings and infrastructure – and therefore the growth in stocks in the built environment drove significant embodied emissions. However, the total here is for *all* emissions, including the operational emissions from buildings and transport, and the embodied emissions of non-construction manufacturing.

The rise in fossil-fuelled construction, manufacturing industry, transport, and consumption, are all of a piece in the economic boom after 1950.

The rise of concrete, which came to dominate construction post-war, has been – and remains – hugely consequential for climate-forcing emissions, and the embodied carbon of the built environment. Not least, this is because of its large "process emissions" (see Part 7).

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[5] Graph D in the graphic above deserves some additional comment. Note that the "baseline" entry stock at 1900 is in the 10s of gigatonnes for the world as a whole. All the graphs rely on statistical reports related to industrial development. But as mentioned by some of the same authors in a later paper, existing material stocks prior to industrialisation are probably underestimated – think, for example, of historic towns and cities, and all the earthworks, whose construction predated the industrial era. So it is likely that the curve of graph D should be shifted further upward to reflect a larger legacy stock of buildings and infrastructure before 1900.

Nevertheless, it is the *shape* of the curve that matters most to climate politics. Prior to around 1950, those legacy stocks were accumulated *slowly* – as were *all* stocks (graph C). The difference made by industrial development on a fossil fuel basis after 1945 was that the built environment then expanded *massively and rapidly*.

Additionally, reporting gaps remain for some materials: bricks, sand and gravel go under-reported. So do illicit material flows. For obvious reasons, informal, non-industrial construction is also under-reported – including traditional construction, and construction in informal settlements and slum neighbourhoods.

However, in quantitative material terms, the volume of such construction probably remains tiny compared with the sort of industrial construction that leaves a statistical footprint – although it provides essential "services" to populations outside the mainstream of industrial consumption.

Reinforced concrete – usually using steel rebar – became the standard-bearer of international construction, with buildings and infrastructure between them consuming most of the world's steel.

Concrete is an ancient material. However, only with the onset of a high-energy, high-carbon society could the combined structural-engineering and economic efficiencies of steel-reinforced concrete become a reality at scale – and thereafter the basis for a globalised construction industry.

Moreover, structural dependability combines with entrenched economic interests. Both presumably contribute to the professional habits of mind that retain reinforced concrete and structural steel as the mainstays of buildings construction and civil engineering.

In buildings design, there is also an aesthetic component to this. In the 20th century, steel and concrete became the main materials for a form of modern architecture that sought to "dematerialise" the structure of buildings behind curtain walls of glass. And yet the quality of engineering strength that helps steel and concrete to "disappear" can correspond to *vast* material and emissions footprints during the whole life cycle of a building.

Much architectural and civil engineering design has *repressed*, or been blind to, its wider relationship to the environment – and this continues in many instances today.

Arguably, the repression, or the blindness, has been foundational to the psychological construction of the mainstream of "modernity" – a kind of imperial standard.

Very many countries have also been incredibly industrious in stockpiling asphalt, through car-centric planning, and car-dependent infrastructures of roads and suburbs.

In the US and elsewhere, this is tribute to the political-economic sway of the fossil fuel and motor car industries – and how they have successfully embedded their interests in the entire form of the built environment.

The historic removal of public transit in the US, and the rise of car-centric environments, by the 1960s ensured high per-capita rates of energy consumption in transport, forcing people to travel unduly large distances, often individually, and (until the advent of electric vehicles) exclusively powered by oil.

Besides the *direct* money costs of transport, highly distributed road systems and low-density urban sprawl have also baked in enormous ongoing embodied costs – in particular, for road maintenance. Those have proven to be fiscally bankrupting to many US states and cities without federal assistance.

After 1955, the more "developed" economies became increasingly dependent on the global south for many more materials – and far less self-reliant than they had been before. For example, they have imported most metal ores, although North America is the exception here.

For industrialised states such as the US, UK and Japan, fossil fuels fed comparatively developed systems of production, and increasingly energy-dense habits of consumption and mobility.

Most poorer countries grew heavily dependent on imports of oil and manufactured goods. Fossil fuels were disproportionately the means of "catch up" development: building out the basic requirements of modernisation and industrial development, including vital infrastructure, electrification and housing.

Fossil fuels also enabled a decreased dependence on biofuels for domestic heating and cooking (athough it remains high worldwide – see below). This transition is vital to lifting domestic air quality, respiratory health, and related burdens of disease.

In the global south, workers could buy slightly more with their wages at the end of the 1920s than they could around 1875.[6] However, from the 1950s onward, poorer non-oil-producing countries faced constantly-worsening terms of trade.

The international supply of raw materials and produce grew, and this drove prices down – which in turn brought declines in foreign exchange income. Poorer countries therefore faced perennial downward pressures on their currencies, even as they sought to acquire dollar-denominated manufactures to carry their economies along the path of "modernisation".

Another aspect of the "great acceleration" that followed the second world war was an unprecedently rapid growth of population.

The post-war period brought unprecedented declines in mortality across the "developing" world. This was caused by the increased use of insecticides, vaccines and antibiotics, and public health interventions that effected a revolution in the treatment of communicable disease, e.g. via improvements in everyday sanitation.

Civil engineering projects for delivering clean water and managing waste also helped substantially, especially in cities.

From these improvements to public health, rapid population growth followed, with the world's population expanding at over 2% a year by the early 1960s – and by more than 3% a year in some poorer countries. Just a 2% annual rise implied a doubling every 35 years.

Notwithstanding the availability of, and use of, artificial contraception in some countries, the unprecedented declines in mortality continued to be bolstered by high rates of fertility in many regions, and across "less-developed" countries as a whole – including in Brazil, Nigeria, the Democratic Republic of Congo, India, and Egypt. In such regions, population expanded rapidly through the 1970s – and in most cases *continues* to expand now, although often at diminishing rates.

This demographic expansion has tended to be focused in urban areas – cities already being places where people live in greater numbers. This "natural" demographic expansion has been the main factor driving urban population growth in poorer countries, although migration into cities from also-more-populous rural areas has been significant too.

Rural-urban migration can be driven by many factors besides the pull of potentially higher wages. People can be pulled by personal circumstances. Or they can be *pushed*, as

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[6] Bairoch, Economics and World History, pp. 115-116.

when dispossessed from land-based livelihoods by politically-sanctioned land-grabs, by the prevalence of political instability and war, or by encroaching environmental devastation. "Environmental migration" is already a significant factor affecting the lives of millions of people.

All net growth in urban population has obvious impacts on states' and markets' ability to meet populations' material needs – and that includes through the "services" of the built environment.

However, although the post-war population expansion is usually considered to be part and parcel of the "great acceleration", the link to exponential rises in material consumption and climate-forcing emissions is partial at most.

In part 2, I cited a series of Oxfam/SEI studies[7] that allotted consumption emissions to the world's individuals in proportion to their income. Those studies conclude that greenhouse gas emissions are *almost entirely* caused by the high levels of material consumption – flows and stocks – from the world's rich. The bottom 50% of people by income are responsible for only 7% of global consumption-based CO_2 emissions, according to Oxfam/SEI.

Those studies make simplifying assumptions. However, it is clear that responsibility for the environmental impacts of high rates of consumption lies with a minority of richer consumers, and with the world's corporations and states devouring ever-more resources – not with the world's poor, however numerous.

A large minority of the world's population "may not even have any net contribution to [greenhouse gas] emissions", according to the researcher David Satterthwaite.

Indeed, where populations have expanded significantly after 1960, they have tended to do so primarily in the *absence* of rising incomes and economic growth, and in the absence of equitable access to material resources, stocks, and services. Per capita access to services has usually struggled – and in many cases failed – even to keep up with the growth of populations, and populations have struggled to "get out of poverty".

Nevertheless, two additional factors should be mentioned.

First is the widespread use in poor countries of biomass combustion for domestic cooking and heating – often linked to deforestation. That is a huge cause of respiratory illness and ill health. It is also a not-insignificant cause of greenhouse gas emissions. (See part 9 and Appendix 3.)

Secondly, we should all want the material conditions of the world's poor to *improve* significantly – and that would include increased material consumption, in the form of electricity, food, and other services.

If that is to occur, under present consumption norms, then *both historical and future* population growth amongst the world's poor *would* then result in increased emissions. As things stand now, however, that has substantially *not* occurred. What is needed is "contraction and convergence", and energy transition. (See part 6.)

According to the World Bank, more than 80% of world GDP is now generated in cities. And with a rising majority of the world's population (about 56%) living in cities, it is hardly surprising that a majority of the world's material consumption is also *on average* concentrated in cities.

And yet, in circumstances where population growth continues to outpace economic development, urban growth is certainly *not* – as it is sometimes presumed to be – an automatic indicator or driver of economic improvement and the improvement of people's lives.

Instead, the question is whether sufficient economic activity – formal or informal – can be generated to *absorb* a growing population that lacks any other non-market means of subsistence. Furthermore, a circuit of under-consumption can have a self-reinforcing character.

Just this kind of dynamic is at play in the growing populations of sub-Saharan Africa and India – in particular, in cities – where an even greater future population boom is forecast. I look at the implications of this for decarbonisation and the built environment in part 6.

3.3. From the 1970s: growth through downturns

Whereas the 1950s and 1960s were characterised by the diffusion and convergence of countries' per capita GDP gains and material footprints, the 1970s brought considerable divergence.

In the USA and other historical centres of capital, many people benefited from the golden age – but by no means everybody. Capitalists, the otherwise wealthy, and those with rising terms of employment and social rights benefited. There were clear racial components to the patterns of social and workplace gains, and the intergenerational transmission of wealth and oppression.

As the post-war world economy grew, it also brought newly-industrialising export economies a competitive edge. However, heightened commercial competition within key sectors eventually came to impinge on profit rates in the rich countries.

Alongside the US's war in Vietnam, expanded world trade had *also* brought a swollen demand for US dollars internationally. As a result, not only was confidence in the convertibility of US dollars to gold shaken, exchangeability became all but impossible to uphold. An overheated domestic US economy generated inflation, and this was transmitted around the world through the fixed exchange rate system.

When Richard Nixon, the US president, unilaterally ended the Bretton Woods system in 1971, and let go of the "monetary anchor" of dollar convertibility, it was in part in defence of domestic production. Implicitly, however, the US had come to accept its economic position as the international "consumer of last resort" – of movable commodities – in a world economy largely denominated in US dollars.

With OPEC's subsequent withholding of oil production in 1973, the price of crude oil rose nearly fourfold. In the rich capitalist countries, this set off a wage-price spiral in

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[7] As I complete this series of articles, Oxfam/SEI have released a new 2023 study, reported prominently in the Guardian newspaper. This updates the 2020 study, with some changes to data sources. However, the methodology remains the same.

which capital and labour, "fought it out for who would take the real income loss arising from the imported oil prices" in the words of economist Bill Mitchell. Not least, the full coercive force of the old imperialist states was used to squeeze labour on behalf of capital. Labour lost.

This immediate victory of capital was subsequently secured for the next 40+ years by globalisation, with its perpetual threat of offshoring, combined with the elite capture of social democratic labour parties.

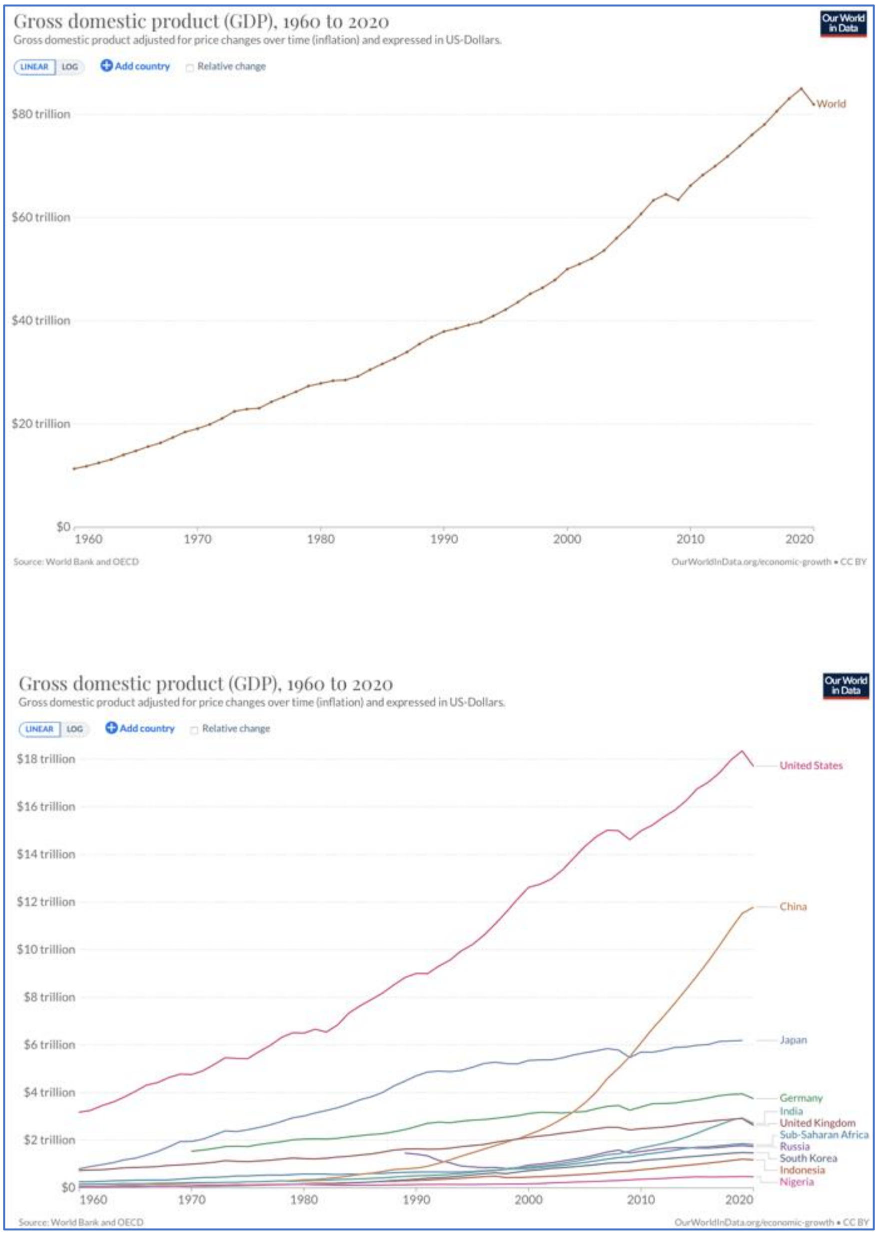
The domestic economies of the capitalist core were *wound down*, driving them into recession. Functionally, this drove the bargaining power of labour into the dirt, while eventually re-securing a low-inflation environment based on the disempowerment of labour.

For reasons of monetarist ideology and capitalist self-interest, current spending and investments by the state were meanwhile made subsidiary to the fortunes of capital.

Annual spending by government was pegged to the scale of tax "revenue" out of the non-government sector. Government investments were "funded" by bond sales – a blatant subsidy to large commercial banks. These constituted *policy choices* about the social function of a national currency.

Under the neoliberal consensus, henceforth, deficit and debt became dirty words, wherever they threatened to deliver broad social uplift. Governments tended to prioritise assistance to capital and the wealthy, ahead of building stocks of social welfare.

Growth in territorial material use across the core industrial economies slowed abruptly through the 1970s. In the national industrial sectors, profitability also slumped.



Source: Our World in Data

Integrated steel mills, for example, depended on high throughputs to maintain competitiveness. Globalisation meant they faced competition from newer integrated mills and mini mills abroad – although those were often owned or financed *from within* the capitalist core economies.

Favourably located close to new and cheaper sources of ore, these new mills also benefited from technological upgrades that made them less labour-intensive, and from comparatively cheaper and more "flexible" labour relations. The market in low value-added finished steel products was globalised: this included the market for steel rebar used in construction.

At the same time, the oil price hikes reasserted the fact in the minds of fossil capitalists, and to all states dependent on oil imports, that they were vulnerable to interruptions in the supply of fossil fuels, so long as their dependence continued.

But while the inflationary spiral had led bosses and states to impose wage stagnation and recession in the capitalist core, the 1973 oil shock was far worse for the people of poorer oil-importing countries.

It drove their economies through the floor: import prices rose, currencies depreciated, and export markets dried up – which crippled economic growth in Africa, Latin America and the Middle East, already suffering under unfavorable terms of trade. The external debts of these countries soared. Capital took advantage with new rounds of plunder, particularly through land grabs from agrarian economies.

Meanwhile, across Africa and Latin America, development needs went unmet – not least in urgent infrastructure spending.

But more than anything, labour militancy and inflation in the core, and the post-1971 monetary environment, combined with improvements in transport and communications to encourage ever more global "offshoring" of extraction and manufacturing.

Industrial and manufacturing businesses looked beyond the old industrial core to the newly industrialising countries that already had a foothold in providing infrastructures and workforces amenable to capital. The bid here was to find more and readier access to cheap labour, and it paid off.

So as capital imposed 40+ years of stagnated or declining wages in the rich economies, it invested in production and economic growth globally – primarily in East Asia. From the 1970s onwards, East Asia's per capita growth *improved* from the "golden age". South Korea, Taiwan, Vietnam and China all replicated Japan's earlier growth spurt. Those shifts entailed *wholesale build-outs of the production and export capacities of those "emerging" economies* – from the fixed capital of heavy industry and manufacturing, to infrastructure; but also, more and more capital funding and materials for civil engineering and housing.

That expanded productive base thereafter mobilised progressively greater throughputs of materials in production, subsequently embodied in oceans of new products, whose lower prices found a growing market of buyers globally. The expansion of the global labour force meanwhile lifted incomes, which in turn fed more demand into the system, realising and continually raising the promise of expanded reproduction.

It is those *changing geographies of production* that enabled the continued expansion in the world economy *through* the 1970s and through the period of "secular stagnation" in the old core economies – even as high rates of competition continued to hold down the declared average rate of profit across the G20 group of rich nations. (The G20 comprise around 90% of world GDP and two-thirds of world population.)

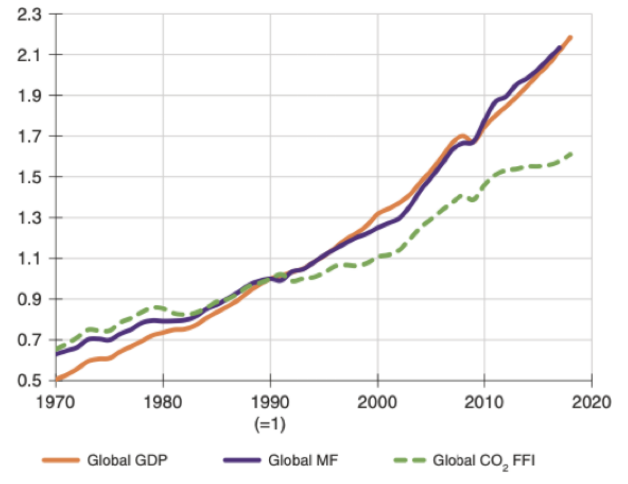


Fig. 1 Relative change in main global economic and environmental indicators from 1970 to 2017. Shown is how the global material footprint (MF, equal to global raw material extraction) and global CO_2 emissions from fossil-fuel combustion and industrial processes (CO_2 FFI) changed compared with global GDP (constant 2010 USD). Indexed to 1 in 1990. Data sources: https://www.resourcepanel.org/global-material-flows-database, http://www.globalcarbonatlas.org and https://data.worldbank.org.

Economic growth, raw material extraction and emissions from fossil fuel use. Source: Thomas Wiedmann et al (2020)

I say *declared* rate of profit, because so-called "profit shifting" had a role in accentuating the outward appearance of stagnation. It is reckoned that the actual rate of profit was higher than declared, and wealth increasingly hidden offshore. But at the end of the day, it was the massively increased *scale* of investment that more than compensated for a reduced *average rate* of return.

Meanwhile, in the old "core" economies, – in particular in the US and UK – corporate profits and private wealth after around 1980 have grown along four main paths: first, the "classical" route to enrichment by investment in production, often in emerging markets; second, "fictitious" capitalisation of assets and the raising of debt; third, rent-seeking and associated forms of secondary exploitation; and fourth, overtly politically-enabled accumulation, with funds siphoned directly from states and central banks into the pockets of the 1%, via the private banking sector, privatisation of public assets, untendered contracts, bailouts, "tax cuts", and the like.

As world GDP continued to expand, it ensured the *continuity* of a robustly *secular expansion* in volumes of extraction, production, consumption, and waste products. Correspondingly, greenhouse gas emissions continued their upward trend.

After 1980, the rises in global GDP and global material footprints seem to have correlated to one another, following a minor decoupling during the 1970s.

And within that, the expansion in "stocks" – principally concrete and other building materials – has been unprecedented.[8]

In Part 4, I focus on China, where the building boom has in the last two decades dramatically outstripped all other regions, and all previous phases of growth.

Finally: the 1970s also showed that organised grassroots struggle *can* have a dramatic impact on the course of urban planning and the built environment.

In the Netherlands, post-war planning through the 1960s had carved up historic neighbourhoods, in favour of the motor car. But in the 1970s, mobility protests reversed that tide. They drove a fundamental rethink in planning, to support walking, cycling, and public transit – in urban, suburban, and rural locations.

Now, compared to other similar countries (like the UK), the Netherlands has – amongst other things – strengthened the rights of children and those with mobility impairments to travel safely and independently. In the Netherlands, 75% of all secondary school children cycle to school (2008 data) – although poorer families often lack access to bikes. Cycling is one of the many reasons why Dutch children have the highest well-being across all rich countries, according to UNICEF.

These positive changes in the built environments of the Netherlands are not perfect, and the process (and struggle) is ongoing. Areas of habitation are just one important part of the global built environment.

However, pleasant, walkable neighbourhoods – and a people-centered built environment in general – are not a pipe dream. They should be available to all, globally.

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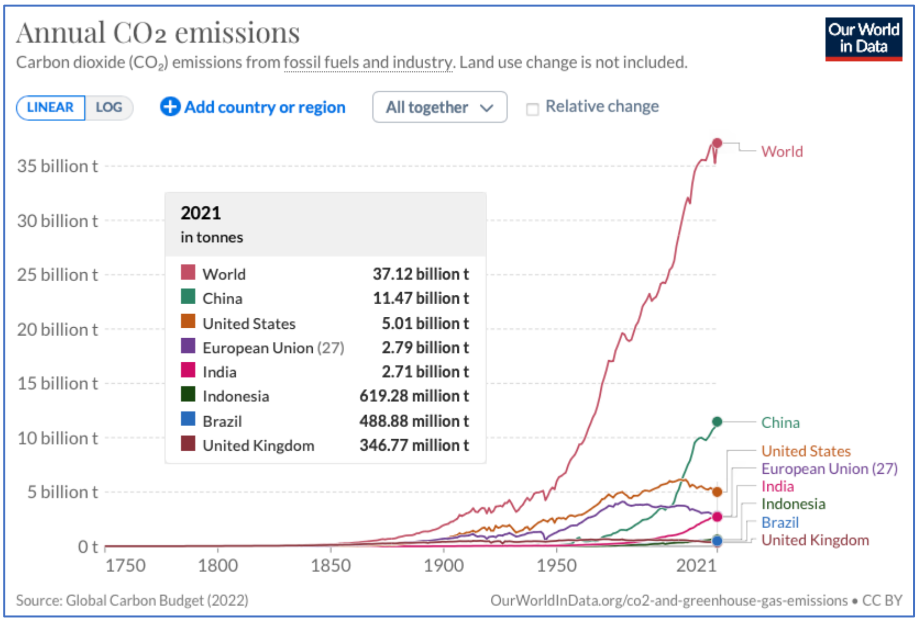
[8] On material stocks, see the paper mentioned above: Fridolin Krausmann et al., 2018

Part 4. The China shock

The most dramatic example in history of production-based expansions in the built environment have taken place in China.

Since 1978, the Chinese economy has grown at around 10% per annum, as measured in terms of gross domestic product (GDP). Under Deng Xiaoping, the opening of the economy, and market reforms, coupled with massive state interventions, have brought large foreign capital inflows.



2021 in tonnes	
World	37.12 billion t
China	11.47 billion t
United States	5.01 billion t
European Union (27)	2.79 billion t
India	2.71 billion t
Indonesia	619.28 million t
Brazil	488.88 million t
United Kingdom	346.77 million t

Annual production-based emissions since 1750. Source: Hannah Ritchie and Max Roser / Our World in Data CO_2 emissions dataset

With its build-out in industrial and manufacturing capacity, rising incomes have drawn people to cities, spurring urban enlargement. Economic growth has therefore been the carrot for mass rural-urban migration; forced ejections by private enclosures of the countryside have been the stick – such that China's rate of urban population growth has outpaced that of its population as a whole. There has also been considerable urbanisation of the countryside "in situ", either through the explosive growth of small towns, or the growth of whole cities from scratch. China has escaped both the "shock therapy" experienced by Russia in the 1990s, and other forms of structural adjustment that pushed poor regions to the wall.

China's coal economy today is several orders of magnitude larger than the UK's was in the 19th century. On a production basis, the UK's annual CO_2 emissions in 1900 were around 420 million tonnes; in 2020, China's were 10.67 billion tonnes. Per capita, China's production-based emissions have overtaken the EU-27. China's consumption-based emissions have been rising towards Western footprint sizes, and today they are close to those of the EU-27.

In this part, I will look at China's rapid economic expansion since the turn of the century, the role of the built environment in that (section 4.1), and at the discussion in China on future economic and climate policy (section 4.2).

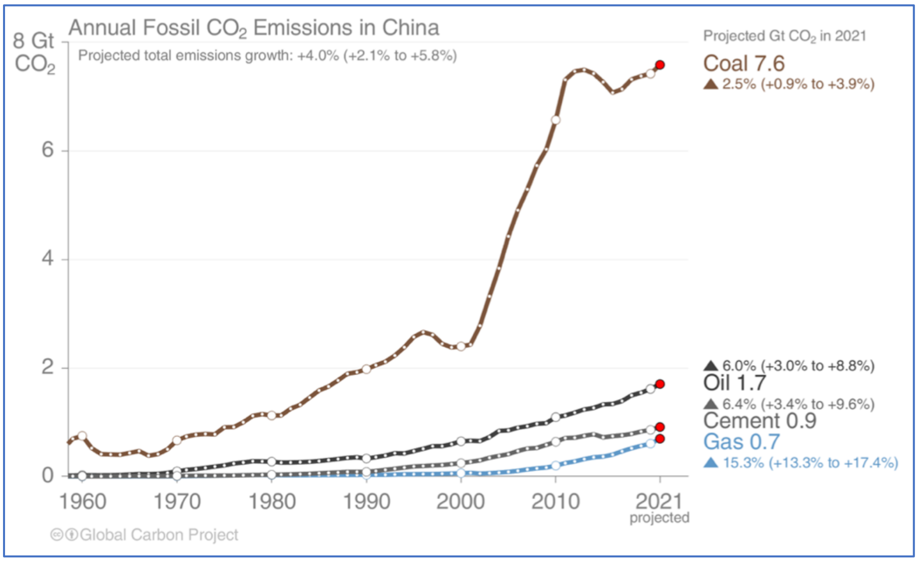
4.1. China's "great acceleration"

Since the turn of the century, and following China's admission to the World Trade Organisation in 2001, an enormous growth spurt ensued in global material consumption – a second "great acceleration", centered on China's coastal export-production zones.

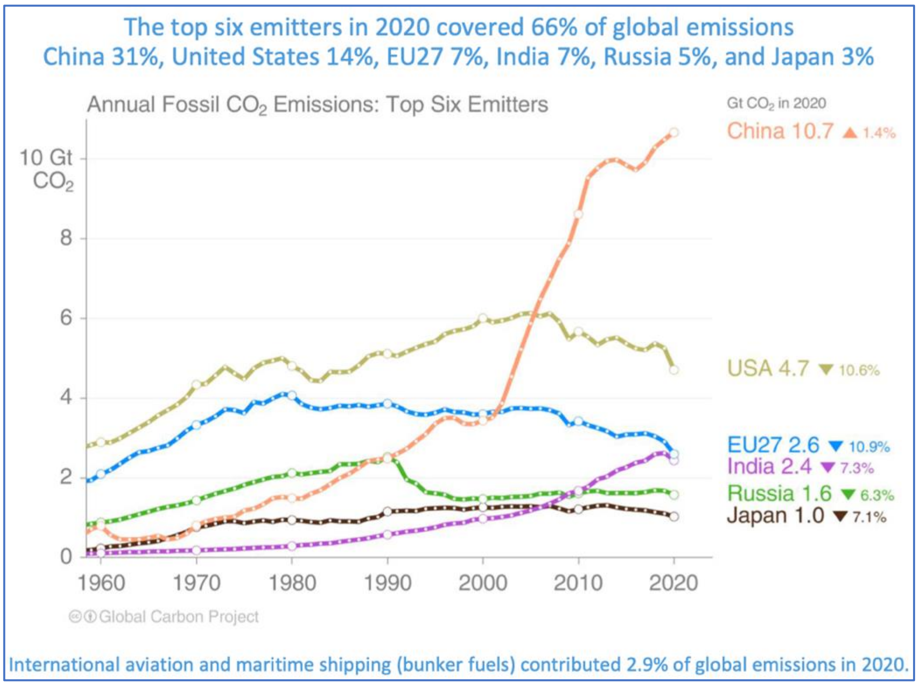
However, despite its "Chinese characteristics", China's development since the 1980s has been powered by a conventional embrace of fossil fuels. Its development model has been based entirely on the instrument of *winning export share to a growing pie of world consumption*. Increasingly, that "export" has been into China itself.

Unfortunately, China's has been a coal-led boom, justified on grounds of energy security and economy. The fact that China has become the new centre of industrial and manufacturing production has returned the world economy to the bad old days of coal-based production and accumulation in England, only on a vastly greater scale.

In consequence, products manufactured in China have reliably out-competed competitor goods on price. But per commodity, per quantity of use-value, or per mass of commodities, they have also tended to have a larger embodied carbon footprint. And since the volume of Chinese production has been so great, the emissions effects have been huge.



China's production-based emissions. Source: Pierre Friedlingstein et al. (2022) / Global Carbon Budget 2021



The top six emitting countries' production-based emissions, since 1960. Source: Pierre Friedlingstein et al. (2022) / Global Carbon Budget 2021

China's production-based emissions really took off on the back of coal around 2000. But production has not simply shifted to pre-existing export production zones in China. Rather, world industrial and manufacturing production to a large extent *physically reconstituted itself in China on a vastly expanded material and energetic base*.

That has imposed huge material and emissions footprints in the enlarged scale of production – and in construction of the built environment too. The statistics are notorious. "How China used more cement in 3 years than the U.S. did in the entire 20th Century", one headline said.

"Construction" here includes the infrastructure that has allowed China to add volume to the existing relations of fossil-intensive production, circulation and consumption globally. It also includes speculative real estate. Production for export has been the chosen path to economic expansion; construction has been the lever.

Construction has therefore come ahead of stimulating incomes or household consumption, or of addressing social needs directly. Construction also remains the favoured tool for moderating the effects of economic shocks, via the fiscal firepower of state-owned banks.

Throughout the post-2001 boom, the result has been frequently over-zealous symphonies in concrete, dedicated to capital and the Chinese state. A ready inflow of speculative capital and a stream of building permits have left whole "ghost cities" part-built, dormant and unused – a flagrant sign of speculative oversteers and over-production.

Nevertheless, the Chinese Communist Party (CCP) continues to favour construction as a means to pump-prime economic growth.

The problem is not just the scale of production per se, but its energetic basis in coal, and its mis-direction with respect to real human needs.

Even without coal, construction is among the most emissions-heavy forms of production, and much of that concerns the enormous embodied emissions (including the "process" emissions) of concrete and steel production (see part 7).

China's development since 1978 has done a great deal of good domestically, insofar as it has significantly depressed burdens of disease, and raised standards of living. But the 1990s were an inflection point. After the suppression of pro-democracy protests on Tiananmen Square in 1989, a policy of rushing headlong into export-led growth was adopted.

This policy choice was about three things, Richard Smith, the Marxist historian of China, argues. First, for geopolitical and world historical reasons, the CCP engaged in a competitive race to grow the size of the Chinese economy. Second, to tame the political ambitions of its people, it sought maximum employment – often comprising make-work projects superfluous to genuine social need. Third, this also involved lifting consumption, but along the lines of excess consumerism – meant again to sate, pacify and distract China's population.

China's birth rate seems already to have undergone the lion's share of its moderation *before* the top-down coercive measures of its One-Child Policy were introduced in 1980. The dominant drivers of fertility reduction, even after the policy's introduction, were policies of public health intervention that were common worldwide, alongside the various socioeconomic changes outlined in part 3, and related shifts in social attitudes to fertility.

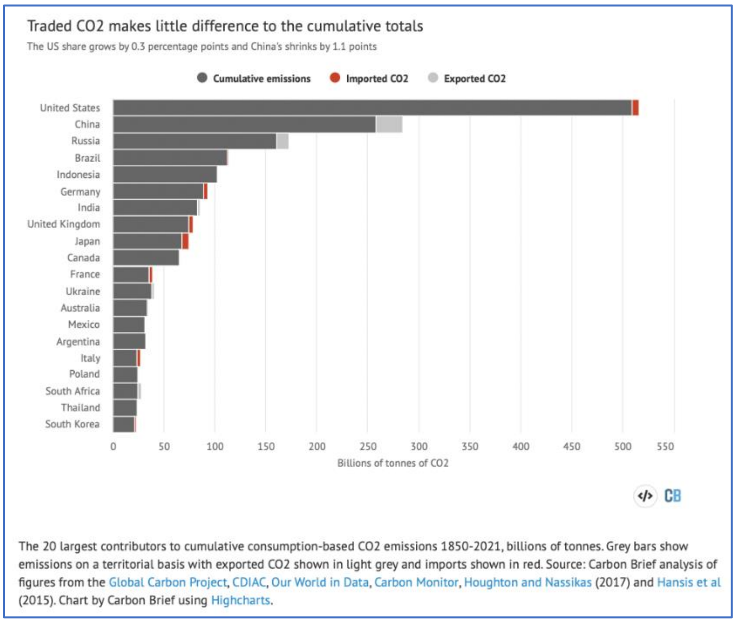
During the 1990s, 165 million people in China were lifted out of poverty, where this is measured as living on less than the $1.08 per day (1993 prices at Purchasing Power Parity). At a $1.25 (2005 PPP) poverty line, the number is 400 million.

The anthropologist Jason Hickel points out that it was only thanks to China, and some creative accounting, that the UN was able to construe its poverty-reducing Millenium Development Goal 1 as a success. Yet it was China that specifically *rejected* the UN's development advice in the 1980 and 1990s, which was to follow the prescriptions of the World Bank and IMF.

China's economy probably only boomed as it did because of the state's willingness to *pump prime and selectively direct* foreign direct investments to its domestic advantage. Foreign firms have been obliged to partner with local and state-bankrolled enterprises, and this has facilitated a very effective technological transfer that Chinese firms have been well-placed to exploit.

Moreover, having side-stepped shock therapy and avoided ceding control of the economy to foreign investment banks, the Chinese state, regions, and state-owned banks have been able to channel huge monetary resources into fiscal expansion. They have financially back-stopped the "private" domestic engines of that expansion, wherever that has been deemed strategically necessary.

In short, the expansion of fossil capitalism in China has been produced by two factors. (1) A *policy choice* to pursue


Traded CO2 makes little difference to the cumulative totals

The US share grows by 0.3 percentage points and China's shrinks by 1.1 points

The 20 largest contributors to cumulative consumption-based CO2 emissions 1850-2021, billions of tonnes. Grey bars show emissions on a territorial basis with exported CO2 shown in light grey and imports shown in red. Source: Carbon Brief analysis of figures from the Global Carbon Project, CDIAC, Our World in Data, Carbon Monitor, Houghton and Nassikas (2017) and Hansis et al (2015). Chart by Carbon Brief using Highcharts.

Source: Simon Evans (2021) for Carbon Brief

economic development according to existing competitive, fossil-capitalist norms. (2) The needs of global capital to plug into ready sources of labour, export infrastructure, and material resources. The scale of the resulting production-based *emissions* has been due to coal as the strategic fuel of choice.

To reiterate the message from the graphs above: as of 2019, China's production-based CO_2 emissions were 28.6% of the world total. China's growth in emissions has been the largest component of global emissions growth post-2000.

China's GDP per capita in 2021 (~US$12,500) was around 25% that of the UK (~US$47,000), and ~18% that of the USA (~US$69,000)[1] – but China's per-capita consumption-based CO_2 emissions (averaging across all regions and social classes) are now about 85% those of the EU-27 and UK. Many of those consumption-based emissions from China are presumably due to *disproportionately high embodied emissions in the built environment*, which come from the reconstruction of global production there since the 1990s, on the back of coal – and rehousing a large proportion of the population in order to do that.[2]

China is now second only to the USA in its *cumulative* production- and consumption-based CO_2 emissions by country. However, when correcting for population size, China is nowhere near the top in cumulative per-capita CO_2 emissions, even on a production basis.

There is an argument that says China has *at least some right* to consume fossil fuels and to emit greenhouse gases on a scale comparable to the historical emissions of the most developed nations, like those of the EU-27 and the United States.


Production vs. consumption-based CO₂ emissions, United States

Annual consumption-based emissions are domestic emissions adjusted for trade. If a country imports goods the CO_2 emissions needed to produce such goods are added to its domestic emissions; if it exports goods then this is subtracted.

Source: Global Carbon Project OurWorldInData.org/co2-and-other-greenhouse-gas-emissions/ • CC BY
Note: This measures CO_2 emissions from fossil fuels and cement production only – land use change is not included.

Production vs. consumption-based CO₂ emissions, China

Annual consumption-based emissions are domestic emissions adjusted for trade. If a country imports goods the CO_2 emissions needed to produce such goods are added to its domestic emissions; if it exports goods then this is subtracted.

Source: Global Carbon Project OurWorldInData.org/co2-and-other-greenhouse-gas-emissions/ • CC BY
Note: This measures CO_2 emissions from fossil fuels and cement production only – land use change is not included.

China and the US: how production- and consumption-based emissions compare. Source: Our World in Data / Global Carbon Project

In terms of *morality*, one counter-argument could begin by urging the exceptional and existential nature of the climate crisis over and above other valid development needs. I could also point out the historical recklessness of China having departed on its fossil-intensive path of development once the facts of global warming were well known. (That applies to *all* fossil-heavy and fossil-dependent investment after 1990 at the very latest.)

The science of global warming was pretty secure by the early 1980s – some argue it was much earlier. Yet the major powers failed to change the course of their own fossil-backed development up through the 1980s and beyond – due to political indifference, vested interest, and campaigns of misinformation. But the sheer speed and scale of fossil-backed growth in China after the 1990s has been in another league.

Moreover, a fossil-intensive path of development *was not the only available path of development*. The CCP need not have simply plugged China into the status quo of fossil capitalism.

Alternative, more ecologically sustainable paths, that need not have compromised development needs, were available.

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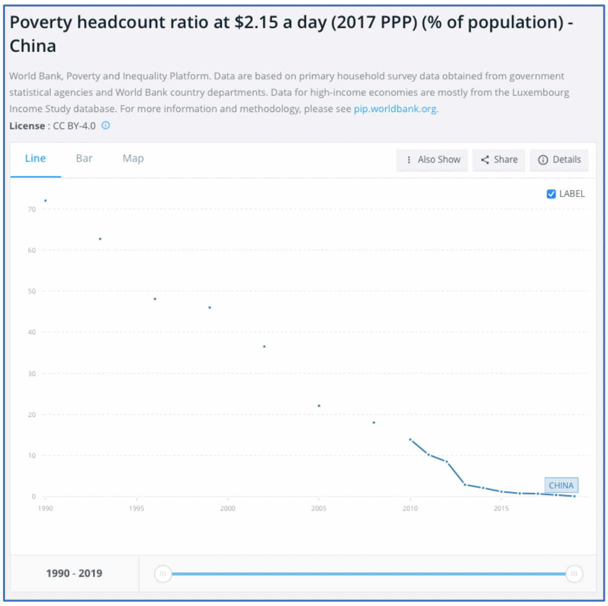
[1] Consumption-based CO_2 emissions in this case represent the effective trade balance in embodied carbon, excluding CO_2 emissions from land-use change. As you can see in the graphs above, about 10% of China's domestic CO_2 emissions (~1 billion tonnes CO_2/year) are embodied in goods that get exported for consumption elsewhere; whereas the US presently consumes about an extra 7% (~0.4 billion tonnes CO_2) in imported embodied CO_2 emissions, above those that are produced and consumed domestically.

[2] In Appendix 1, I explain that, although many buildings and infrastructure are put in place to enable exports, the associated embodied emissions are very often under-counted in the consumption-based emissions accounts of importing countries.



Poverty headcount ratio at $2.15 a day (2017 PPP) (% of population) - China

World Bank, Poverty and Inequality Platform. Data are based on primary household survey data obtained from government statistical agencies and World Bank country departments. Data for high-income economies are mostly from the Luxembourg Income Study database. For more information and methodology, please see pip.worldbank.org.

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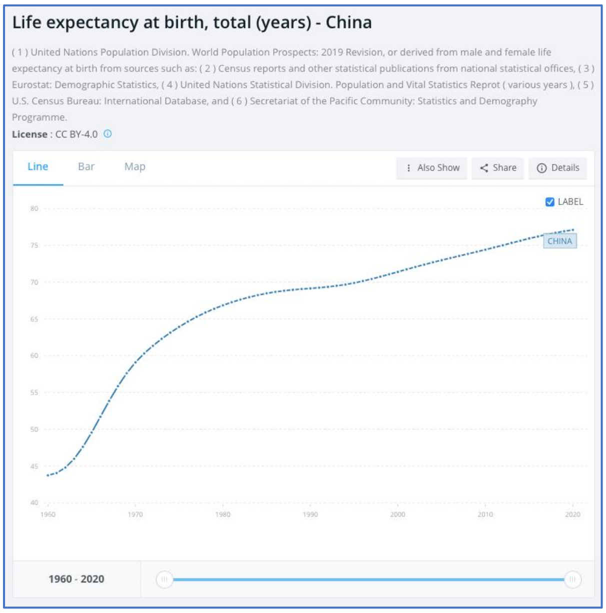

Life expectancy at birth, total (years) - China

(1) United Nations Population Division. World Population Prospects: 2019 Revision, or derived from male and female life expectancy at birth from sources such as: (2) Census reports and other statistical publications from national statistical offices, (3) Eurostat: Demographic Statistics, (4) United Nations Statistical Division. Population and Vital Statistics Reprot (various years), (5) U.S. Census Bureau: International Database, and (6) Secretariat of the Pacific Community: Statistics and Demography Programme.

License : CC BY-4.0

Source: World Bank

Greener alternatives were suggested – for example, by Deng Yingtao in 1991 – but were not heeded.[3] The CCP chose instead what Deng termed the "classical" route of development. This meant working the lever of competitive production on a coal-fired basis, to deliver rapid returns to capital and per-capita income gains. The built environment and human settlement were shaped to fit, via rapidly expanding cities and infrastructure, delivering low-cost workers and materials to logistically-convenient manufacturing hubs.

That economy, and that production – like the vast majority of *all capitalist production* – have been based on *any old production that brings the healthiest return*. Social needs have certainly been met on a greater scale, and human development indices have continued to move in a positive direction. But social needs have been re-made, and perverted to meet the needs of capital and state, instead of being addressed directly.

Moreover, along that export-based path, while domestic consumption has grown according to a western norm of "excess", China's GDP growth has depended nonetheless on a relative *suppression of domestic economic demand, growing and maintaining enormous levels of domestic economic inequality*.

In a capitalist economy, ordinary household income is what really counts when it comes to maintaining economic growth and increasing welfare over the long run. But in China, household income is very low, as the economist Michael Pettis has pointed out. Workers' income, at roughly 50%, comprises one of the lowest shares of GDP of any country in history, Pettis writes. He suggests that China's "real, underlying growth rate" is "probably around half reported growth rates".

That skewed export economy has expanded with scant regard for the wider ecology, to say nothing of the absence of individual political freedoms.

After the financial crash of 2008, China's export trade declined; it rebounded after 2010, but then declined again. Global capital flows and value chains stopped expanding. Arguably, the benefits of export production narrowed and slowed. The political dominance of "hyper globalisation" and its advocates also waned.

Since 2017, the CCP has sought to reduce the "urban bias" of its development policy.

As of May 2020, and in the context of sharpening geopolitical and trade rifts with the US, China put in place a so-called "dual circulation" policy. This meant that the Chinese state would focus above all on building out "internal" *domestic* circuits of production, distribution and consumption; and aim for "external circulation" only so far as necessary. The direction of China's internal energy economy, outlined briefly below, is an important part of that.

With its intervention into Evergrande's liquidity crisis in August/September 2021, the CCP also set itself the mammoth task of engineering a "managed collapse" of the company, and winding down the level of speculation in the overall real estate sector.

By this time, such a policy had already been on the cards for a while. The CCP's 14th Five-Year Plan (14FYP), drafted in October 2020, and passed by the National People's Congress in March 2021, stated: "We will uphold the principle that housing is for living rather than for speculation."

Since the 1990s, the CCP has sought to develop *competitively* and *capitalistically* on the established high-energy norms of production, distribution and consumption. And this remains the case now, even as the CCP focuses more on domestic "internal circulation", and a massive build-out in green energy.

Like most capitalist countries, and thanks to popular pressure and binding international treaties such as the 2015 Paris agreement, China has also been investing in emissions reductions. However, in China's case, that entails an *enormous* course correction.

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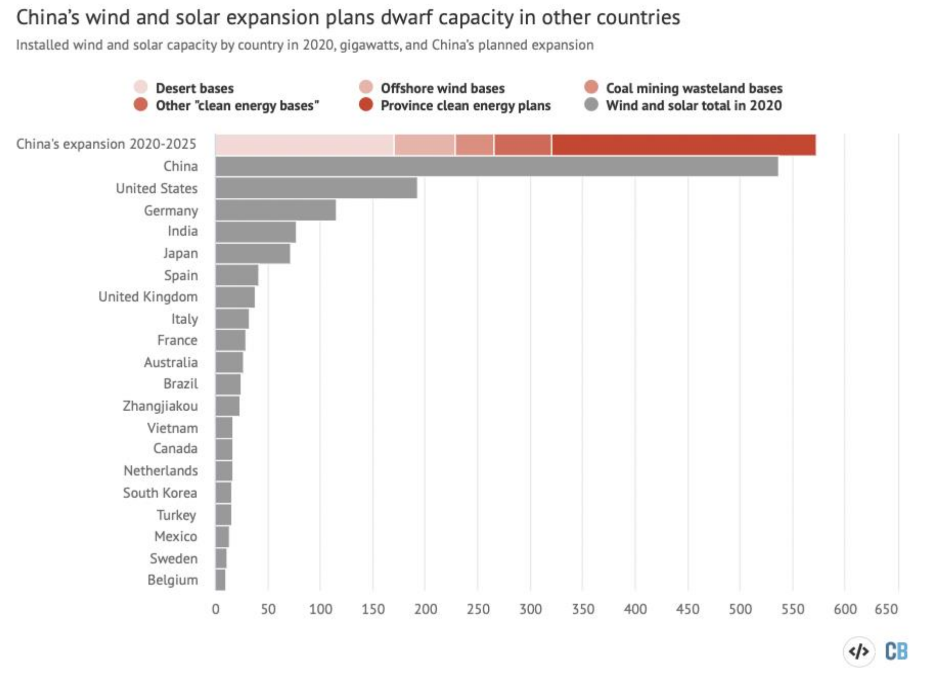
[3] You can read about Deng Yingtao on People and Nature here and here.



Total installed wind and solar capacity by country at the end of 2020, in comparison with China's planned expansion from 2020 to 2025. Source: Capacity by country for wind and solar; China's planned expansion based on authors' compilation of central and provincial government targets. Chart by Joe Goodman for Carbon Brief using Highcharts.

Source: Lauri Myllyvirta (2022a) for Carbon Brief

China prioritises continued *economic growth*, combined with continuity in the supply of energy and energy security. Everything seems to boil down to "stability" – political stability, economic stability, energy stability.

Yet, the danger – elsewhere, too, but more so for China – is that established norms of consumption, the economy, and the built environment, and their energy- and carbon-intensity, are themselves a barrier, hard to reform, and "locked in" for the future. So the forms of consumption encouraged by policy are an obstruction to a sustainable future.

Despite the turn to "dual circulation", it is also obscure to what extent future development stands to decrease economic inequality, and lift the income share of GDP.

All of that said, China has so far made *by far the largest historical contribution of any single state to building out infrastructures of renewable energy, and to decarbonising industry*.

This is as it should be, given that China contains so large a slice of existing global productive capacity, and that China's productive capacity is disproportionately CO_2-intensive thanks to a continued reliance on coal.

By the end of 2020, China's installed wind and solar capacity far outstripped any other country, at 536 gigawatts (GW), compared to the EU's total of 354 GW. (See the chart above.) By the end of 2022, China had 366 GW of installed wind capacity, and 393 GW of installed solar capacity – so, ~760 GW in total.

I outline in Appendix 2, however, how China's coal-fired power capacity continues to expand alongside renewables, in order to secure continuity of supply. (See Appendix 2: China's climate policies.)

4.2. China's future

More important still are China's plans for the future. At the UN in March 2021, Chinese premier Xi Jinping announced the CCP's so-called 2030/2060 "dual carbon targets": to peak China's domestic CO_2 emissions before 2030 and to achieve what Xi termed "carbon neutrality" before 2060.

It is the 2030/2060 goals that form the backbone of China's nationally determined contribution (NDC) under the 2015 Paris agreement, Article 4 of which requires that NDCs represent the "highest possible ambition", oriented towards "achieving the purpose of this Agreement".[4]

The CCP's 14th Five Year Plan, covering 2021-25, is linked to these goals. (See Appendix 2.)

China's NDC remains focused entirely on CO_2 emissions to 2030. Researchers at Climate Action Tracker see the 2060 goal as focused on CO_2 only, to the exclusion of other greenhouse gases.

They estimate that, if *all* greenhouse gas emissions were subject to China's NDC pledges, it could be in striking distance of meeting Paris-compatible emissions goals – but, as things stand, China's decarbonisation efforts are "consistent with global warming of over 2°C and up to 3°C by the end of the century (if all countries had this level of ambition)".

The Paris agreement makes unspecified allowance for "common but differentiated responsibilities and respective capabilities, in the light of different national circumstances". Implementation is placed, "in the context of sustainable development and efforts to eradicate poverty"; while, "recognising that peaking will take longer for developing country Parties".

These phrases give the Chinese government wide room for manoeuvre in deciding the pace of decarbonisation.

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[4] The purpose of the Paris agreement includes holding global temperatures "well below" 2°C above pre-industrial levels, *and* aiming to limit them to 1.5°C above pre-industrial levels. To do that, global greenhouse gas emissions should peak "as soon as possible", rapidly reduce after that, and reach net-zero emissions "in the second half of the century". According to the IPCC, meeting those aims means reaching net-zero of CO_2 emissions globally by around 2050, alongside deep reductions in methane emissions and other greenhouse gases. After 2050, negative CO_2 emissions – active CO_2 removal – will be needed to abate residual non-CO_2 emissions. (See here for a useful overview.)

Construction workers in Beijing, March 2013. Photo by Joe Tymczyszyn / Creative Commons

The CCP claims for China a degree of exceptionalism under a normative "right to development" – with a "right to pollute" on the basis that "China still needs to develop".

But to what level? In what form? What *kind* of development? When has "development" proceeded far enough?

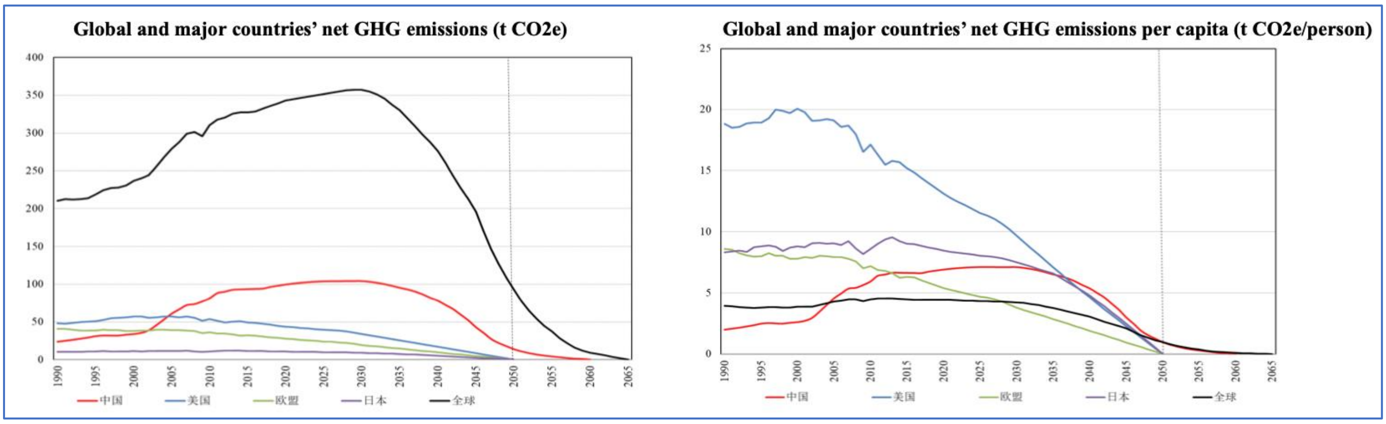
According to World Bank metrics, China is an upper-middle income nation – as noted above, GDP/capita is about US$12,500.

The CCP seemingly wants to maintain high returns to capital (including state capital), high rates of employment, the *promise* of rising incomes, and high and rising levels of domestic material consumption – all within the status quo ante of production and consumption on the established model. The ambition, presumably, is to pursue the established pattern of economic gains *unabated as far as possible*, and in the meantime retrofit the economy with an eco-modern, low-carbon energy base.

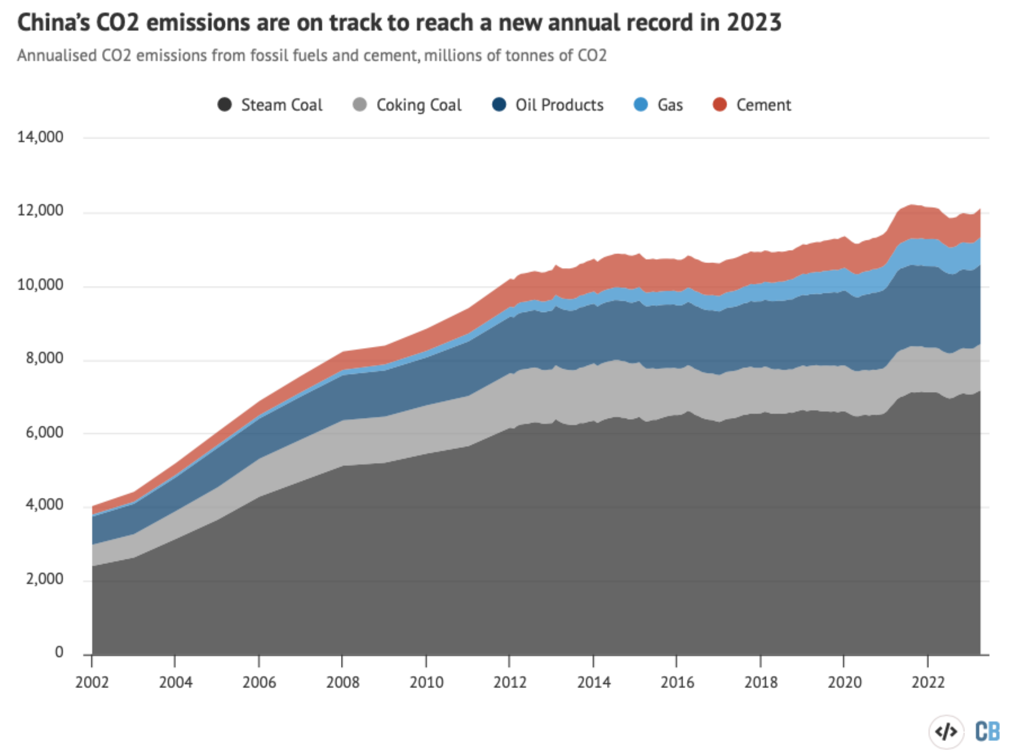
And aside the very welcome build-out in renewables capacity, production and consumption remain oriented on *any-old production* for which profitable returns can be made. It is the capitalist way.

In these circumstances, it may be crude simply to counterpose emissions reductions to economic growth and political stability. But insofar as the Chinese economy depends heavily on coal, the aims of economic growth and reduced emissions pull *at least somewhat* in contradictory directions – and will do so until the non-fossil energetic basis of the Chinese economy is suitably enlarged.

Most rich industrialised economies have now peaked their *territorial* greenhouse gas emissions, and are enjoying 30-40 years ostensibly to transition to net-zero greenhouse



Projections of future emissions by China-based researchers. Source: He Jiankun, Climate Change and Sustainable Development (ICCSD), Tsinghua University (2020). Red is China, blue is USA, green is EU, purple is Japan, black is world. Note: these projections are for *all* greenhouse gas emissions, and seem to exclude those from land-use change.



China's CO2 emissions in 12-month moving sum, broken down by cement, gas, oil, coking coal and steam coal. Emissions are estimated from National Bureau of Statistics data on production of different fuels and cement, China Customs data on imports and exports and WIND Information data on changes in inventories, applying IPCC default emissions factors and annual emissions factors per tonne of cement production until 2019. Monthly values are scaled to annual data on fuel consumption in annual Statistical Communiques and National Bureau of Statistics annual Yearbooks. Chart by Carbon Brief using Highcharts.

Source: Carbon Brief, May 2023

gas emissions by mid-century – though many of the planned routes look spurious, such as an over-reliance on carbon capture and storage (CCS).

You can see the projected course of emissions (CO_2e) reductions in the graphs on page 26 – for China, and a handful of other major economies. Note the equally steep, but longer-lasting, reduction in *per capita* emissions demanded of the USA.

According to the Intergovernmental Panel on Climate Change (IPCC), the consensus scientific view indicates that a "linear path" of abatement is economically optimal – that is, not delaying the heavy lifting for later.[5]

According to analysis by the Institute for Climate Change and Sustainable Development (ICCSD) at Tsinghua University, it is also *economically optimal not to delay*, but to proceed faster and sooner with decarbonisation efforts.

It is inevitable that the early years of energy transition are the hardest, and that it becomes easier the further you go into it.

Ever since the 14FYP, commentators have noted that the CCP often under-promises and over-delivers. Recent upward revisions in planned renewables capacity need to be seen in that context.

If the goal of peaking CO_2 emissions by 2030 and then reaching net-zero CO_2 by *2050* were to be met, with net-zero greenhouse gas emissions by 2060, that would mean China cutting its overall emissions at an average rate of ~10% per year after 2030.[6]

The China researcher Lauri Myllyvirta estimates that, with the rise in tempo of the original 14FYP, if the 2060 zero-carbon, net-zero greenhouse gas emissions goal were to be met, China would need to average 150-200 GW of new renewables capacity installed *every year after 2025*. That is around 20-25% of *total* installed capacity at the end of 2022.

Recent increases in renewables capacity targets are very welcome. However, they need to be met with a qualitative shift in the *forms* of end consumption – fewer cars, less air conditioning. This would entail a thorough re-engineering of China's built environment, as well as all other sectors of the economy.

Energy *needs* should also be met through more efficient uses of energy. For instance, air conditioners should be replaced with heat pumps and district cooling; and buildings should be designed in order to minimise the need for extra energy. (See parts 8 and 10.)

It is very well to say that homes are for living in, instead of speculating with. But the point should also be to live *well*, and live *sustainably*.

Yet little seems to have changed in the CCP's bias towards *any old construction* as the lever to achieving GDP growth. Since the Covid pandemic, China's administrative authority has introduced several rounds of stimulus, aiming to "revive" real estate *while* deflating the bubble, *and* pushing new spending in infrastructure.

With spending overseen by the provinces, infrastructure stimulus would likely *divide fairly evenly* between developing new coal-fired capacity, and bringing in the new renewables and electricity infrastructure that are essential for the CCP's 2060 decarbonisation agenda, Myllyvirta argues.

The weight of coal within this policy response would, "determine whether China's emissions have already peaked, or whether they will rebound before peaking later this decade." The role of provincial politics is key, for managing

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[5] See the IPCC's 2018 Special Report on Global warming of 1.5°C

[6] These are my approximations – but similar numbers are given in the ICCSD research

coal as *only* an occasional "support" for renewables. As of the end of Q2 2022, China's economy had registered four consecutive quarters of falling emissions, compared with those same quarters in 2021.

By the first quarter of 2023, China passed the "symbolic milestone" of renewables and nuclear power capacity combined comprising more than 50% of installed power capacity.

Emissions in 2023 have been rising again. (See the chart on page 27.)

The main cause of the rise is that, so far, China's demand for electricity has grown in 2023 compared to 2022, despite its stalling economy. China's CO_2 emissions in the first three months of 2023 were up 4% on the same period in 2022. The growth in emissions in 2023 has been driven by industrial demand, Carbon Brief reports.

Next to that, a summer of record high temperatures, just like in 2022, has ensured that *operational* energy consumption from air conditioning remained enormous in 2023. Household electricity consumption fell on 2022, with fewer people hunkered at home – but consumption from offices and the service sector grew.

Moreover, according to Carbon Brief, the recourse to coal in order to meet peak demand has also led China recently to exploit a *degraded quality of domestic coal*, with a lower energy content per tonne burned. The CCP has ended up *importing* coal, revealing some limits in its energy security policy.

The next major cause of the emissions rises after energy consumption was higher production volumes of construction materials – with their process emissions. Complaints have followed, that the outputs of heavy industry are of greater concern to the CCP than air quality.

The third major cause has been a greater use of oil products than the year before – such as in transport. Once again, that follows on the turn away from zero-Covid.

Updated analysis by Lauri Myllyvirta now suggests that China's emissions *could* peak in 2024.

Meanwhile, a new stage of interstate rivalry, especially between China and the USA, has begun. The US has its Inflation Reduction Act, which aims to make the US a renewables manufacturing powerhouse and reduce dependence on imports from China.

China has reached a point of diminishing returns on infrastructure investment, the historian Adam Tooze has argued – but China's investments in green energy infrastructures *need to accelerate* over the next decade and

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more. That needs to happen whether or not those investments translate into greater aggregate profits.

More broadly, huge questions remain over the carbon content of any future reorganisations in global production, and anticipated accelerations in urban development. Any substantial *enlargement* of the material basis of world production, wherever it happens, would likely outstrip any shift to renewable energy, or any other carbon mitigation measures, if it remained simply *any-old production*.

More factories and yet more materials in motion, more cement and steel deposited in infrastructure, fixed capital, and real estate.

And yet, a radical redistribution *is* required in the use-values available for humanity as a whole. Moreover, economies throughout the global south need to industrialise along a green development pathway, if they are to build out their own capacities in green energy, and impose a sustainable form on the built environment.

The argument by Michael Pettis and others is that China needs to stimulate domestic household consumption to get out of the growth doldrums. I think that is convincing. But the *form* of consumption is crucial – it cannot continue on the old model.

There is also plenty of *real demand* going unmet – inside China and the world over – for existing and future products of industry and manufacturing. The obstacle to meeting that real demand *cannot and should not be construed in narrow purchasing power terms*. There is a need globally to build-out green energy infrastructures, and to put human capacities to work for the good of all.

Failing to meet global needs would continue an ongoing disaster for the world's poor. Failing to meet those needs in a sustainable way would be disastrous for the world's environment . What is needed, urgently, is "contraction and convergence" (see part 6).

All of this suggests that China, along with other states, should pursue a policy akin to a Green Lend-Lease. Outlays of their own currency (via overt monetary financing – see here and here), should be made in order to ventilate a flow of green finance from existing centres of capital to the economic "periphery".

Those transfers should be matched with technological transfers – on the model of China during its boom years – seeding hubs of expertise in green manufacturing wherever they are needed, alongside green building technologies, electrification, and the production of all other necessary use-values.

Part 5. Quantifying Material Use, Emissions, and the Scale of Decarbonisation

Globally, the built environment’s greenhouse gas emissions comprise those from construction, and those from the operational use of buildings (for electricity, heating and cooling, cooking, etc).

By weight, building and infrastructure construction creates by far the largest “stock” of materials, globally.

In this part, I look at the historical growth in material stocks (section 5.1); the maintenance and replacement of these stocks (section 5.2); how these stocks have accumulated in different countries (section 5.3); and then the impact of land use on emissions (section 5.4). After that I then turn to the present state of man-made emissions in the built environment (section 5.5). Finally, I outline what I see as the big issues raised by decarbonisation (section 5.6).

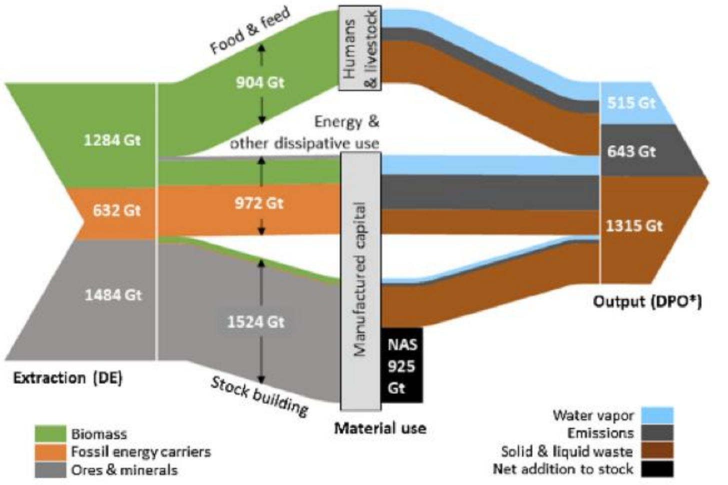

Fig. 4. Sankey diagram showing the cumulative flow of materials through the global economy from extraction to use and output of wastes and emission from 1900 to 2015. Note that NAS of humans and livestock (1 Gt) are not visible.

Source: Fridolin Krausmann et al. (2018). NAS = net additions to stocks

5.1. A history of material stocks

Much of the greenhouse gases emitted in the history of the fossil economy is embedded in material stocks of metals, building materials and waste. To quantify the emissions, we need to quantify the scale of these material stocks and the flows that produced them. To do so I will draw on work by a team of researchers mostly based at the Vienna Institute of Social Ecology.

A series of studies shows that, globally, about 1000 billion tonnes (1000 Gt) of physical materials are embedded in buildings and infrastructure. One such study, published in *Nature* in 2020, was reported with the headline: “Human-made materials now outweigh Earth’s entire biomass”.[1]

There are bound to be discrepancies in such stock calculations, due to different estimates of the baseline weight of pre-industrial construction, the scale of informal settlements, reporting gaps, and so on (see also part 3, footnote 4). But, in terms of the overall scale of stocks, all the studies came to similar conclusions.

The study by Krausmann et al also contained the remarkable Sankey diagram above. It shows the estimated global balance of stock accumulation, versus dissipative use and waste, out of materials extracted globally, for the period 1900-2015.

The sum of global material extraction

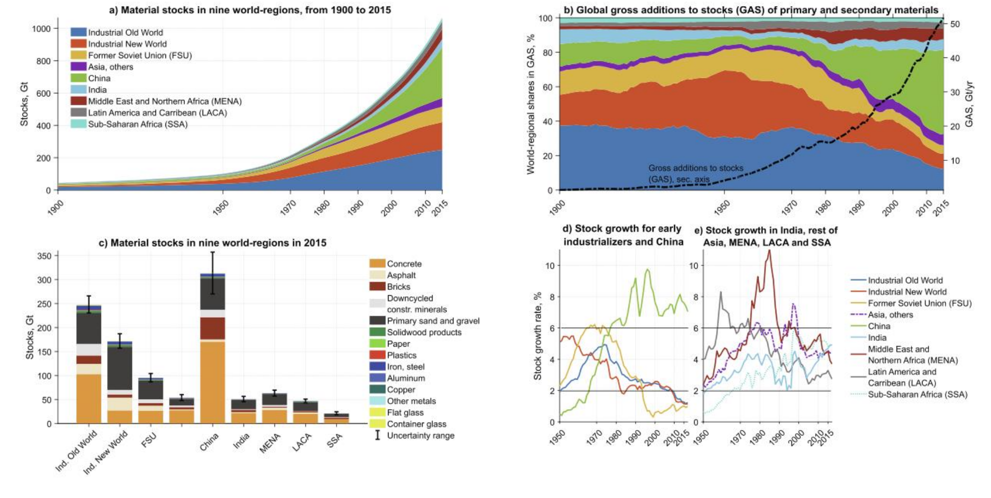

Fig. 2. Stock-flow dynamics from 1900 to 2015 in nine world regions. (a) total material stocks in nine regions, sharing colours and legend with (b) global distribution of gross additions to stocks; (c) the resulting levels and composition of stocks for 2015. (d-e) Stock growth rates; note that axis and legend of these latter graphs are identical. Detailed results, a description of data sources, and the modelling framework are found in the SI and supplementary data file.

Stock-flow dynamics, 1900-2015. Source: Dominik Wiedenhofer et al (2021)

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[1] The study in *Nature*, by Emily Elhacham et al, used a figure of 1100 billion tonnes (Gt). Another study (Fridolin Krausmann et al., 2018) estimated that there were around 925 Gt of physical material stocks worldwide in 2015. A third study (Dominik Wiedenhofer et al, 2021), found total material stocks, across nine world regions, of 1050 Gt as of 2015. The vast majority were building materials: aggregates for building and road foundations were 49% of total stocks (~514.5 Gt); concrete about 28% (~294 Gt); and asphalt concrete (ie, bitumen-based road asphalt / tarmac) 11% (~115.5 Gt). All metals, including iron and steel, comprised ~4% of total stocks (~42 Gt) – smaller than the others by weight, yet they provide a “functionally crucial role” across manufacturing industry and in the built environment.

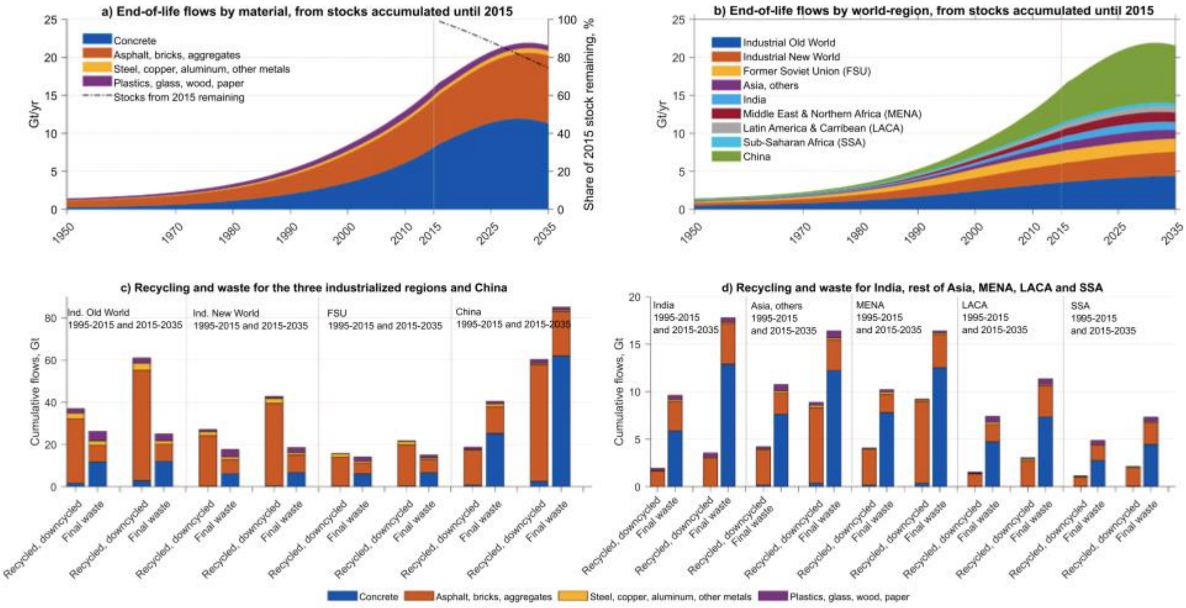

Fig. 5. End-of-life (EoL) flows only from stocks accumulated in 2015 and the estimated recycling, downcycling and final waste flows globally (a & b) and for nine world regions (c). Note that for 2016 to 2035, EoL flows are modelled only for stocks existing by 2015, to explore the magnitude and dynamics of future flows already locked-in. Additionally, future recycling and downcycling rates are held constant to estimate numbers shown in (c & d).

The built environment's end-of-life stocks. Source: Dominik Wiedenhofer et al (2021)

just in 2015 (biomass, fossil fuels, metallic and non-metallic minerals) was around 90 Gt, according to estimates in the same article.

China has over the last 20 years played an outsized role in the accumulation of world material stocks and their associated emissions, as outlined in part 4.

By 2015, around 50% of the world's gross additions to stocks (GAS) (by weight) were taking place in China. You can see this in Fig. 2(b) on page 29: China's share is coloured green. Data assembled by materialflows.net shows that, in China as well as globally, just under half of extraction by weight consists of construction minerals.

China's accumulation of stocks has also been incredibly rapid. Over those last 20 years, Chinese material stocks have grown at least twice as fast as any other comparable region or economic group. Material stocks in China *now comprise around 35% of the global total weight of built stocks*: this is shown in the graphic, Fig. 2(a).[2]

However, on a per capita basis, China's total material stocks (as yet) remain below those of most early-industrialising economies. In 2015 China had around 220 tonnes of material stocks per person, against around 300 tonnes/person in Europe, and 450 tonnes/person in North America.[3]

More than half (55%) of that sum of stocks in China is concrete, as shown on page 29 in Fig. 2(c). This compares to 41% for the world as a whole. But the proportion is surprisingly at variance with the combined material stocks profile of the USA, Canada, New Zealand and Australia, which is labelled "Ind. New World". For those countries, more than half (52%) of accumulated stocks are assessed to be from primary ("virgin") sand and gravel, 16% from concrete, and 16% from asphalt.[4]

Cement and concrete are central to modern construction, as discussed in part 3. At ~41% of global material stocks, concrete is the most plentiful manufactured substance on the planet, and the second most consumed substance on Earth, after water.

Of the 90 Gt total material extraction in 2015, just under half (43 Gt) was used by the global construction industry, according to a report by the UN Environment Programme. And that is just the physical bricks and mortar, before you even consider the industry's consumption of fossil fuels.

But of that 43 Gt, only around 30 Gt was added to stocks. So about 30% of extraction meant for stock-building goes to waste. Almost all of that is solid and liquid waste. (See the first graphic in this article, above).

That 30 Gt is the net gain to stocks, after demolition. We also need to factor in so-called *end-of-life* (EOL) building waste streams – where old stocks of buildings and infrastructure, along with their embodied carbon, are literally wasted, junked. These are quantified in the graphs below.

These waste flows are dominated by concrete, asphalt, bricks and aggregates (Fig. 5(a), above). Steel is a smaller proportion by weight – and although this high-energy, high-carbon product is readily and widely recycled, when it is in the form of concrete reinforcing bars, the concrete around it gets smashed apart.

Demolished concrete can be crushed and "down-cycled" as construction aggregate, but lots goes to landfill. Asphalt concrete is readily recycled, as the bitumen binder can be

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[2] Non-industrialised and pre-industrial stock construction is under-reported, as mentioned above and in part 3. Nevertheless, they are massively outweighed by newer and industrial stocks

[3] See research by Dominik Wiedenhofer et al (2021)

[4] In the graphs on this page and page 29, "Industrial Old World" = most of Europe, plus Japan and South Korea; "Industrial New World" = "the affluent Anglo-American colonial settler societies USA, Canada, New Zealand and Australia with relatively low population densities"

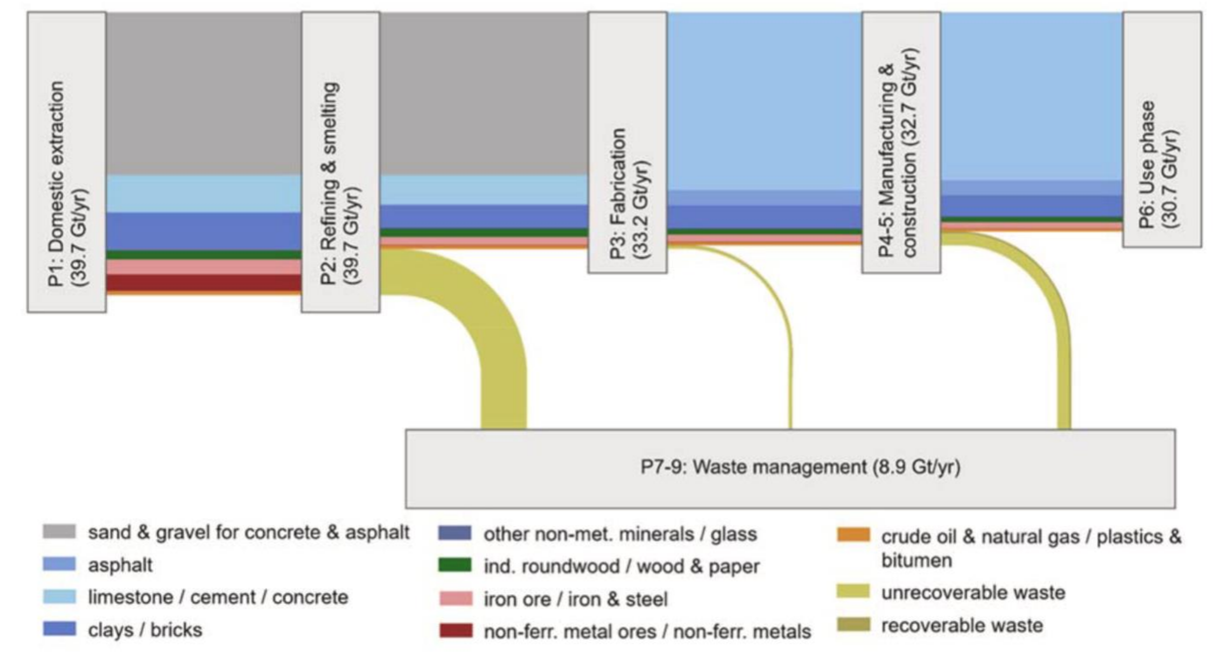

Figure 2. Global primary stock-building materials traced from extraction via processing of raw, semi-finished and final products to use, 2016. Material definitions can change along the process chain (see table 2 in the related MethodsX paper).

Extraction, processing, use and waste of stock materials. Source: Barbara Plank et al (2022)

reactivated by heating – although usually with a reduction of quality, due to accumulated dirt. Road construction is also a large sink for downcycled materials, especially in roads' lower layers.

The next diagram, above, shows the estimated flow of global primary construction materials for 2016, including production waste flows, but excluding end-of-life waste flows.

Almost always, old parts of the built environment are demolished so that something new can be built in their place, bringing in an entirely new round of embodied material and carbon footprints. In 2015, at the world scale, there was around 16 Gt of end-of-life waste. Of that, around 8 Gt of built stocks were trashed in China; around 4.5 Gt were trashed in Europe, Japan and South Korea combined.

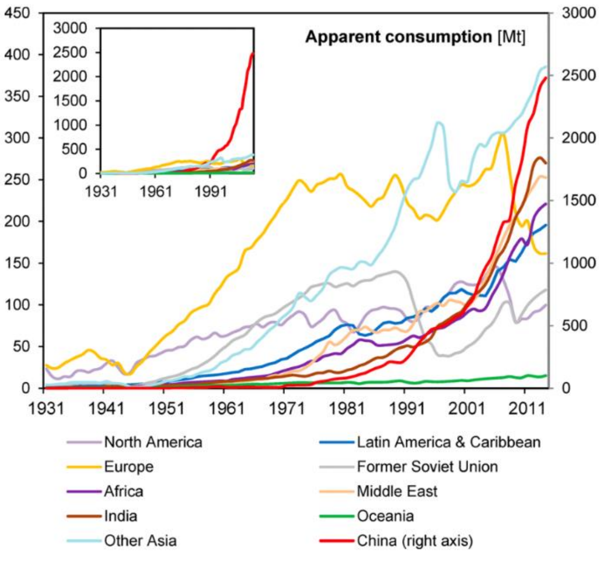

Figure 2. Apparent cement consumptions in the 10 world regions (1931–2014). Values for China are displayed on the right axis, all other countries and regions on the left axis.

Cement consumption: China and the world. Source: Zhi Cao et al (2017)

Sixteen billion tonnes (16 Gt) is an awful lot of *prior construction*, sacrificed on the altar of new construction. On top of that 16 Gt of end-of-life waste, 13 Gt of extraction for construction also goes straight to waste.

The amount of waste is alarming – though presumably *some* degree of material waste is inevitable in the production of material stocks.

In addition to the waste, the rate of stock building, and both the absolute and relative scale of construction, are staggering: the 30 Gt of new built stocks added each year is a whole 3-4% of the entire ready-existing stock of buildings and infrastructure.

That is: *a fresh 3-4%, annually, of existing stocks, are commissioned and deposited into the built environment*. This is simply in order to construct whatever new buildings and infrastructure get made every year. *Simply to keep the existing form of economic growth and development on the road.*

Out of the 30 Gt of annual stock additions, about 4 Gt is CO_2-intensive cement. About 0.6 Gt of the 30 Gt is steel, plus smaller quantities of other metals such as aluminium and copper, for which the extraction processes are intensely polluting and the manufacturing processes hugely energy-intensive.

Regional, annual statistics of cement consumption in the twentieth century are also instructive (Fig. 2, left).

In these indices, you can see some clear disparities of stock accumulation internationally – a tangible physical record of the history told in part 3. You can see the "rise of concrete" after the second world war.

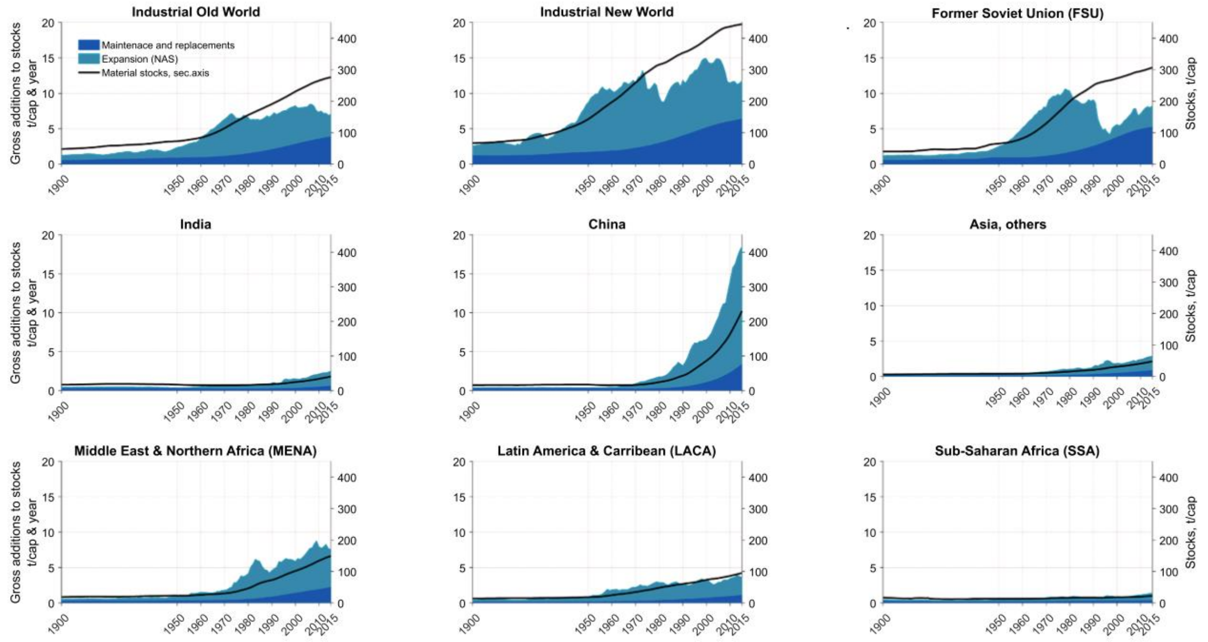

Fig. 3. Material stocks in nine world regions and their expansion versus maintenance and replacement flows, from 1900 to 2015. Please note that all figures share the same axis scaling and labelling. Maintenance and replacement flows are calculated from modelled end-of-life outflows due to the age dynamics of stock cohorts and the resulting difference between gross and net additions to stocks (see method section and (Shi et al., 2012; Wiedenhofer et al., 2015)). Please note that this approximation creates a smooth trend not reflecting short-term oscillations to be expected due to socio-economic conditions influencing year to year demolition and renovation activities, but it can be expected to approximate the long-term trend.

Expansion, versus maintenance and replacement. Source: Dominik Wiedenhofer et al (2021) (see footnote no. 4 for region definitions)

Again, China's annual absolute consumption of cement after the 1990s is an order of magnitude greater than all other regions – scaled separately on the right-hand side of the graph.

5.2 Maintenance and replacement

We can also compare the *per capita per year laydown of material stocks*, versus "maintenance and replacement" flows – see Fig.3, above. The black graph lines (scaled on the right-hand axes) give the per capita *cumulative* stock levels for each region.

The peaks of the black graph lines in Fig. 3 also give an apparent window into the different "stock saturation" points for different countries and regions – the points at which the rates of increase of total stocks in the built environment have plateaued or declined.

"Stock saturation" can speak to many different *varieties* of stock-flow relations, and many different levels of *stock-flow efficiency*, with regard to human needs and the delivery of services.

For example, the US has a very high level of "stock saturation": per capita, the weight of material stocks is very high. Meanwhile, the stocks that exist in the US – notably, roads – require very high levels of annual maintenance and replacement. As such, the built environment in the US has very poor *stock-flow efficiency*.

I have mentioned already how, in the US, road maintenance has proven to be fiscally bankrupting to states and cities, in the absence of federal assistance. The US is notorious for the degraded state of its infrastructure more broadly.

And yet, looking at the blue graphs in Fig. 3, annual "maintenance and replacement" flows are distressingly high throughout the "developed" world.

The world would benefit from stocks that require far less maintenance and replacement – and from services provided on a more efficient material basis. That is, the world would benefit from much better "stock-flow service efficiencies".

5.3 An unequal distribution of the built environment

And look at the *distribution* of the built environment. For example, sub-Saharan Africa has a miniscule per capita level of built stocks, and a tiny level of maintenance and replacement flows, compared to the rich countries.

Today, just as we find the world economy drastically ill-formed, we also find the built environment dramatically mis-shapen: quantitatively mal-distributed, and qualitatively distorted, with respect to social and environmental needs.

Construction is over-accumulated where it is not needed. Developments threaten to "lock in" tremendous inefficiencies in operational usage and maintenance flows associated with those built stocks.

(An example of the over-accumulation of stocks and inefficiencies mentioned is that UK material stocks continue to expand by ~1% per year (in 2016, about 374.1 Mt). Gross annual additions to asphalt stocks are typically about 10-12% of this. In 2016 they were ~40.2 Mt; but of this, only ~21.4 Mt were for new roadway additions. The rest went on repair and maintenance to existing stocks, replacing surfaces lost to wear and tear. The UK, with 0.85% of the world's population, accounted for about 1.9% of the world's asphalt concrete consumption (see Barbara Plank et al, 2022).)

Alongside those sorts of *over*-accumulation, we find the *under*-accumulation of suitable construction where it *is* needed. And yet still, what does get built, in such circumstances of "underdevelopment", is invariably tailored by boosterish ideologies – *not* toward the provision of essential services and needs, but toward the highly questionable, and environmentally calamitous, economic lever of expanded material throughput.

For despite claims to the contrary, by the UN amongst others, world poverty – by any reasonable measure – has continued to increase *alongside the boom in world output after 2000*. Using ActionAid's measure, that anyone with income under $10 a day is in poverty, that now includes two-thirds of the world's population (or 84% of people in low and middle income countries).

The material and social links are key: between stocks, flows, the provision of "services" and human wellbeing.

5.4 Emissions and land-use change

Before turning to the details of the embodied and operational emissions of the built environment, we need to consider the built environment's role in land-use change, and the loss of carbon sinks due to processes such as deforestation.

In 1850, effective emissions from the loss of land-based carbon sinks were around 2.54 billion tonnes of CO_2, against around 197 *million* tonnes of CO_2 from burning fossil fuels. Effective annual emissions from land-use change have been surprisingly steady worldwide ever since, *and* through the post-war period: in fact they peaked around 1960 and since 2000 have been *lower* than they were in 1950. (See section 3.2 above.)

According to the Global Carbon Project, land-use change since the advent of fossil capitalism is responsible for about a quarter of all sociogenic carbon emissions, through the loss of land-based carbon sinks.

However, in contrast to the 1850 baseline, only an estimated 60% of those land-use changes are *direct* – that is, deliberately caused by humans. The most significant of these are the clearance of tropical forests for agriculture. The remaining roughly 40% comes from *indirect* drivers such as climate change.

The point is that while *some* of the net loss of forest cover in recent years is due to urban sprawl and resource extraction – for example in eastern China – "at the global scale, the growth of urban areas accounts for a small fraction of all land changes", as a US-based research team showed recently. It seems fair to infer that rural and other non-urban elements of the built environment, such as roads and infrastructure, will still have a meaningful effect on land-use CO_2 flux – but these effects still appear to be much smaller than the effects of agricultural expansion and climate change.

5.5 Built environment emissions

Globally, then, the built environment's greenhouse gas emissions are almost entirely captured by the embodied carbon of the flow of building materials into building *stocks*; and the operational carbon flows of building and infrastructure *use*. In this section, I will use the available data to quantify these as accurately as possible.

The International Energy Agency (IEA) makes comprehensive calculations of the built environment's *global* emissions footprints, the best that I know of. Most other analyses defer to the IEA, look only at buildings or at particular materials, or only at material use and not at emissions. The UN Environment Programme (UNEP) partners with the IEA for its work on the built environment, and they jointly publish reports as the Global Alliance for Buildings and Construction (GlobalABC).

The IEA's built environment analysis focuses mostly on *energy*. It is based on energy-related CO_2 emissions, and does not include non-CO_2 emissions. The global picture is set out in the panel on page 34.

◻ Graph (a) on page 34 shows the most up-to-date estimate of total global greenhouse gas emissions for 2018 (in blue), and its various components.

◻ Graph (b) shows some important components of that total. This includes the GlobalABC's estimate for the total CO_2 energy-related emissions from the built environment in 2018 (in orange).

◻ Graph (c) gives a breakdown of that GlobalABC data, to show where the different components of those energy-related built environment emissions come from, for 2018. To that I have also added estimates for four other categories of emissions: the CO_2 "process" emissions from cement and steel manufacture; the methane emissions associated with the operational use of buildings, globally; and a recent estimate for the *non-renewable* CO_2 wood combustion emissions associated with household cooking.

CO_2 wood combustion emissions are a component of the category "land-use, land-use change and forestry" (LULUCF). They are *not* included in the IEA's "energy-related CO_2 emissions" data.

Note that the operational emissions shown are *only* for buildings, while the embodied emissions come from the construction of both buildings and infrastructure.

For more detail on the graphs, and how these emissions totals are worked out, see Appendix 3.

The main takeaway from this chart is that the annual embodied and operational CO_2 carbon footprints of the global built environment are of comparable magnitudes. Embodied CO_2 emissions are about 8.4 Gt CO_2; operational emissions are about 11 Gt CO_2.

And the rough picture of built environment emissions as a share of the total is: out of 58 Gt CO_2e of sociogenic emissions in 2018, the construction, maintenance and inhabitation of the built environment globally was responsible for about 17.5 Gt CO_2e in energy-related emissions, and about 1.8 Gt of process-based CO_2 emissions from concrete and steel combined.

And to be clear: this picture is a snapshot from 2018. We are looking here at the *components* of built environment emissions, and their proportions.

The crucial historical fact is the continual drive upwards, globally, of the *absolute* level of global emissions. That is what needs to be reversed, as a matter of urgency.

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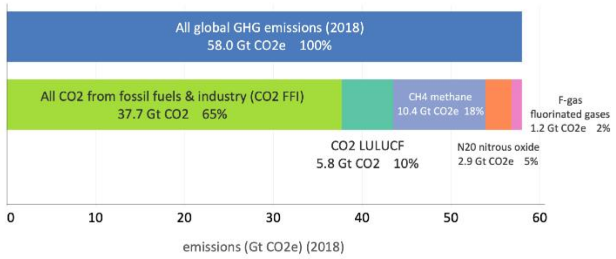
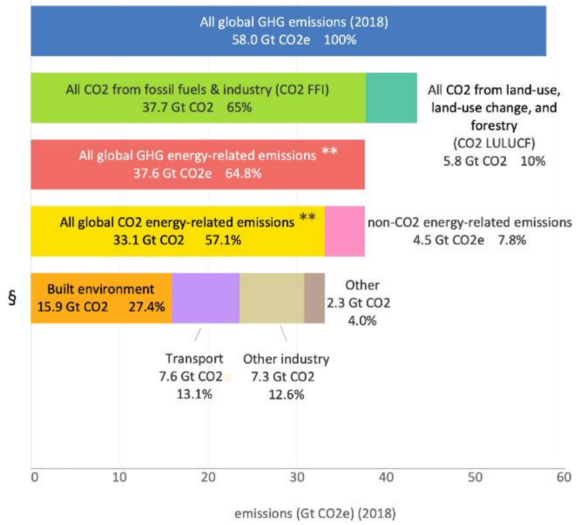
Global greenhouse gas emissions in 2018. Percentages indicate proportions of the total

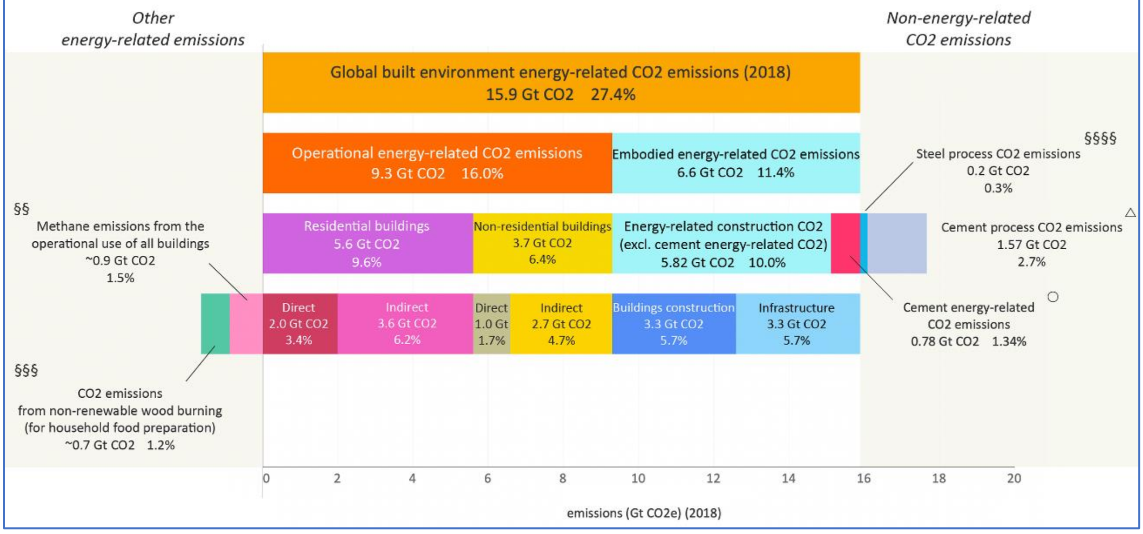
(a) emissions by gas (CO_2e) *



(b) energy-related emissions, disaggregated by sector



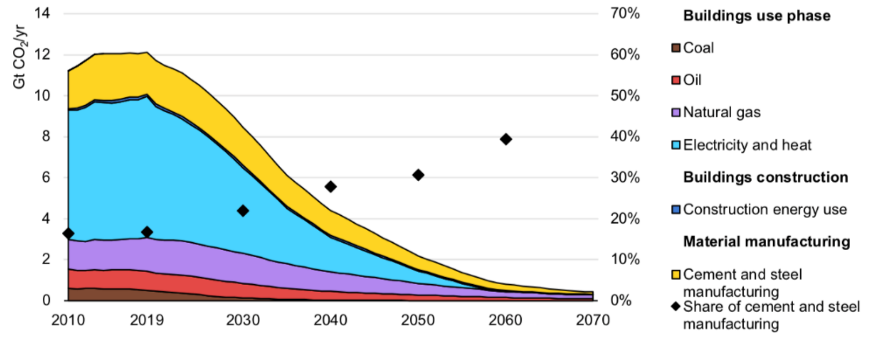
(c) Global built environment emissions §



Sources: * Global Carbon Project / Jan C. Minx et al (2021) (EDGAR dataset); ** IEA (2019), Global Energy & CO2 Status Report 2019; § IEA / UNEP (2019), IEA / UNEP (2021); △ Robbie M. Andrew (2019); ○ Global Carbon Project (2020) Supplemental data; §§ Global Carbon Project / Jan C. Minx et al (2021), IEA (2020a), IEA (2020b), IEA (2020c), IEA (2021a), IEA (2021b), IEA (2022); §§§ Alessandro Flammini et al (2023); §§§§ IEA (2020) (note: this is the 2019 figure – see Part 7) Note: based on global warming potentials with a 100-year time horizon from the IPCC Fifth Assessment Report (AR5).

5.6 Decarbonising the global built environment

Figure 4.22 CO_2 emissions in the buildings and construction value chain in the Sustainable Development Scenario, 2010-70



IEA 2020. All rights reserved.

Source: IEA (2020)

This graph, from an International Energy Agency (IEA) report, represents the proposed decarbonisation of buildings and construction, over the next half century (considering only CO_2, but not other greenhouse gases).

This graph, like all of the IEA's recent work on decarbonisation, reflects the agency's Sustainable Development Scenario, which aims to integrate the Paris Climate Accords with the UN's Sustainable Development Agenda. This includes a technological and policy agenda for reaching "net zero" by 2070, plus the aim of universal access to modern energy by 2030.

So we are talking about the emissions from construction, and the operational carbon of buildings use. There are also the operational emissions of various services provided by infrastructure. Operational emissions involve the energy sector; construction emissions involve large-scale industry, and again, in turn, the energy sector.

There are differences between the issues facing the older, richer, economically dominant countries and others.

Most built stocks, including buildings, exist in the countries that are most "developed" on the model of the fossil economy – mostly the older, richer economies, plus the rapidly developing "emerging markets".

Meanwhile, the areas now being integrated into the world economy have lots of new construction. Other, "underdeveloped" countries and regions have the eye of capital on them, and are desired locations for *future* construction.

Poorer regions are also often in tremendous need of new infrastructure and housing – an agenda often rhetorically collapsed into capital accumulation and/or the project of economic enlargement, although these projects are really distinct.

These "developing" and poorer countries are likely to be, and in most cases need to be, the location for most new construction. Their futures therefore contain the largest share of "mitigation potential" when it comes to *embodied* carbon.

On the other hand, the highest *immediate* mitigation potential for *operational* carbon is in the rich countries, with their vast accumulated stocks of buildings and infrastructure.

It is in the interests of the world's poor, especially, to mitigate the carbon load, and the operational costs, of using buildings, alongside decarbonising energy systems – especially now, as fossil fuel prices rise. That applies all the more to *populous countries*, and those experiencing the most rapid growth in population – many of which are poor.

Out of all buildings-related emissions worldwide, operational emissions presently comprise around 75%, with embodied emissions at around 25%. (See Appendix 3, Step 3, for more details.) This means that, while the greatest *immediate* operational emissions mitigation potential is with rich countries, it is the populous countries, with the fastest-growing populations, where the greatest *long-term* mitigation potentials exist: for embodied emissions *and* for operational emissions.

And the "long term" starts now – especially where countries already face enormous deficits in the provision of housing and other services.

As the Intergovernmental Panel on Climate Change (IPCC) Working Group III on mitigation stresses, in respect of both operational and embodied emissions, "the 2020-2030 decade is critical".

To date, around two-thirds of countries have included operational building *energy* codes as part of their Nationally Determined Contributions (NDCs) under the Paris Agreement net-zero pledges.

But the UN Environment Programme (UNEP) notes that building *materials*, and therefore embodied emissions, are insufficiently addressed, and the legal extent of commitments is patchy. (This on top of the blatant and deliberate inadequacy of net-zero in providing a sufficiently rapid path to zero emissions.)

UNEP in 2021 highlighted Viet Nam for having an NDC Roadmap, "that lays out a low-carbon, climate-resilient buildings and construction sector". Papua New Guinea has "extensive detail" about buildings in its most recent NDC.

The NDCs of Colombia, the EU, Lebanon, Maldives, Montenegro, Panama and Vanuatu also "mention efforts to either improve energy efficiency in buildings or reduce building-related emissions." The 2018 Caribbean Regional Energy Efficiency Building Code (CREEBC) – a measure to address *operational* carbon – is being implemented now.

However, a large proportion of future construction is forecast to take place in countries without the protections of mandatory environmental building codes or buildings-related NDC commitments. This is a significant problem with meeting the Paris goals.

For example, the most recent NDCs of the USA, India, Nigeria and Bangladesh, all have some mention of buildings' energy efficiency, but little about broader adaptive measures. The USA explicitly *removed* previous commitments during the 2017-21 Trump era; so did Canada.

In the following parts of this series, I will look more specifically at the embodied and operational emissions of the built environment – and what removing the emissions from each could or should look like. =

Part 6. Contraction and convergence, development and urbanisation

From the perspectives of real human needs and capacities, and present forms of technology, it is perfectly possible for all the world’s peoples and societies to follow a low energy and low emissions economic path from now onwards.

The obstacles to that come from the forces of capitalist growth, and the powerful interests invested in a more destructive future.

The obvious *rational* route to decarbonisation and a more liveable environment is “contraction and convergence”, a concept pioneered by the Global Commons Institute.

It means that the world’s high consumers of materials and energy need to *contract* their material and energy footprints dramatically; in turn, that creates consumption space for the world’s poor to consume more per capita use-values than they do now – to *converge* upwards on the per capita living standards of the global north.

All of that needs to happen across all sectors of the economy. It also needs to happen within a *shrinking* material consumption budget globally – and in the context of steep rises in forecast population.

There is plainly a tension between the extent of “permissible” material consumption, and the enormous needs for social development internationally. At least half the world’s population lives in material poverty.

But it would also be a mistake to embrace “development” goals that take the expanded reproduction of capital as the necessary lever for achieving them. Convergence is not possible on that basis.

From this, some principles follow:

□ Worldwide, people’s direct and collective needs – decent housing, sanitation, food security, wellbeing – must be prioritised, *by provisioning from nature along sustainable and environmentally reparative lines*.

□ “Development” needs must be *autonomised from the needs of capital*, and from the expectation of export-led growth, and pocketable profits for the global 1%.

□ In terms of the built environment, contraction and convergence means prioritising socially necessary construction. Large volumes of new or improved infrastructure and housing are desperately needed.

□ Yet whatever construction *is* necessary needs to proceed on the most abstemious material and emissions basis possible. *All unnecessary construction needs to be prevented from happening in the first place*. And the material composition of all new construction needs to change dramatically.

□ In addition to that, all infrastructure and all buildings—new and old—need to be made much more operationally efficient in the delivery of services.

□ Some of the most crucial construction is of renewable energy, energy transfer and storage infrastructure. While around 68% of all current greenhouse gas emissions are energy-related, access to reliable, sustainable electricity is one of the most useful instruments for improving lives globally.

□ But all new construction should also be resourced, as far as is possible and useful, *out of the capacities of the rich states and from capital resources already accumulated* – especially those states and fractions of capital who owe their inherited wealth to emissions-intense pathways of development, and to the historical horrors, and economic inequalities, of slavery and colonisation.

In this Part, I will consider, first, a path the built environment could follow in a world where energy consumption is kept low (section 6.1); then I focus on people’s homes (section 6.2), and how forecast population growth might translate into increased constructed floor area (section 6.3). Finally I set out my view of a meaningful “contract and converge” strategy (section 6.4) and what that could mean for urban planning (section 6.5).

6.1 A low energy demand scenario

Contraction and convergence implies very many changes to the status quo – from land-use and agriculture, to manufacturing production and habits of consumption. Here, though, I want to focus on energy, and the role of the built environment in energy consumption.

According to a 2018 study by Arnulf Grubler and colleagues, a *low-energy consumption global development path* is essential for limiting global warming to 1.5°C. They term this a Low Energy Demand (LED) scenario.

They do not even think the LED requires a wholly different form of society to emerge – a point I disagree with. What it does require, they argue, is for the present form of society to be forced to adopt very significant *global reductions in overall energy consumption compared to the present*.

Moreover, within that overall reduced scale of energy consumption, final energy consumption needs to be targeted according to an *equitable delivery of use-values*, globally.

In this way, the authors set out an energy-based scenario of “contraction and convergence”, unfolding, “despite rises in population, income and activity”.

Note that the LED pathway looks at energy consumption holistically. *It includes all the embodied energy that goes into manufacturing and construction*, on the way to a Low Energy Demand society – here termed “upstream energy use”.

I showed in part 5 that, just looking at *buildings*, embodied emissions comprise about 25% of all buildings-related emissions globally, and operational emissions about 75%. The LED model assumes that many construction and manufacturing projects will be necessary globally, in order to meet global needs and to implement energy transition.

To that end, the LED pathway depends primarily on energy efficiency measures. There are broadly three types. First, efficiency of the technological systems through which energy is consumed (in power stations and electricity networks, for example). Second, providing *useful* energy to end users more efficiently (by replacing gas boilers with heat pumps, for example). Third, reducing the amount of energy end-use needed in the first place (by insulating homes to reduce the amount of supplemental heat that's required to stay comfortable, for example).[1]

With energy consumption suitably constrained globally, the model shows that the vast majority of the energy consumed can be decarbonised.

The authors of the 2018 study orient their LED development pathway on quality-of-life indices, outlining some core use-values and services they deem necessary for human wellbeing in general. (I will mention some of those in what follows, in relation to the built environment, such as adequately-serviced living space, and thermal comfort.) For each of those indices, they describe in broad brushstrokes the state of energy services now, and how they are skewed between the global north and south.

Crucially, they model how those imbalances can and should be *de-skewed*, from a social and technological standpoint.

In my view it is doubtful that energy consumption in the global north can be reduced *voluntarily* on the necessary scale, *without* in the process radically changing the dominant form of the society we live in.

In any case, the paper argues that a low-energy path of development could constrain global final energy consumption to 245 Exajoules (EJ) by 2050. This is around 40% lower than global final energy consumption today.

In constraining world energy consumption to 245 EJ, with the energy coming from a decarbonised energy system, the world would meet the 1.5 °C Paris climate target, and also satisfy many of the UN's sustainable development goals – "significantly expanding human welfare and reducing global development inequalities".

This is all using *currently available and well-established technologies*, and without depending on highly spurious negative emissions technologies such as carbon capture and storage (CCS) and bioenergy with carbon capture and storage (BECCS).

Grubler et al certainly are not alone in proposing a more use-values-based approach. However, they clearly sketch what is *physically possible*, in distinction from what is cynically "realistic".

Their modelling assessments aggregate data into worldwide "global north" and "global south" averages. *Within* those very large north-south divisions, a properly eco-socialist politics wants to ensure a massive *redistribution of use-values according to need* – away from the rich, and towards the global working class, peasantry and indigenous peoples.

That needs to happen for the world economy as a whole, and for the built environment.

Plainly, however, *world economic redistribution can rarely include the physical redistribution of buildings and infrastructure*.

The issue, instead, is to *steer existing use, and future material and energy flows, in the direction of an equitable distribution of use-values and wellbeing*.

I noted already in part 5 that most built "stocks" of materials worldwide exist in the countries most "developed" on the model of the fossil economy. By weight, those stocks are mostly buildings and infrastructure, but also include the uneven distribution of consumer durables and capital investments.

By contrast, poorer regions are most in need of *new* infrastructure and housing, while also being the main "sinks" for waste and pollution.

It is poor countries that need now to build large volumes of new infrastructure and housing. They therefore have the largest opportunities for "mitigation potential", i.e. reducing the materials that go into buildings and infrastructure, and the associated emissions (embodied emissions).

Poor countries also have the highest potential for curtailing long-term operational emissions: for example, in home heating and cooling, electricity, and transport. On the other hand, the highest *immediate* mitigation potential for operational emissions is with the rich countries, with their vast accumulated stocks of buildings and infrastructure delivering use-values daily. Those need to be retrofitted accordingly.

Note, however, that existing stocks of buildings and infrastructure are sometimes very poorly specified, and themselves need to be substantially repaired or replaced for the sake of safety. In the UK, the example of Grenfell Tower's deadly cladding jumps to mind. So too does the ongoing crisis from historical uses of aerated concrete in many schools, hospitals, and other public buildings.

Poor country infrastructures and buildings obviously need to be adequately specified – and, from the get-go, built to last.

6.2. Homes

We need to think of decent housing as a universal human right. Decent housing means sufficient interior living space for everyone, with homes adequately and safely serviced in terms of essential amenities – such as safe energy for cooking, and clean electricity for appliances.

Homes the world over should effectively protect people from the elements outside: from the cold and the heat – and do so with a minimal outlay of supplemental energy (see part 9).

All of those essential facets of housing, except for the last bit about energy, are recognised in international law as essential human rights: part of a Right to Adequate Housing, enshrined in Article 25 of the UN's Universal Declaration of Human Rights (1948) and Article 11.1 of the International Covenant on Economic, Social and Cultural Rights (1966).

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[1] Researchers distinguish between primary energy (e.g. the available chemical energy stored in coal or gas, or the energy in wind that pushes a wind turbine), final (or "secondary") energy (that has undergone some processing, e.g. electricity generated in a power station or refined fuel), and useful energy (the energy as it is put to use by a final consumer, e.g. as light in a room in the evening, the movement of a car driven by the fuel). For a fuller explanation see here

Arguably, this right is relevant to all states vis-à-vis all people around the world – not simply relevant to a state with regard to the people living within its own borders.

The associated guidance for those agreements also contains a provision on habitability, which includes that everyone have adequate living space, though how much that means is not specified.

The 2018 Grubler et al study reports that, worldwide, average residential floorspace per capita is 23m^2 – though plainly many live with much less, and many live with much more. In the global south, the mean average is 22m^2 of residential floorspace per person. In the global north, it has plateaued to 30m^2, but single-family suburban homes can approach 70m^2 per person in some areas – it is a question of geographical averages.

The world's population is projected to rise from ~7.7 billion in 2020 to ~9.2 billion in 2050. Grubler and his co-authors follow the prevailing wisdom on rates of urbanisation in the global south, to suggest that per capita floor areas in the global south are also likely to plateau, at ~29m^2 by 2050.

They think that densification of housing in the global north will likely mean that the present extent of floorspace in the suburbs will trend downwards to a similar amount.

In other words, they think that prevailing economic tendencies are already in place, such that more people globally will have a greater share of residential floor area. However, they think this tendency should be further encouraged, in order to engineer contraction and convergence, towards a 30m^2 per person global average.

They do not go so far as to benchmark a necessary minimum floor area per person. By contrast, a 2017 paper by Narasimha Rao and Jihoon Min considered that the "material prerequisites" for a decent standard of living include a minimum of 30m^2 of *total interior floor area per household of up to three people*, with an additional 10m^2 for each additional person. So, a three-person home cannot be smaller than 30m^2, and a five-person home would need to be at least 50m^2.

Note that this recommendation is *universal*. The idea is that the minimum necessary residential floor area for a person is not something that varies from culture to culture.

There is an economic issue: access to decent housing should not be tied to people's ability to pay. By extension, the growth of global housing floor areas should also not be tied to people's ability to pay to occupy it.

As for the Right to Adequate Housing, in my view, safe and decent living space is a human right, and the economy needs to be shaped to provide that. It is the obligation of the world, and in particular the rich, to make space for everyone to live well.

6.3. Floor area forecasts

One practical way to comprehend the post-2000 China-led construction boom is through measurements of the total buildings floor area worldwide. According to the IEA, between 2000 and 2020 the total buildings floor area leapt by a startling 90 billion m^2, from around 156 billion m^2 in 2000 to around 246 billion m^2 in 2020 – an increase of nearly 60%, or about 2.3% per year.

But these figures underestimate total buildings construction. They appear to exclude industrial premises. And they *do not include the replacement floor areas for those buildings that have been demolished*.

More dramatically still, in its *Global Status Report for Buildings and Construction* (Global ABC report, 2021) with the UN Environment Programme (UNEP), the IEA projected that the total global floor area (excluding industrial premises) could be more than 476 billion m^2 in 2060 – almost twice the 2020 level, and three times more than in 2000.[2]

When building demolition and replacement is factored in, this apparently means that an average of 6.5 billion m^2 of floor area will be constructed every year over the next 40 years – "the equivalent of adding the total floor area of all the buildings in Japan to the planet every year to 2060", according to the IEA, or the total floor area of Paris every week.

In these forecasts, Chinese expansion slows down around 2040 – and in that respect the forecast is already out of date (see part 4). New buildings construction is seen skewing away from rich states, and heavily towards large cities in Africa. Beyond 2040, the new floor area is seen mostly in Africa, albeit with continued centres of construction in China, India, Indonesia and Brazil.

The UN International Resource Panel (IRP) estimated in 2018 that urban growth alone would cause cities' share in total *domestic* material consumption to rise from around 40 billion tonnes per year in 2010, to 90 billion tonnes per year in 2050. For the Intergovernmental Panel on Climate Change (IPCC) Working Group III, the task is then about "[m]inimising and avoiding raw material demands […] while accommodating the [inevitable shifts in] urban population."

The Covid-19 pandemic did not initially blunt those projections much: floor area continued to grow robustly through 2020, even as economies stalled and emissions from the use of buildings plummeted. However, Chinese construction growth has slowed since the pandemic.

Much existing floor area has also remained unused. China is notorious for this, with the collapse in real estate speculation leaving an extraordinary home vacancy rate of ~12% in 2022.

The IEA has forecast that, for the world as a whole, *almost two-thirds of the building stock to 2060 would be standing by 2035* – while the IPCC in 2022 gave the world an eight-year window to reduce emissions to 55% of 2010 levels, in order to limit global warming to a liveable 1.5°C.

If most of forecast construction demand to 2060 materialises before 2035, it first needs to be put in the right place – not in ghost towns. But secondly, it will also need to be realised *within a rapidly shrinking carbon budget if severe climate change is to be avoided.*

The IEA's 2017 floor area projections are shown in the charts on page 39.

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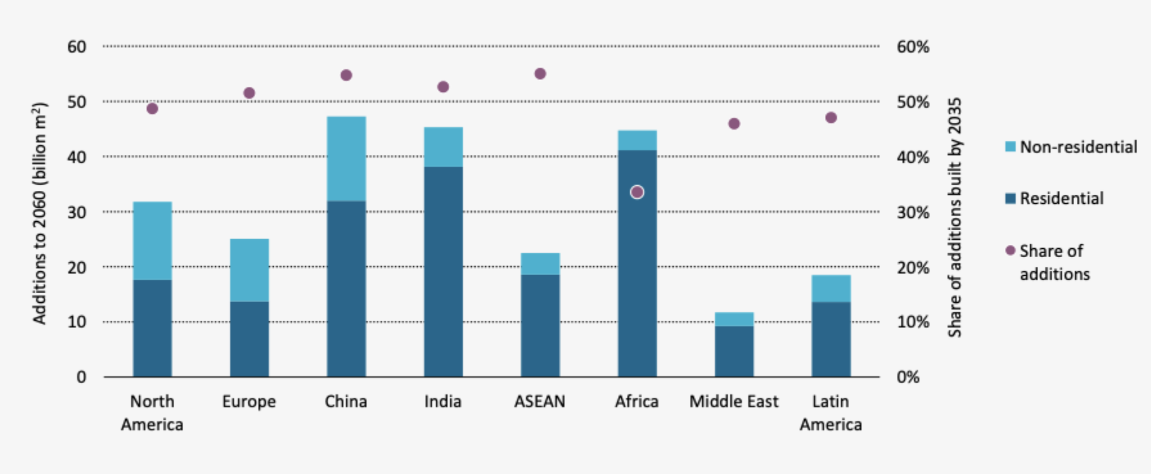
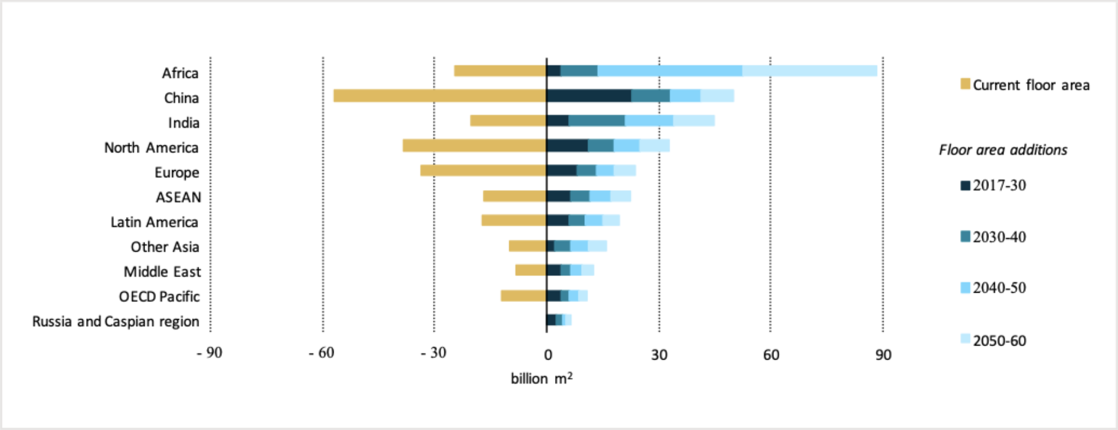
[2] The IEA appears to use the same projections up to 2050 in the most recent (2022) Global ABC report

Figure 3.4. Floor area additions to 2060 and share of additions built by 2035 for selected regions



Note: ASEAN = Association of Southeast Asian Nations.

FIGURE 3 Floor area additions to 2060 by key regions



Notes: OECD Pacific includes Australia, New Zealand, Japan and Korea; ASEAN = Association of Southeast Asian Nations.
Source: IEA (2017), Energy Technology Perspectives 2017, IEA/OECD, Paris, www.iea.org/etp

Source (top): IEA (2017), (above): UNEP/IEA (2017), based on IEA (2017)

However, there is a big discrepancy between the way the two graphics forecast floor area additions in Africa – by 2060, the forecast is of 45 billion m^2 of additions in the first graph, and of 88 billion m^2 in the second graph – and I do not know why.[3]

No doubt, the floor area additions in Africa will be considerable, and need to be. The main influencing factor will be population growth, expected to be faster there than elsewhere. (See also section 6.5 below.)

The IEA's 2017 report also forecasts the total floor area in OECD countries (that is, broadly speaking, the richest countries) to roughly double between 2017 and 2060, although the growth in developing economies is expected to be even faster. (See the first graph.)

The IEA frames this as "roughly 65% of the total expected buildings stock in 2060 is already standing today" – hence a large existing stock of buildings will need to be renovated to improve their operational energy performance.

Anyway, it is disturbing to consider that, even in the world's richest countries, normative expectations are for the building stock to roughly double in size.

Before leaving the subject of floor area, I offer a comment on the assumptions underpinning the forecasts made by the IEA and other agencies.

First, it is wrong to assume, as they often do, that greater urban population will automatically lead to economic growth, let alone a growth in household income. The way that urban populations are expanding in the global south is not following this pattern.

Second, it cannot be assumed that the way to fix this is to apply high levels of capitalist investment. (These issues are discussed in more detail in Appendix 4: What drives floor area increases?)

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[3] I asked the IEA about this discrepancy, but received no response. According to the first graph, for Africa as a whole, ~41 billion m^2 of residential floor area additions are deemed likely from 2017 to 2060, versus ~4 billion m^2 in non-residential additions. That is, about 91% of floor area additions are forecast to be for residential use.

This first graph is in line with the projection I mentioned previously – of around 230 billion m^2 worldwide additions to 2060, taking the floor area total to ~476 billion m^2 in 2060. The second graph forecasts add up to something like 325 billion m^2 of worldwide floor area additions from 2017 to 2060.

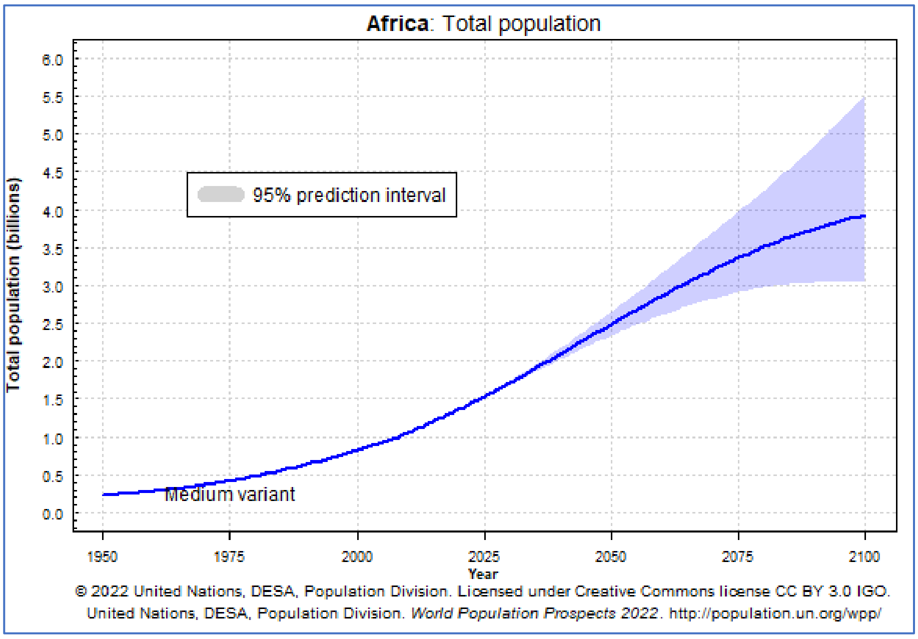
According to the second graph, ~24 billion m^2 of current floor area (residential + non-residential) was in use in Africa in 2017. At that point, the population of the whole of Africa, according to the UN, was ~1.26 billion. Applying the previous residential/non-residential forecast breakdown to the existing building stock suggests that in 2017 there were ~21.9 billion m^2 of residential building space – that is, an *average* of about 17.4 m^2 per person.

6.4. Steps towards "contraction and convergence"

Contraction

As far as rich countries are concerned, the only building with a carbon footprint that should be happening *at all* is that which is (a) actively *redistributing* material wealth to those in need; and (b) essential infrastructure – that is, necessary for provisioning and maintaining essential use-values.

No infrastructure should be built that is simply pump-priming an economy for excessive material consumption and emissions. No housing should be built that is meant only to offer its private developers high margins of profit.



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Source: UN DESA Population Division

All construction should also be done in ways that reduce absolute material use, and bring climate-forcing emissions rapidly towards *absolute* zero (not "net zero"). Anything less is a repudiation of rich countries' historical and ethical obligations to climb down off the fossil economy.

In the UK, for example, more or less any new road or runway construction would be in breach of what is needed. So is the excess of luxury housebuilding in large cities, much of which lies idle. Of course, in provisioning terms, such housing is also enormously detrimental, in that it pushes up all house prices (including rents), and effects a transfer of wealth *up the wealth ladder*.

In London, councils regularly, wastefully demolish council housing to build entirely new housing in its place – and do so to turf out existing residents and established communities, in order to build homes for sale at incredibly high market prices. Examples are legion, but these are as often as not *Labour*-led councils – such as Southwark and Lambeth.

The logic here seems to be twofold. The first is fiscal: acute housing need and inadequate state-led spending on social housing encourage, and often force, local authorities and housing associations to fund social rent homes via the construction of high-priced private developments, on a "cross-subsidy" basis.

But this dynamic dovetails with another classic: political corruption. London's local authorities and housing associations – like local governments all over the world – are now theatres for the ransacking of public housing and land for private gain.

Instead of this, maintenance and refurbishment of *existing* structures, for the good of their residents, is needed. They should be retrofitted to meet improved operational standards such as thermal efficiency (see part 9) – not junked, with their historical embodied emissions wasted. Most important, existing communities should themselves be maintained, instead of being demolished, and they should be afforded secure and generous dwellings to live in.

Convergence

Let us return to the question: how much more floor space might be needed in Africa, in the coming decades? This can help us to visualise what "convergence" means.

Estimates published by the UN and IEA suggest that: Africa's population is now about 1.4 billion. More than 600 million of these people live in urban areas – and about half of these, i.e. 300 million, are in slums and informal settlements. The same agencies project that, by 2060, Africa's population is likely to more than double to 2.86 billion. (See the graphic.)[4]

From those forecasts, then, it seems that dwellings for at least 1.47 billion more people will be needed in Africa between now and 2060.

The 2018 study I cited previously, by Arnulf Grubler and his colleagues, suggested a global average residential floor area of 30m^2 per person. I contrasted that with a 2017 paper

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[4] According to the UN, the mid-year population of the whole of Africa in 2021 was 1.39 billion people, with 43.9% (610 million people) living in urban areas. According to the UN Human Settlements Programme (UN-Habitat), just in Sub-Saharan Africa, 230 million people (50.3% of the urban population) live in slums and informal settlements. That's *the very minimum estimate* for the number of people who lack decent housing at the present time, just in cities. Projecting the Sub-Saharan figures onto Africa as a whole would suggest a figure of ~300 million.

The UN's medium-fertility pathway meanwhile forecasts that the population for the whole of Africa will reach 2.49 billion in 2050, and 2.86 billion in 2060, as shown in the graph. (The annual rate of population increase is forecast to remain positive beyond 2100.) That is, the mid-estimate is that there will be ~1.47 billion more people living in Africa by 2060 – more than double the population now.

The UN's forecasts for the scale of urbanisation don't extend beyond 2050. However, in 2050, the UN forecasts that 58.9% of Africa's population will be living in urban areas – that is, 1.47 billion people: an increase of 860 million between 2021 and 2050.

by Narasimha Rao and Jihoon Min that proposed a minimal acceptable standard of 50m^2 for a five-person home.

The Grubler et al study, applied to those 1.47 billion people, implies 44.1 billion m^2 of new residential floor area in Africa. The more basic Rao and Min proposal would suggest just an extra 14.7 billion m^2 of housing.

However, we need to consider three more factors on top of that: the current under-provision of residential floorspace; the prevalence of poor quality slum housing; and the ongoing movement of people into cities.

I estimate that, once these factors are taken into account, the total extra residential floor space needed – based on Grubler et al's 30m^2 per person – could be closer to ~53 billion m^2 by 2050 and ~65 billion m^2 by 2060, rather than ~44 billion m^2.

Clearly, *across Africa alone*, an approximate doubling of the population over the next 40 years will necessitate a huge increase in the number of homes that need to be built and serviced, while the supply of materials and energy needs to shrink rapidly. In my view, it is very unlikely indeed that those needs can be met by capitalist business-as-usual.

The IPCC notes that "about half of the increase in urban population through 2050 is forecasted to concentrate in eight countries" – in ranking order: India, China, Nigeria, Democratic Republic of Congo, Pakistan, Indonesia, USA, Bangladesh. Of these eight, says the IPCC, all but the USA will need significant levels of *funding assistance* to build adequate homes, roads, and other urban infrastructure to cope with the levels of urbanisation.

The UN-Habitat agency states plainly: "The rate at which adequate/affordable housing is supplied and provided on the global market is way lower than the rate of urban population growth."

The message is clear: capitalist development on its own cannot hope to address the real needs of people for decent homes – let alone their needs for public buildings, and infrastructure. Those essential needs must be met instead *directly*, without boosterish claims about capital investment, and without the lever of capital accumulation.

All new construction should also be resourced, as far as is possible and useful, *out of the capacities of the rich states and from capital resources already accumulated*.

As far as I can tell, one possible way to accomplish that – and much else – would be a policy akin to a Green Lend-Lease.

Governments – those in the rich world, and those with suitable productive capacities, such as China – should make outlays of their own currencies. Overt monetary financing (see here and here) could fund transfers to the global south – providing whichever moneys are required to procure goods not available for purchase in poor countries' own currencies. This would have the added benefit for rich countries of feeding economic demand into the "value-added" sectors of their own domestic economies.

The aim would be technological transfer, and to ventilate growth in the real capacities of poor economies – in order to meet real needs, alongside green energy transition. A flow of productive capacity from existing centres of capital to the economic "periphery".

As things stand, "development assistance" and "climate finance" from rich to poor states are a disgrace. They are meant to pay *just* for climate change mitigation and adaptation measures, and *not* for existing and future needs beyond that.

Even mainstream economists estimate the necessary scale of funding for the transition at $5-6000 billion per year.[5] Meanwhile, rich countries have fallen short of their comparatively *tiny* 2009 pledge to provide $100 billion per year of climate finance by 2020 – in 2020, just $83.3 billion was "mobilised".

Moreover, current investment planning internationally still points towards ~US$ 1,000 billion of annual investments in fossil fuel-based technologies, according to the International Renewable Energy Agency (IRENA). Those will need to be "redirected towards energy transition technologies and infrastructure".[6]

This is in the context of a world economy where total GDP (money value of all goods and services transacted) in 2022 was US$ 101,000 billion; where the authorised budget for the US Department of Defence was about $750 billion; where the world's largest company by revenue, Walmart, earned $611 billion; and where the *profits alone* of the six largest energy companies in 2022 totalled $279 billion, of which more than half went to one company, Saudi Aramco.

Worse still than the inadequate scale of "climate finance" is that, according to the OECD, in the period 2016-2020, 72% ($269 billion) of it was given in the form of *loans*. Direct grants comprised just 25% ($93 billion), with the remaining 3% comprising equity.[7]

In the face of climate change there should be no talk of loans – only of reconstruction and social need; of cancelling

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[5] The so-called Independent High-Level Expert Group (IHLEG) on Climate Finance, chaired by Vera Songwe and Nicholas Stern, recently estimated the scale of necessary funding. Theirs is a "growth-oriented, resource-intensive vision", notes Adam Tooze. It is specifically *not* about contracting and converging demand and consumption. That said, the proposal is to: meet all the UN's Sustainable Development Goals (SDGs); green the international energy system within a 1.5°C temperature warming goal; address growing climate vulnerability through investments in adaptation and resilience; and invest in sustainable agriculture.

The authors estimate that a total of about US$5,900 billion of annual finance is needed for "emerging markets and developing countries" (EMDCs), *excluding China*, every year by 2030. That's US$5900 billion per year – US$ 2250 billion of it for "climate related investments".

The International Renewable Energy Agency (IRENA) give a larger estimate. They suggest that *energy transition alone*, from 2023 to 2050 requires $US 150,000 billion – averaging over US$ 5,000 billion a year. They note that, "energy investment remains concentrated in a limited number of countries and focused on only a few technologies".

[6] See also here for the IEA and IRENA's recent collaborative "Breakthrough Agenda" report.

[7] The proportion of loans offered on a "concessional" basis varies by source. Oxfam estimates that in 2017-18, around 40% of overall climate finance was "non-concessional" – that is, loans with a market-based interest rate, or otherwise lacking in suitable concessions. These climate loans, Oxfam says, "force poorer nations to fall further into debt as they struggle with the impacts of climate change". Market-rate loans have also been the basis of China's enormous investments in infrastructure across Africa.

debts, transferring resources and technology, and redirecting productive output.

The same also applies for meeting all forms of social need, such as essential housing and infrastructure, which are crucial for the wellbeing and "resiliency" of low-income populations – those most exposed to climate change and other forms of environmental degradation.

Indeed, considering the extent of world inequality and deprivation, *and* global warming, it is really scandalous that any construction takes place *at all* in the rich countries, beyond the strictly necessary. I say this from a social and an emissions perspective.

The productive capacities and resources of the rich states need to be redeployed entirely towards socially useful ends, at home and abroad.

6.5. Reducing the carbon load of urbanism

There are also many ways in which the built environment at the scale of whole settlements can be *spatially planned* to permit less carbon intensive, more environmentally friendly, and healthier ways of life.

For example, urban life holds out the promise of material and carbon efficiencies – through integrated spatial planning, transit-oriented development, and environments that support and encourage walking and cycling wherever possible. In these ways, the built environment can potentially help reduce other lifestyle emissions, such as those associated with private car ownership and use.[8]

There are also ways that the needs of climate, and the environment more broadly, dovetail with improving people's quality of life, particularly in cities. Clean air should be a priority, and can be aided by the widespread presence of trees and other plants; urban space should integrate habitats for biodiverse wildlife; and mental health improved by access to green space, clean air, flowering plants and other forms of wildlife.

Communities' resilience to climate change should additionally be helped, through the widespread use of shade and water to protect against high temperatures, and effective natural drainage to protect against flash flooding.

However, once urban environments have already been built, root-and-branch changes can be difficult to implement. The form of the built environment can become locked in, as discussed previously with respect to car-centred suburban sprawl. Once dense forms of habitation, economies, utilities, lifestyles and cultural values become layered on top of the built environment, it can become a self-reinforcing mess.

On the other hand, while urban environments can never lock in *low*-emissions lifestyles, they can make them possible. It is important that the construction of new urban spaces is meaningfully designed to help with that.

And it is important that whatever *can* be done *is* done to renovate existing patterns of settlement, so that the carbon *benefits* of construction significantly outweigh the carbon costs of implementing them, over a reasonable lifecycle of use, upkeep and maintenance. Depending on the degree of lock in, that can be technically challenging, often expensive, and predictably piecemeal – which itself can be a high political barrier to success.

There's a big "but".

While urban life can be designed in such ways as to make low carbon lifestyles *possible*, in practice the *over-riding* predictor of per-capita material and carbon footprints still remains *per-capita income* (see part 2) – not urban form, and not urban, rural or even suburban location. Here again, though, the picture is often mixed.

In Beijing, for example, urban geographical and population expansion has been associated with higher incomes. Economic growth in China after the 1990s pulled people into the city, and expulsions often also pushed them there (see part 4).

The resulting higher incomes induced higher *indirect* per-capita consumption, compared to locations in rural Beijing. However, rural locations have tended to be, and remain, *more* polluting overall on a per-capita basis, despite being poorer – due to high *operational* emissions from burning coal for home heating and for cooking.

On the other hand, a recent study of per-capita material footprints in Sydney, Australia, found that total (direct + indirect) carbon footprints in urban neighbourhoods are higher on average than those in the suburbs. This is largely because of a tendency for generally wealthier urban dwellers to own a car (with substantial embodied emissions) *in addition* to living in areas well-served by good public transit.

Other consumption indices, such as food, between city and suburb are roughly on a par, when comparing households with the same income. So measures specifically designed to *impede* car ownership, as well as making it unnecessary, would seem to be called for in cities.

In any case, urban life *in itself* is not automatically a route to lowered material and carbon intensity. Incomes and consumption patterns combine with urban form; and household income – in the absence of low-carbon consumption options or preferences – is the main determinant of individual and household emissions.

Moreover, even though a large slice of the world's GDP is associated with cities, *that does not mean either that cities in and of themselves drive GDP growth*, or that urban population growth or rural-urban migration are synonymous with job creation, and with increased material consumption. Both urban and rural populations can and do often grow without a sufficient supply of paid work, formal or informal. It is the dominant story of many local economies in India and Sub-Saharan Africa.

In those countries, urban life is often associated not with *generating* higher wealth, income and emissions, but with increased burdens of collective impoverishment.

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[8] As I mentioned in part 3, more than 80% of the world's GDP is associated with cities, according to the World Bank. And with a rising majority of the world's population (about 56%) living in cities, it is hardly surprising that most of the world's material consumption is also-concentrated in cities. According to the UN International Resource Panel (IRP), total urban material consumption *calculated only on a domestic-basis* (i.e., excluding imported goods) comprised around 58% of the world's total material consumption in 2015 (~52 billion out of ~90 billion tonnes)

Both of these trends, *the enrichment and the impoverishment*, are the products of chronic maldistributions in the world's material and economic resources, towards centres of economic wealth.

Of course, enrichment and impoverishment often overlap and coincide spatially. It is even commonplace that the capitalist city contains within itself *both wealth and poverty, as equally constituent parts*. Individual neighbourhoods see "growth" alongside deprivation and dispossession, with the former accentuating the latter through rising prices, and the poor economically displaced as the rich arrive. If the market rules, high urban land values also tend to make poorer dwellings more dense and crowded, and leave them lacking in amenities like public green space.

And wherever the rise of urban populations is associated with improved private incomes, new urban construction is more likely to follow, financed on the same basis.

In China, with its "classical" mode of urban-based accumulation, this new urban construction has been the *means* and one of the *drivers* of economic development – and also one of the main engines for the economic redistribution of people. Furthermore, construction still seems to be the Chinese Communist Party's favoured lever of growth.

In such cases, new buildings and infrastructure will tend to be associated with greater lifestyle emissions amongst a given population, alongside the large embodied carbon footprints of new construction – just another expression of increased consumption.

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But where urban populations lack the economic means or prospects to justify private investments in construction on a capitalist basis; where they either stay in place or migrate in the absence of gains in income – *those people will often be those most in need of new housing and infrastructure.*

So it is also, sadly, a mistake to assume, in a capitalist society, that construction will respond to the needs of the population, without the economic lever of lifted incomes.

The world's poor, urban and rural, urgently need new buildings and infrastructure, on a non-capitalist basis, while the capitalist over-accumulation of the built environment needs to be curtailed, dramatically.

Furthermore, urban and rural homes *for everyone* need to be designed in all the ways that maximise wellbeing, encourage low-carbon lifestyles, and build environmental resiliency.

In the case of slum housing, slum clearance should also be anathema. What is needed again is retrofit, and a "participatory slum upgrading approach", as UN-Habitat argues: to move people out of slum-like *conditions*, while dramatically improving the quality of their homes and their access to amenities.

The aim should be to *maintain communities intact and where they are*, while expanding and redistributing the economic availability of use-values.

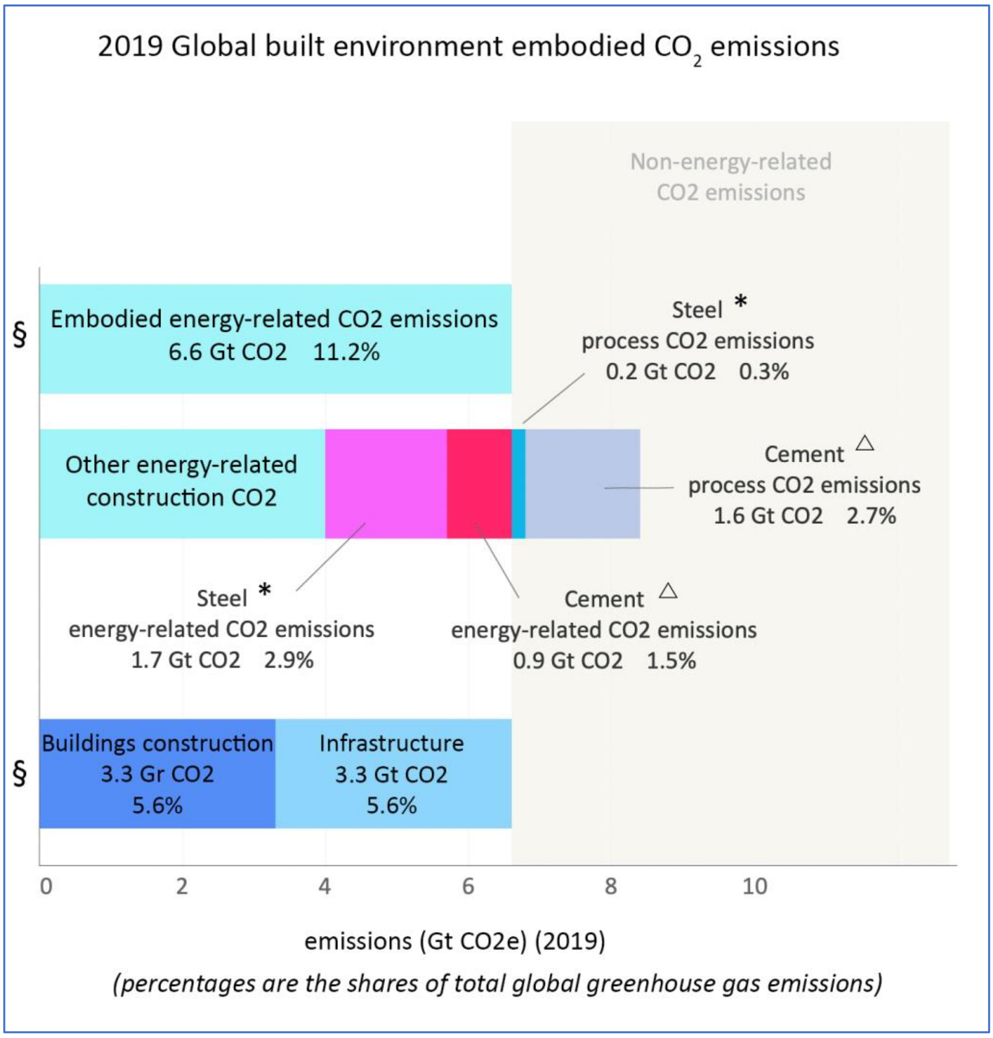
All of that, moreover, needs to happen in the context of reducing the overall risk exposure of poor populations – for which safe and secure housing is essential, but insufficient on its own.

Part 7. Embodied emissions

In this part, I give an overview of the problem of embodied emissions, i.e. those emitted in the construction of buildings and infrastructure (section 7.1); then some details about concrete and steel (section 7.2), and cement recarbonation (section 7.3); and about roads (section 7.4).

7.1. Overview

This graphic shows the sources of the built environment's embodied CO_2 emissions for 2019, including emissions from steel manufacture.[1] Each row represents a different breakdown of the same total – the 6.6 GtCO2 of embodied, energy-related emissions. The second row, unlike the other two, also shows the process emissions from the production of steel and cement.



Sources: * IEA (2020); △ Robbie M. Andrew (2022); § IEA / UNEP (2020), IEA / UNEP (2021).

The vast majority of the built environment's embodied emissions come from the burning of fossil fuels during the *manufacture of building materials.* For example, in the case of buildings construction, in 2019 just 0.13 Gt CO_2 emissions globally came from the buildings construction stage – a comparatively tiny proportion of the roughly 4.45 Gt total embodied emissions.[2] The rest came from the manufacture of building materials *prior* to construction.

Of the carbon footprint of those materials that went into buildings construction, around 60% of emissions came from cement and steel manufacture, and 40% from the manufacture of other buildings materials. For the construction sector as a whole, the ratio is something like 50:50 cement and steel emissions to other emissions.

This underlines the point, emphasised in part 3: steel and cement (and concrete made from cement) are the high-energy ingredients of choice for fossil-fuelled global construction.

Sand and gravel are also major inputs. Indeed, the construction sector is driving an impending sand crisis. The main emissions cost of these is the energy of extraction, processing and transport.

In addition, construction consumes 26% of global aluminium output and 19% of all non-fibre plastics.

The levels of embodied emissions in common construction materials can be seen in the "Construction Material Pyramid", shown on page 45, designed by the Centre for Industrialised Architecture in Denmark. The values given are averages that include direct and indirect emissions footprints by point of sale (cradle-to-gate).

At the base of the pyramid are materials that have a low emissions intensity, i.e. that typically require just a small input of energy or other sources of emissions in their production: rammed earth walls, plywood, construction timber. (Wood here even gets a negative value as a material that "sequesters" carbon, although I think that framing can be misleading. See section 8.4 below.)

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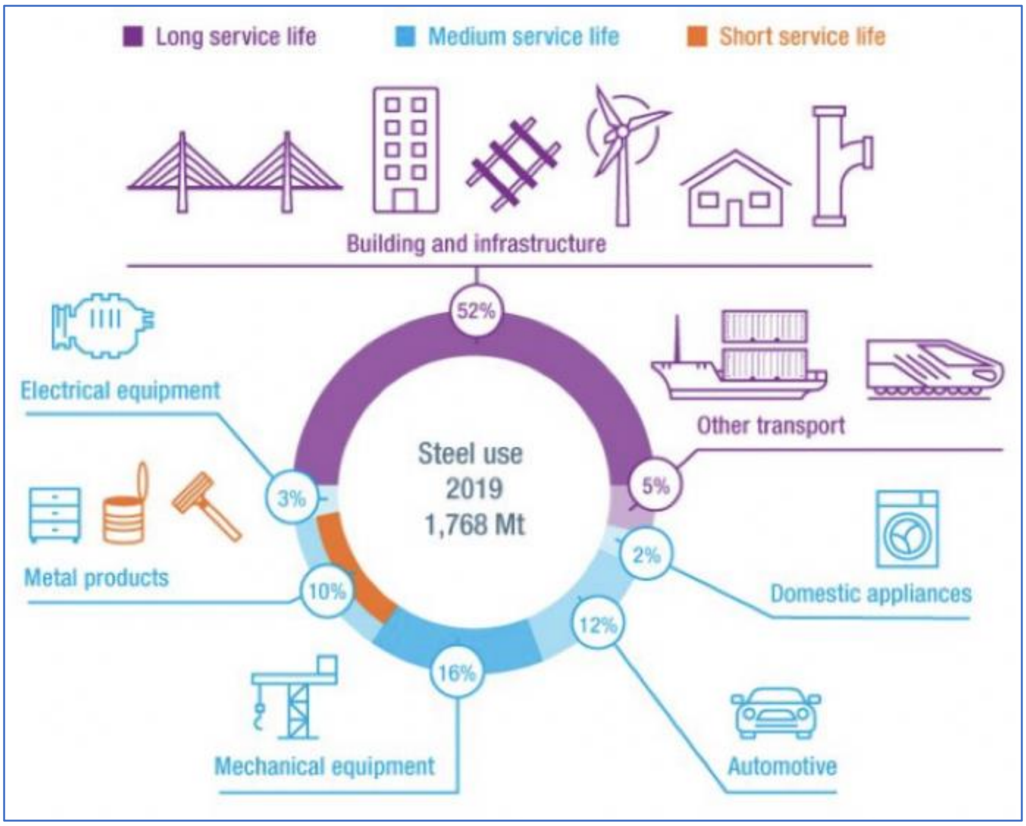
[1] This is an update from the 2018 figures in part 4. (I have switched to 2019, because other data relevant to this section are not readily available for 2018.) Percentages in the graph are the share of total global greenhouse gas emissions, based on a provisional estimate for 2019 of 59.1 Gt CO_2e (±5.9 Gt) (EDGAR dataset, cited in UNEP, 2020)

[2] Statistics from the 2020 GlobalABC report by the IEA and UN Environment Programme (UNEP)

Source: Centre for Industrialised Architecture Below: global steel use. Source: World Steel Association



Grouped around the top of the pyramid are materials with a high emissions-intensity – those that require either a high expenditure of carbon independently of their energy footprint, or those with a large energy footprint that is entirely or overwhelmingly carbon-based: these include conventional C20 and C25 grades of concrete, structural steel, galvanised steel, and at the peak, aluminium sheetwork.[3]

7.2. Concrete and steel

Because they are so dominant, I will focus here on concrete and steel emissions.

In part 3, I mentioned the aesthetic and ideological role played by concrete and steel in modern and contemporary architecture.

The Seagram Building in New York City is a good example of this. Designed by Ludwig Mies van der Rohe, and completed in 1958, it is an icon of architectural modernism. However, specified as it was in the Cold War era of fossil capital, its minimal aesthetics hide a very dirty material reality.

Barnabas Calder and Florian Urban, two architectural historians, write that concrete accounts for 79% of the Seagram Building's mass – most of the rest coming from high-energy steel and glass. Moreover, it spews out vast volumes of operational emissions (see part 9).

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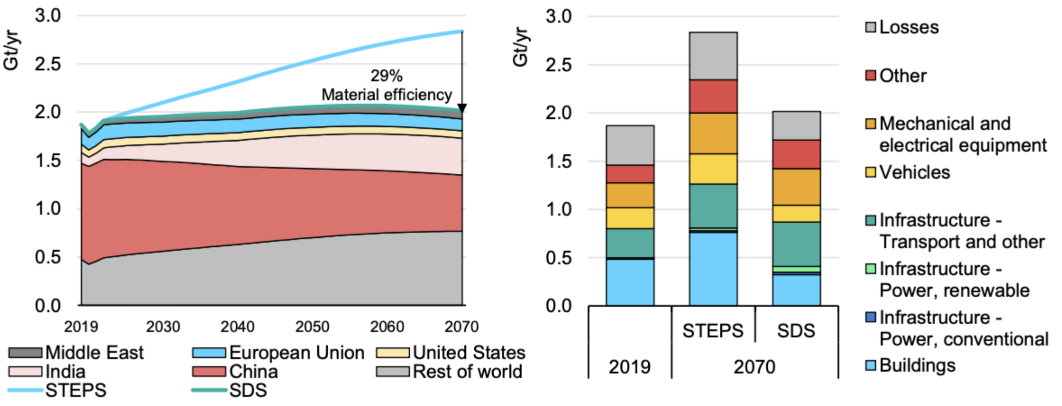
[3] For built environment professionals, there are tools like the Embodied Carbon in Construction Calculator (EC3)

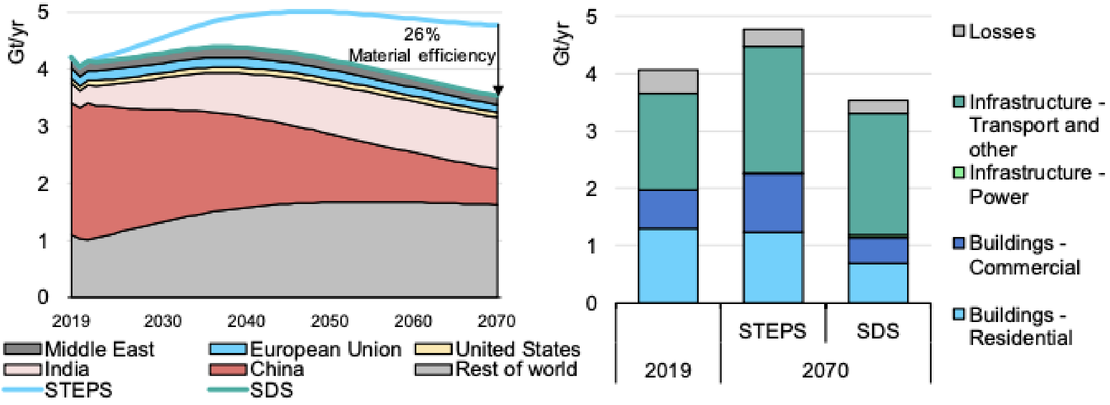
Figure 4.9 Global steel production by region and end use, 2019-70



IEA 2020. All rights reserved.

Notes: STEPS = Stated Policies Scenario. SDS = Sustainable Development Scenario. *Other* includes metal goods, domestic appliances and food packaging. Losses is equivalent to scrap generated in the semi-manufacturing and manufacturing stages.

Figure 4.15 Global cement production by region and end use, 2019-70



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Notes: STEPS = Stated Policies Scenario; SDS = Sustainable Development Scenario. Losses represent onsite construction waste and other losses throughout the value chain.

Material efficiency gains have the potential to reduce global cement demand substantially, notably in China and the advanced economies.

Global production forecasts for steel (top) and cement (above). Source: IEA (2020)

The combination of steel and concrete can perform incredibly well in structural terms.[4]

Concrete, and its crucial binding agent, cement, are consumed almost entirely by the construction sector. Steel, by contrast, is used in all sorts of manufactured goods.

By mass, concrete is roughly 10-15% cement (depending on its specification). The other components are aggregates such as sand, gravel and crushed stone, plus water and chemical additives. The cement produces most of the emissions.

The bar chart, right, shows that in 2019, the global construction industry used around 4.1 Gt of cement. As well as being used in concrete, cement is a crucial component of mortar.

The graph shows that around 31% of the world's cement went on residential buildings; 17% on commercial buildings; 42% on infrastructure; and 10% is lost or wasted.

According to the World Steel Association (WSA), construction uses 52% of the world's steel products by weight – around 0.92 Gt out of the total 1.77 Gt in 2019. To make those products, 1.87 Gt of crude steel was used. Somewhere between crude steel production and the finished steel outputs, there was a loss of about 0.4 Gt (~21%). This is shown on the right hand side of Fig. 4.15, above.

Of the finished steel products that went to infrastructure, almost all of it went towards transport infrastructure (e.g. rail tracks and bridges). This graphic shows the WSA's estimates of the final uses of steel globally.

The cement industry was responsible for around 2.5 Gt CO_2 of emissions in 2019, or about 4.2% of all sociogenic greenhouse gas emissions. (See the graphic at the start of part 7, the second row.)

The iron and steel sector produced a total of 3.6 Gt CO_2 of emissions in 2019.

Assuming all end-uses for steel have the same carbon intensity, the iron and steel that goes to the construction sector produces about 1.9 Gt CO_2 emissions annually.

Why do cement and steel manufacture for the built environment produce so much greenhouse gas emissions?

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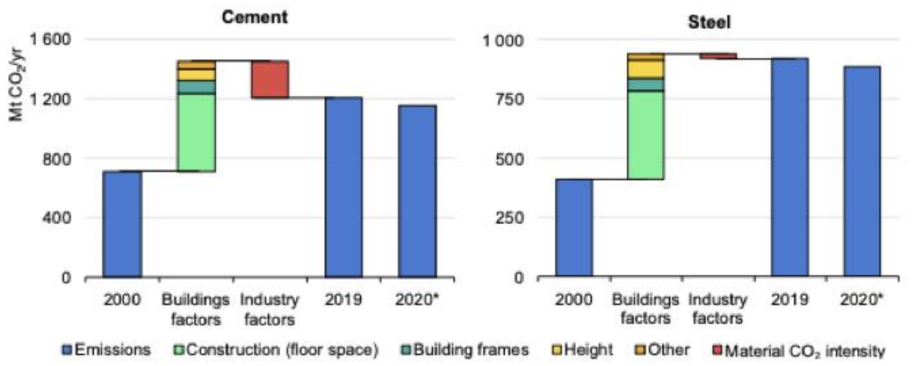
[4] On the other hand, if they are mis-specified or under-engineered, or if substandard materials are used to save on costs, over-confidence in these materials can be deadly, as shown by appalling cases of collapsing buildings and infrastructure.

Figure 4.20 Decomposition of embodied cement and steel sector CO_2 emissions in buildings construction, 2000-20



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* Projected emissions for the year 2020 account for construction activity indicator for the first half of 2020 followed by an assumed economic recovery facilitated by no further major lockdowns for the second half of 2020.

Notes: This figure is based on a logarithmic mean divisia index which compares each influencing factor contributing to embodied emissions in 2019 relative to 2000 to assess their contribution to the change in emissions. *Other* includes increased material use per unit of new floor area related to changes in building code enforcement and construction practices, as well as the effect of existing floor area renovation.

Embedded emissions in the cement and steel used in buildings have increased sharply since 2000, with increased construction and other factors outweighing the effect of a fall in the carbon intensity of both materials – particularly cement.

Source: IEA (2020)

In part, because so much is produced (the 4.1 Gt of cement and 0.92 Gt of steel, in 2019, mentioned above). But the main thing is that each of those tonnes is so emissions-intensive.

The production of 1 tonne of cement emits 0.5-0.6 tonnes of CO_2, according to the IEA. Steel is even worse: for each tonne of finished steel products, on average 2.0 tonnes of CO_2 emissions are dumped into the atmosphere!

Estimates of the emissions from steel and cement manufacture are shown in the table below. "Process" emissions are those that come from the immediate chemical reactions that take place during production. They are distinct from energy-related emissions, e.g. from electricity, or from direct fossil fuel combustion.

Estimated CO2 emissions from the manufacture of cement and steel

Global totals for 2019	**Cement**	**Steel (construction sector only)**
Total world output	**4.1 Gt cement**	**0.9 Gt steel**
Process emissions	*1.6 Gt CO2*	*0.2 Gt CO2*
Energy-related emissions	*0.9 Gt CO2*	*1.7 Gt CO2*
Total CO2 emissions	**2.7 Gt CO2**	**1.9 Gt CO2**

Source: the author / IEA

Cement is usually made by heating limestone (calcium carbonate, $CaCO_3$) in a kiln with other minerals, such as clay, so that it breaks down into quicklime (calcium oxide, CaO) and CO_2. This is called calcination (or decarbonation), and produces clinker as an intermediary product. The CO_2 process emissions of cement manufacture are those from calcination.

The heat to produce clinker is incredibly energy-intensive, and for reasons of economy tends to come from burning coal. Those energy-related combustion emissions (categorised as CO_2 FFI), alongside other processes that use electricity – such as grinding, milling and loading ingredients – comprise the other one-third of cement's CO_2 emissions.

The *weight* of cement's CO_2 process emissions comes from the quicklime that goes into cement manufacture, whereas the weight of cement combustion emissions comes mostly (~73%) from oxygen in the air. (See also Appendix 3.)

Steel production is dominated by energy-related emissions (89%) – although some process emissions come from the use of lime fluxes, graphite, and ferroalloy production. There are many manufacturing pathways, but the main energy-related emissions come from heating a blast furnace to produce molten pig iron at temperatures of up to 1400-1500°C. Most steel manufacture uses coal to provide that heat.

Global cement production nearly doubled from 1.7 Gt in 2000 to 3.3Gt in 2010, growing to 4.1 Gt in 2019 (United States Geological Survey). As you would expect, annual CO_2e emissions due to cement manufacture over the 2000-2020 period have also almost doubled. Steel emissions have more than doubled too.

Crucially, the doubling of both concrete and steel emissions since 2000 has massively outweighed some emissions-saving changes in their manufacture.

This is reflected in the bar charts above, which show the embodied CO_2 emissions of the cement and steel content of only *buildings* construction, in 2000 and 2019. The IEA's decomposition analysis shows the proximate drivers of that growth dominated by demand for more floor space. The red bars show emissions savings per tonne of output – moderate for concrete, tiny for steel. (Projections for 2020, made before the Covid pandemic, are also included.)

The expansion of cement's greenhouse gas emissions footprint since 2000 is almost entirely due to construction in China (see part 4).[5] Steel's carbon footprint enlargement is also mainly driven by demand for steel in China, both for construction and other manufacturing.

7.3 Cement recarbonation

One further point about cement is that it also has an important role as a carbon *sink*. Cement re-absorbs CO_2 from the atmosphere like a sponge, during curing, through a process called cement carbonation or recarbonation. CO_2 in the air recombines with calcium hydroxide ($Ca(OH)_2$) in the

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[5] See the IEA web site

cement to form calcium carbonate ($CaCO_3$) – i.e., limestone, the main production ingredient of cement. Recarbonation occurs with concrete, or in any similar cementitious material.

But this re-absorption happens *very slowly indeed*: it is thought that 10-30% of cement's production emissions are typically reabsorbed over the next 50-100 years. So just using more cement is hardly a carbon-capture solution.

Carbonation happens from the surface inwards, and the amount of CO_2 reabsorbed depends on the surface area and physical characteristics of a cement-containing material. For example, carbonation is reduced by surface coatings such as paint. Cement in demolition waste carbonises quicker, so long as it is above ground, because more of its surfaces become exposed to air.

However, when carbonation happens in built structures, it has the disadvantage that, over time, it can compromise the structure of cement-based materials – causing cracking, for example, and the eventual rusting of steel rebar.

Carbonation increases as built cement stocks increase – and is greater if a cement structure remains in place for longer. By one recent estimate world cement carbonation has risen from an average of 0.07 Gt CO_2 per year in the 1960s, to an average of 0.7 Gt CO_2 per year during the decade 2010-2019. A separate study calculated that, by 2019, about 21 Gt CO_2 had been absorbed into cement produced between 1930 and 2019. The 2019 cement carbonation sink alone was roughly 0.89 Gt CO_2, about a third of the cement-related emissions for 2019

However, a more apt way to look at it is that the quantity of cement emissions *from new construction alone* in 2019 was double the uptake of CO_2 by the world's entire accumulated cement stock.

The comparatively high rates of cement carbonation simply echo the devastating extent of *historical* cement-related emissions. They certainly do not stand in cement's favour from the perspective of decarbonising the built environment.

7.4 Roads

Finally, I will touch on the material footprint and carbon footprint of roads and their associated infrastructure – also important components of the contemporary built environment.

Asphalt road surfaces comprise asphalt concrete (AC, commonly referred to as asphalt, tarmac, or bitumen macadam), which consists of aggregates of a given size grade (sand, gravel), bound together with heated bitumen. Bitumen is a semi-solid form of petroleum found naturally, or manufactured, which, confusingly, is also called asphalt. Typically, AC is about 95% aggregates to 5% bitumen binder.

The world's total material stock of asphalt concrete was estimated by researchers in 2015 at around 115.5 Gt.[6] In 2013, about 18 Gt of the stock of asphalt concrete were contained in roadways in the US, according to the US National Asphalt Pavement Association.

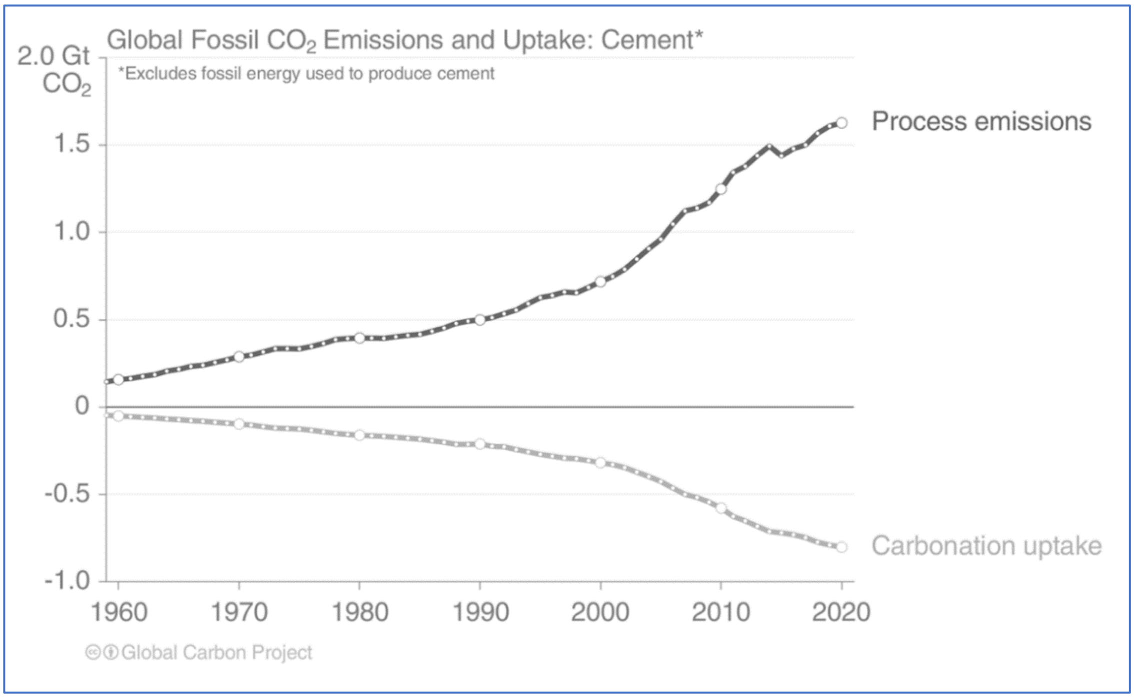
Global consumption of asphalt concrete was estimated in 2016 at about 2.1 Gt per year,[7] for new construction, plus large amounts of repair, and maintenance related to subsurface infrastructure such as water pipes and communications cables.

Naturally, the ratio of asphalt cement used in new road construction versus maintenance varies geographically, according to the relative volumes of new road-building versus legacy stocks.

A recent case study of road construction in Vienna, Austria, for example, found that in the period 2011-15, road maintenance comprised ~58% of road construction mineral inputs; maintenance of subsurface infrastructure was the cause of a further ~32%; whereas newly built roads consumed only ~10%. (See graphic on the next page).

Of course, many roads are not made of tarmac. The structure and sub-structure of tarmacked roads also depends on the situation: for example, urban roads will often be supported by ancillary structures made of reinforced concrete.

In terms of greenhouse gases: a recent case study of the construction of the La Abundancia-Florencia highway in Costa Rica estimated that the direct and indirect embodied emissions from the construction of the road surface,



Source: Pierre Friedlingstein et al. (2022) / Global Carbon Budget 2021

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[6] According to a study I quoted in part 4 (Dominik Wiedenhofer et al, 2021)

[7] According to another study already cited (Barbara Plank et al, 2022)

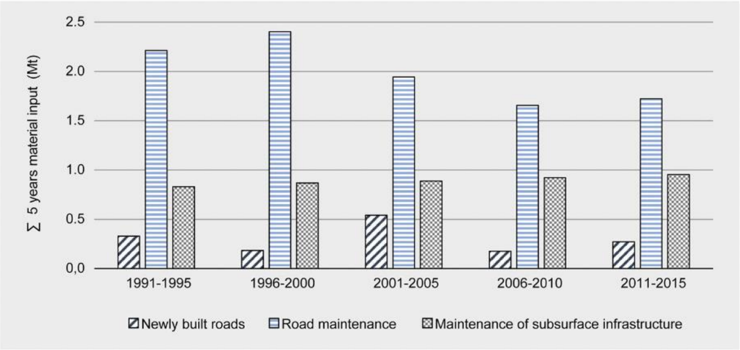

FIGURE 5 Five-year sum of mineral road construction material input caused by road construction and maintenance as well as maintenance of subsurface infrastructure networks (pipes and cables). Underlying data used to create this figure can be found in the Supporting Information S2

Road construction & maintenance material use in Vienna. Source: Andreas Gassner et al (2020)

consisting of hot mix asphalt concrete, was 65.8 kg CO$_2$e per lane per kilometre. This does not include subsequent maintenance and upkeep.

Another 2017 case study of the area inside the 5th Ring Road in Beijing (~670 km^2) estimated that, on average, around 73% of lifecycle emissions were due to the use of concrete in large urban ancillary structures such as bridges, and other cement products such as pre-cast raised kerbs. Emissions during the production stage of the average road were 1,850 tonnes CO$_2$e/km across the study area. Emissions during a lifetime of maintenance were 1,760 tons CO$_2$e/km. The net contribution of recycled materials to these sums was -200 tonnes CO$_2$e/km.

All these embodied emissions are besides the *induced* carbon load associated with a greater use of private transport on roadways. Tarmac roads and reinforced concrete flyovers can be reserved for pedestrians, cyclists and e-scooters, but that does not usually happen. Most new roadways go to private motor vehicles and haulage traffic.

That induced carbon load (classified by researchers under transport emissions) is both embodied in the means of transportation, and operational in the use of fuel. For the time being, motor vehicles mostly still run on fossil fuels.
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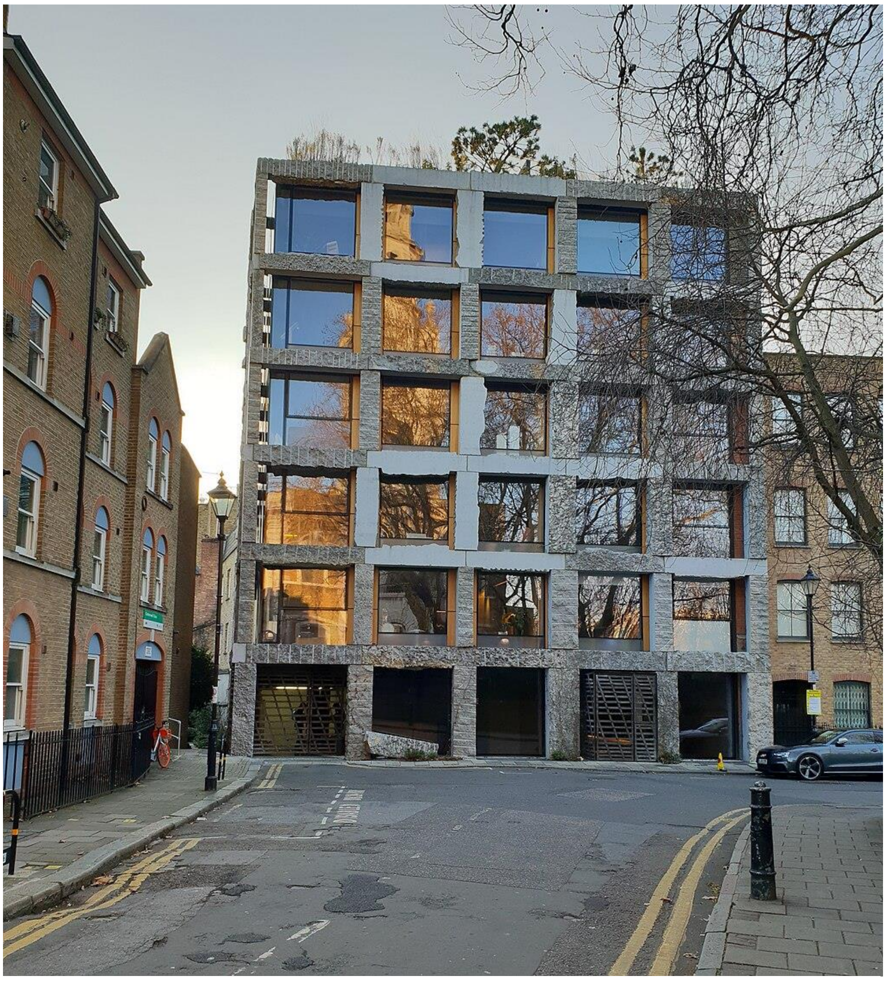
Setting aside heavy goods vehicles and looking just at cars: for an average 200,000 km of lifetime mileage, emissions are around 36 tonnes CO$_2$e per vehicle, according to the IEA in 2021.

But even if an electric vehicle (EV) is run entirely on renewables (for now, a big if), its average embodied emissions are still around 8-9.5 tonnes CO$_2$e per vehicle lifetime, compared to around 6 tonnes CO$_2$e for a fossil-powered car. As and when the carbon footprints of manufacturing motor vehicles decline, those numbers will also move – but again, that seems a long time coming.

In part 8, I will consider how embodied emissions in the built environment can be reduced.

Part 8. Decarbonising embodied emissions



15 Clerkenwell Close, London. Photo by Chris Wood / wikimedia commons

There are two main ways to cut greenhouse gas emissions from construction, that will be covered in this part. These are:

a. Demand reduction: mainly, reducing the quantity of unnecessary new construction. This means extending the lifetime of buildings and infrastructure, and reducing waste.

b. Decarbonising construction: mostly, reducing the embodied emissions in construction materials. The prime targets here are the embodied emissions of cement and steel.

One way of decarbonising construction is to replace those existing construction materials wholesale, with alternative, lower carbon alternatives. I will consider some of those alternatives here, including so-called bio-based materials.

A second way to decarbonise construction is to engineer down the use of cement and steel – for example, by using them in conjunction with low carbon alternatives, and by using them more efficiently through changes in design and through waste reduction. A third method is recycling.

Another approach to reducing embodied emissions in construction – unsurprisingly the dominant focus for capital-intensive industry – is to try to decarbonise the production of existing construction materials. The focus is on cement and steel, but other high-energy materials, such as glass, also need to be decarbonised.

Reducing the carbon intensity of cement and steel is challenging: their production emissions are considered "hard to abate" – especially process emissions that comprise two-thirds of cement production's footprint. This area is full of technological innovators seeking to insert themselves into essential supply lines of construction.

In this part, I begin with *demand reduction*: the avoidance of unnecessary construction and demolition, and the potential for re-using materials (section 8.1); then the importance of material efficiencies (section 8.2). Then I look at ways of *decarbonising construction*: some low carbon materials (section 8.3) and controversies around plant-based materials and their potential benefits in terms of carbon sequestration (section 8.4). After that, I provide an overview of steps to decarbonise cement and concrete (section 8.5) and steel (section 8.6), and the projected role of carbon capture and storage (CCS) in achieving those aims. Then I turn to some benchmarking initiatives by architects (Section 8.7). I have commented critically on the IEA's approach to decarbonisation in Appendix 5.

All in all, construction should in future have a qualitatively different material relation to the world. Not only does it need to be less energy- and material-intensive, but also those same principles need to extend to the operational use designed into buildings at the commissioning stage (see parts 9 and 10). And construction should proceed on the basis of *enhancing* ecological reconstruction and wellbeing.

8.1. Avoiding unnecessary new construction and demolition, and re-using materials

Avoiding unnecessary new construction and demolition needs to be the starting point for decarbonising the built environment. This applies to buildings and to infrastructure.

Reducing construction means that, as far as possible, existing structures should be retained for use – retrofitted and updated as necessary, in order to extend their lifetime of use. This means avoiding demolitions, which create needless demand for new construction, and waste already-existing embodied materials and previously imposed environmental burdens. (This is to say nothing of deliberate destruction of buildings and infrastructure in wars.)

In the words of Carl Elefante, former president of the American Institute of Architects: The greenest building is the one that is already built. The same is true of infrastructure, so long as it works as it should. Instead of new-build, the emphasis needs to be on retrofit, and "adaptive reuse".

According to research by the Royal Institute of British Architects (RIBA) in collaboration with Architects Declare, a 20% reduction in demand for new buildings *globally* could be achieved just by (re)using existing structures better – and this could save "up to 12% of global emissions in the building and infrastructure sector".

Carry the same principle of reuse into construction materials. Avoid construction waste, in favour of deconstruction, reusing materials and construction elements as much as possible ("design for disassembly"). Tap waste streams. Aim for a zero waste, or circular, construction economy.

There are many vanguard initiatives in this vein (for profit, and not) that seek to adapt the principle of reuse to the convergence of ecological urgency and computational possibility. For example, the Dutch group Metabolic, and the cooperative RotorDC, with its waste stream database-cum-marketplace, an eBay of sorts for recycled materials.

The architects' firm Orms has been one leader in the practical development of "materials passports" – intended "to gather and organise data about materials contained within a building", so that they can be effectively harvested for components in the future. Such data would include precise inventory and location data, engineering and performance specifications, and the embodied and operational material and environmental footprints associated with a given component.

At least in theory, this also means that material footprints, and wholelife assessments through to waste disposal and resale, can enter into the design process as active parameters, alongside engineering issues such as building physics, or questions of cost and availability of materials. To this end, architectural and engineering design platforms seem to be trending towards high-level parametric integration, mediating the space between markets and physics.

Of course all of this leans heavily on the quite possibly spurious idea that effective technological and market-based interventions can contribute meaningfully to decarbonising construction – especially outside the "value-added"-rich markets of rich countries. Questions remain around the practical extent of such schemes, and the politics of access to markets, platform data and modelling streams.

In any case, these sorts of initiatives indicate possible directions that a green capitalism might take. They are consonant with trends towards "eco-labelling" in certain segments of the global food industry. But they also suggest one aspect of what an eco-socialist transitionary programme might look like, in terms of steering local and global economies in a sustainable direction.

8.2. Material efficiencies in construction

When new construction *is* necessary – which includes retrofit – embodied and operational emissions need to be factored in as parameters from the start.[1]

The dominant high-carbon construction materials – steel, other metals, concrete and glass – need to be used in moderation, and sidelined wherever possible.

The carbon intensity of construction has come down in recent years. However, decarbonisation of existing styles of construction, to anything like the necessary extent, is likely to be a long time coming.

So long as established construction methods and economies prevail, whatever shifts do occur in the *relative* carbon-intensity of construction will most likely continue to be swamped in *absolute* terms by the volume of construction, at least in the short-to-medium term.

Priority must be given to three things: "build light", aim for materials efficiencies, and use low-carbon construction materials and processes.

"Build light" is an overall ethos. It involves constructing only what is necessary. Building elements can be specified to be literally less heavy, and require less structural support – since structural strength often comes with more embodied emissions.

Materials efficiencies: embodied carbon can be reduced by engineering down the use of construction materials, and especially high-energy materials. Using standardised material sizes can help reduce waste.

So-called "lean" design and construction techniques combine both of these approaches – achieved through changes in design, so that buildings and infrastructure are not needlessly over-designed or over-specified; and through minimising waste during manufacturing and construction.

In theory, off-site fabrication and short-term "flying factories" at construction sites can help to improve material efficiencies and reduce waste. However, designing manufacturing processes and supply lines on a project-by-project basis comes with its own challenges.

Materials like timber that do not require extra finishing treatment – they are "self-finishing" – are also good, because they are more easily deconstructed and recycled in the future. It is also preferable to avoid adhesives for the same reason.

8.3. Low-carbon materials

Worldwide, almost all of the embodied emissions of buildings come from the manufacture of building materials, as described in part 7. Some of the best low-carbon materials are "traditional" ones such as wood, stone and rammed earth. These options are far more practical than they may seem, and more viable in engineering terms than a habituated fetish for fossil-fuel-heavy products might allow.

Traditional construction materials can be a route by which construction and design work can incorporate and learn from local sources of knowledge, about what materials work well locally in relation to factors like climate, and what is available. Engaging and elevating local craft skills is of value in its own right.

Traditional construction materials and methods are usually less capital-intensive than industrial ones. This may well make them less profitable and less worthwhile inputs

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[1] See Feilden Clegg Bradley Studios' whole life carbon review tool

for capital. They may or may not require higher absolute inputs of labour.

By contrast, the type of capitalist housebuilding dominant in the UK is very labour-intensive. Here, profitability for capital is assured by monopolies on land, poor construction standards, favourable access to low interest rates and political favouritism.

But at the level of social use-values in the locales of construction sites, plentiful labour-content can provide a source of employment. In many places, employing and/or training people in traditional construction methods, updated as necessary, can furthermore be a valuable source of local worker-led autonomy.

Local materials can give construction a degree of local texture and specificity it might otherwise lack. Where a small emissions footprint is the aim, less transport can also be a plus. Transportation is usually a comparatively small component of the embodied carbon of high-emissions industrial materials, but when the embodied carbon of manufacture is cut back, so the transport component becomes relatively more important.

Traditional construction methods can also be used to produce prefabricated components, that have a much smaller carbon footprint than prevailing carbon-intensive materials. Flying factories, close to one or more construction sites, could integrate the benefits of traditional modes of construction with the flexibility of prefabrication.

As with agroecological approaches to farming, the point here is to concentrate the "knowledge intensity" of production, rather than the capital- or carbon-intensity. Ways of providing materials can then be found that are environmentally friendly, but also potentially transferable away from the immediate site of production – and, again, also job-creating, in environmentally sustainable industries.

These are some of the important low-carbon materials (not including substitutes for cement, concrete and steel, that are covered in sections 8.5 and 8.6 below.)

□ *Rammed earth* is traditionally used with earth excavated at, or close to, the construction site. It is a good insulating material, possessing tremendous thermal inertia, i.e. its thermal massing retains warmth, or insulates against it, very effectively. It is also available as a prefab, prepackaged, low-carbon means for load-bearing construction.

□ *Stone* is another very effective, and ancient, structural material. A good example of its use is the limestone used in the load-bearing exoskeleton of the Stirling Prize-shortlisted 15 Clerkenwell Close in London. Its embodied carbon footprint is apparently 10% of what it would have been if steel and concrete were used. The cost, too, was a small fraction. The declared embodied emissions for the whole building are 335 kilogrammes of carbon dioxide equivalent per square metre ($kgCO_2e/m^2$).

□ *Hemp* is perhaps the most exciting traditional construction material – one that could be hugely beneficial to bringing down levels of embodied carbon, for example as insulation or in the form of hempcrete (see below). It grows quickly, locking up biogenic carbon, making hemp itself carbon negative.

Also in hemp's favour is that it grows in a wide diversity of temperate climates; it can be grown in untilled soils; and it is harvestable within just a few weeks. As a plant-based material it has high carbon-sequestering capacities through the rapid growth phase, and a rapid rate of throughput from atmospheric CO_2 to a stock of biogenic carbon.

According to a recent study by the Biorenewables Development Centre at the University of York in the UK, industrially-grown hemp crops can sequester up to 22 tonnes of CO_2 per hectare annually – "more than any other crop or woodland". (Although note that the crop's net emissions will be a bit less than that, due to emissions associated with cultivation and processing.)

A serious concern about the widespread use of hemp might be the risk, as with biofuels, of hemp cultivation displacing food agriculture. This is a disadvantage, compared to non-biological, non-renewable materials such as limestone, which are relatively abundant and relatively independent from food markets.

However, also on the plus side is that hemp's root system is extensive, and it tends to suppress weed growth, which means it can help improve degraded soil structures, remediate polluted soils, and boost subsequent crop yields. As a rotation crop it can be used as a "break crop" for all these reasons, to suppress weeds and pests, and additionally support growers' *economic* sustainability.

□ *Hempcrete*, made by combining hemp stalks' inner core with water and lime, is a bit of a wonder material. Like rammed earth, it has great thermal inertia. It is highly flame-resistant, resistant to pests and mould, biodegradable and breathable – meaning that it naturally regulates a building's temperature and humidity, which improves thermal comfort.

Mixed on-site, hempcrete is readily mouldable into large, lightweight bricks, or applied as a surface render. It can also be manufactured into prefab wall panels with very little expenditure of energy.

Hempcrete is comparatively strong, but has only about 5% of the compressive strength of residential grade concrete – so walls made of it require the addition of another loadbearing material such as timber or CLT (see below). But it weighs only about one-seventh as much as concrete. It is well suited to construction in areas at risk of seismic activity, because it is resistant to fracture under movement. Hempcrete can also be *reused* if milled and then rehydrated.

On the downside, like cement, hempcrete produces process emissions in the lime binding stage. These far outweigh other emissions from hempcrete production, such as energy-related emissions. The process emissions tend to be about equal to the carbon sequestered during the hemp's growth phase, so cradle-to-gate hempcrete is roughly carbon neutral. Additionally, hempcrete, also like cement, re-absorbs CO_2 during the remainder of its lifecycle, potentially around 40% of what was produced when it was made – so that cradle-to-grave emissions are carbon negative.[2]

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[2] For a $1m^2$ area of wall made of hempcrete, offering a typical level of insulation (R-20 grade, with a heat transfer coefficient of 0.27 Watts per meter-square Kelvin), process emissions come to about 36 kg CO_2e. Typically, this is roughly equal to the carbon sequestered during the hemp's growth phase.

□ *Bamboo* can have a tensile strength similar to steel, and its compressive strength is double that of concrete! Bamboo is also incredibly fast-growing, making it great for carbon sequestration. (See section 8.4 below.) It is also lightweight – and cheaper than concrete, a big advantage, especially in poor countries.

Indeed, bamboo is already widely used as a building material globally. According to a recent (2023) Global ABC report on building materials, bamboo (like hemp) is a promising material for use in areas prone to earthquakes, and also durable during floods. All round, it is ideal for designing climate-resilient buildings. It can be used directly, in its raw, unfinished state.

□ *Engineered timbers* such as cross-laminated timber (CLT) (also termed “mass timber”) are a recent and important innovation. Like hemp, bamboo, or other timber products, CLT contains whatever biogenic carbon was fixed into it during its lifetime as a plant.

Like bamboo, CLT is capable in many instances of replacing structural steel and reinforced concrete. It has a high strength-to-mass ratio, and can be used for walls, floors, and ceilings. It can be deployed alongside hempcrete to give load-bearing strength, or alongside steel and reinforced concrete as a partial replacement.[3] CLT can also be made out of bamboo.

CLT has been used to impressive engineering effect in recent prestige buildings in the UK: for example, the Stirling-shortlisted Cambridge Central Mosque (embodied emissions, 844 kgCO$_2$e/m^2) – and also here and here. You can even construct highrise buildings out of CLT (albeit with a concrete base, elevator shaft and stair wells).

As with hemp, the sequestration potential of CLT can be increased dramatically by using high-yield, fast-growing crops.

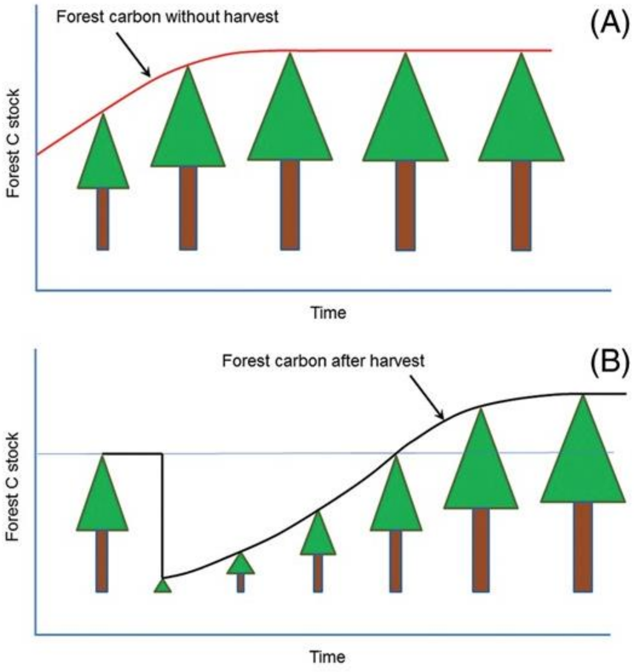
By-products of production, such as off-cuts, can also be used for long-term carbon sequestration as small-scale timber products.

It is also important that petrochemical-based glues, chemicals and coatings used in wood products are phased out and replaced with bio-based alternatives. According to Global ABC, as well as reducing embodied emissions, this could enhance mechanical performance and reduce the unintended movement of heat and damp through structures. i.e. improve hydrothermal properties.

8.4. Plant-based materials and carbon sequestration

Bio-based materials such as hemp and timber can provide very good alternatives to classical industrial building materials like including steel and concrete. They have the additional benefit of storing the carbon accumulated in them during their growth phase in the form of biogenic carbon. This allows for what the Global ABC, the UNEP-IEA building strategy document, calls “carbon pool replenishment”.

Figure 2.



Source: excerpted from Michael T. Ter-Mikaelian et al (2015). “Forest carbon” here means the total level of sequestered biogenic carbon in a forest.

However, the advantages here can also be overstated and misleading. Much depends on what type of biological growth is involved, the rate of growth – and, most importantly of all, whether the materials are sustainably sourced.

In the case of timber, global rates of deforestation presently exceed rates of regrowth. Moreover, the international *trade* in timber shows a marked flow of wood resources from poor to rich countries. Rich countries such as Germany and the USA import wood from the global south for reasons of cost efficiency, even in the face of ample, comparatively untapped wood resources within their own borders.

Hemp, as I have said, grows very quickly. It sequesters carbon rapidly, and provides all sorts of other agricultural benefits. Bamboo too grows very fast indeed. As cultivated crops, *so long as the cultivation is otherwise ecologically sustainable*, those can be win-win. However, most trees grow slowly.

Dead timber used in construction obviously also stops absorbing CO$_2$. A living tree would have continued to grow and absorb more CO$_2$ from the atmosphere during the remainder of its life, and the only net gain in carbon sequestration occurs when a new tree grows in the place of the felled one. Young tree saplings take a while to get going

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Over 60-100 years of use, hempcrete re-carbonation can re-absorb up to around 40% of the original process emissions, according to the study just cited. So hempcrete’s “cradle-to-grave” carbon footprint ranges up to, potentially, the sequestration of about 15 kg CO$_2$e per m^2 for the same R-20 piece of wall.

Different lifecycle emissions of hempcrete are associated with different densities of “mix” and different “model” estimates for process emissions. See here for a useful comparison.

[3] See pages 34-35 in the 2023 Global ABC report.

with their carbon fixing. However, older trees also slow down. (See the illustration on page 53.)

"Don't worry, we'll grow trees to suck up the carbon" is an increasingly common theme from politicians seeking to delay effective action on climate change. And this has led to disputes about how to measure the real effect of afforestation.[4]

The point, in my view, is that carbon sequestration has an important *time efficiency* component, depending on the speed at which farmed trees, hemp, or other materials grow, and the resultant *rate of throughput* from atmospheric CO_2 to biogenic carbon to a biogenic end-product. Again, one of the many attractions of bamboo and hemp is that they grows *fast*.

The Global ABC cites evidence that in China bamboo sequesters carbon 30-40% faster per hectare per year than a tropical mountain rainforest, or a fast-growing variety of fir, and *2-6 times faster than average sequestration rates for forests* in China and globally.

But of course forests also have tremendous ecological value in and of themselves: they are complex ecosystems and carbon sinks that should be allowed to thrive. They are not just a "resource" for wood products or for burning, or a "dividend". In my view, there should be *no* farming of existing old forests.

Timber products should only come from *farmed* timber. And to be truly sustainable, planted forests cannot simply be monocultures, but must be thriving, if transient, ecosystems in their own right.

But Interpol estimated in 2021 that 15-30% of internationally traded timber was harvested illegally. And, according to the UNEP, illegal logging is responsible for up to 90% of tropical timbers felled in the world's main tropical forest regions – the Amazon basin, Congo basin and south-east Asia.

There is presently a big push globally towards bioenergy. In my opinion, there is *no defensible reason to burn wood industrially*: cultivated timber should *only* go into durable products. Household wood combustion should also be phased-out.

Moreover, there needs to be a massive global effort at rewilding, including reforestation and mangrove restoration, to re-establish ecologies and carbon sinks lost to economic development. Much of that needs to happen in rich countries. Globally, rewilding should centre the needs of land-based and indigenous peoples, and not become a further tool of land-grabbing and greenwash.

Meanwhile, the aim for timber products and other bio-based materials should be to *maximise their useful life*, as with all useful materials. *That is why bio-based materials are good for construction*: buildings (and infrastructure) tend to be around a long time – and a long lifecycle of use should also be the norm, in order to minimise new construction.

The counter example would be timber used for cheap, non-durable furniture. Moreover, in the really existing market of timber products, Ikea can get away with being complicit in illegal logging of Romania's old growth forests.

The sequestration potential of *most* CLT is clear. It will be improved if the logging and CLT industries decarbonise their sources of energy. They also need to clear forest residues – a large source of greenhouse gas emissions. Crucially, however, *bamboo*-based CLT is at present a net *producer* of emissions, due to the exceptionally high emissions associated with its manufacture.[5]

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[4] I said that the only extra net gain in carbon sequestration occurs when a new tree grows in the place of the felled one. This is seeing things according to a "debt-then-dividend" (or "carbon repayment") model. However, the other way to look at it is that you *start* with the dividend; then once you fell a tree you are simply back to zero.

These are two different carbon accounting conventions – and they are most salient when applied *burning* biomass, and releasing biogenic carbon into the atmosphere. However, they are also relevant to the stock and flow of timber-based products. Sustainable forestry – amongst other things – is the practice of managing the "flux" in the stock of carbon in a forest over time. In carbon accounting terms, the gains versus losses are recorded under the category "Land Use, Land Use-Change and Forestry" (LULUCF).

But whichever way you look at it, the "flux" of biomass growth is hardly instantaneous. Bamboo produces wood much quicker than most other plants: for most timber products, you might expect forest regrowth to return to pre-harvest levels ("carbon sequestration parity") after around 40 years.

Crucially, the forest by-products of logging also need to be removed, in such a way as to avoid decay on land, which itself releases methane – and to reduce the risk of forest fires. (Note that both living and dead trees transport methane into and out of the atmosphere.)

[5] A recent literature review compiled the reported cradle-to-gate emissions of some CLT manufacturers, based in Europe, North America, and Australia (that is, the emissions flux from growth through manufacture, to point of sale). The average declared sequestration was -643.6 $kgCO_2e/m^3$ of CLT. That is, the CLT has a negative carbon footprint – when also taking account of the other, energy-based emissions that arise during manufacture.

However, a better way to assess the sequestration potential of bio-based products like CLT, is to look at manufacture in the context of land-use; and to consider the *whole life-cycle*, cradle-to-grave. In particular, it is important to consider what happens to forest residues after logging, and what happens to timber products at the end of their life – forest residue decay and land-fill decay are both a significant source of greenhouse gases, including methane.

One recent study cited in the Global ABC report does both of these things. It modelled a 100-year lifecycle for CLT produced in the Southeastern United States, from high-productivity pine plantations, and found that net greenhouse gas emissions could be as low as -1,445 tonnes CO_2e per hectare (100m x 100m). This modelling is based on *current modes of CLT production*: it assumes in this instance that the drying kiln is powered by gas, that all vehicles are powered by diesel, that forests are "clear cut", and that all harvest residues are left on the forest floor to rot. CLT recycling rates are presently low, and the study models 50% of manufactured CLT going to land-fill at the end of a 60-year lifetime of use.

(It is also common – because economical – for timber mills and processing plants to generate heat by burning wood residues and cut-offs. This releases more greenhouse gases than burning fossil fuels – combustion of dry wood produces more CO_2 combustion emissions per unit energy out than coal does. Use of wood residues increases emissions compared to the use of gas.)

All of which indicates that the sequestration potential of CLT could be improved yet further by reducing emissions at all those stages in the lifecycle – and that timber plantations for CLT should be cultivated in more ecologically beneficial ways.

In the case of bamboo CLT, the high rate of carbon sequestration tends to be offset, for the time being, by a very emissions-intensive process of fabrication, when compared to other forms of engineered timber. The same Global ABC report outlines some of what is required in the case of bamboo CLT – carbonisation, high-temperature air drying, synthetic glues and anti-mould treatments. According to recent modelling, that can mean that the CO_2 emissions during the manufacturing stage for bamboo CLT

Optimistic claims about wood, bamboo and CLT also often fail to confront wider issues around land use.

The authors of one paper claim that 90% of the world's new urban populations to 2100 could be housed "in newly built urban mid-rise buildings with wooden constructions", instead of using steel and concrete, saving 106 Gt of CO_2 during those 80 years.

On their calculation, that would require more than doubling farmed forest plantations – adding 1.49 million km^2 to the current 1.32 million km^2 by 2100. That would also mean encroaching on other forested areas that are presently unfarmed – in order to ensure no "major repercussions on agricultural production".

However, a Greenpeace representative quoted in the Guardian points out that additional forested area for construction timber would better come at the expense of meat and dairy farmland, instead of further trampling old and biodiverse forests with monocrop plantations. That criticism is on-point: for the authors, unfarmed forests seem to be available for new plantations, whereas agriculture and other forms of land-use can only ever be ratcheted outwards.

The Global ABC notes that areas available for bamboo cultivation are already scarce, given the existing land-use pressures from agriculture and (to a lesser extent) housing.

Wherever and however bamboo or CLT are farmed, what happens to their biogenic carbon at end-of-life is also crucial: *forget the gate, where is the grave?* Is the wood re-used, keeping the carbon locked away (100% sequestration)? Is it burned, releasing the CO_2 back into the atmosphere (0% sequestration)? Or does it rot in land-fill, releasing methane?

Bamboo, CLT, and similar bio-based construction materials – and timber furniture – should at least impose no net ecological harm. They should *only* be considered viable as mass-market goods when the bio-based materials they are constructed from are harvested in an environmentally positive way. They should also be built to last, within a holistically planned human ecology – not (as with Ikea furniture) produced as a throwaway quick fix.

Forestry residues should be removed, and/or harmful emissions suitably minimised.

In short, carbon-intensive construction materials need to be supplanted with ones that are as close to zero-carbon as possible, and construction materials as a whole used in the most efficient ways possible. But equally, the virtues of bio-based products, and their time-horizons, should not be exaggerated, or abstracted away from the full breadth of social and ecological concerns. Nor should ecologies and biologies simply be regarded as physical materials to be taken at will.

In any case, the entire rationale on which societies "resource-ise" materials from the natural world needs in time to be retrofitted, if not demolished and rebuilt from scratch.

8.5. Decarbonising cement & concrete

In the case of decarbonising cement and concrete, there are possibilities to change the way cement is made. One way is to change the recipe. Brimstone Energy, a US-based start-up, replaces limestone with calcium silicate – which they say avoids the process emissions associated with limestone, and reduces kiln temperatures, making electric kilns feasible.

Another way is through material efficiencies. For example, you can make cement with a lower proportion of clinker, the most carbon-intensive component. Up to 50% of the clinker can be replaced with limestone and calcinated clays. Another alternative is to introduce graphene into the cement mix, to make it stronger and permit a reduced clinker component.

Seratech, a start-up spun out of research at Imperial College London, combines carbon capture with cement manufacture to produce a nominally "net-zero" cement. Their technology removes industrial CO_2 emissions from flues, and uses that to produce carbon-negative silica, which can be used in place of cement. When that is mixed with Portland cement, the negative emissions in the silica are said to balance the positive emissions from the Portland cement, to make an overall "net zero" cement mix.

In the long term, direct electrification of cement kilns should also be possible. That will not reduce process emissions, but would allow the most energy-intensive part of production to be decarbonised.

There are also ways to *grow* cement-like materials biologically, that seem to be free of many of the sustainability and land-use problems that arise with plant-based products.

Biomason, a US company, makes a product called Biocement, or biogenic cement. The company says it uses marine microorganisms to mimic the process of calcination that makes coral. In this way the company "grows" limestone in an effective reversal of cement production. They can do this either in-situ, or to produce pre-cast units.

When used underwater, this process sources its ingredients from seawater, "for propagative calcium carbonate precipitation", which gives underwater structures "self-healing abilities". That sounds great.

Biomason partners with other companies, licensing Biocement for particular uses – for example, BioBasedTile, a Netherlands-based company making pre-cast concrete tiles from recycled waste and biocement. The tiles "grow" in less than three days, and are intended for use on facades, interior walls and flooring. The end product consists of ~85% recycled granite and 15% biologically grown limestone. The

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may end up comparable to those of steel on a per kilogram basis. Those emissions produced during the manufacturing stage are only offset ~35% by the biogenic carbon sequestered in the wood.

However, bamboo is also lightweight. I cannot find any data comparing the lifetime emissions of bamboo CLT and steel on an end-use basis. For example, if a *lower mass* of bamboo than steel imparts similar tensile strength, then that would reduce its real-world embodied emissions.

Another recent study calculated that, on average, CLT manufacture requires felling about $12m^2$ of forest for every m^2 of a finished CLT building. However, in that study, the length of the trees' growth phase and the time to harvest is unspecified. The same study reckoned that, if all new buildings *worldwide* to 2060 were built of CLT, supplying the timber would require 310,000 km^2 of forest – about 0.8% of the world's "available" forested area of 40.6 million km^2. (The volume of construction required is based on international agencies' forecasts, discussed below.)

company claim their tiles are three times as strong as traditional concrete tiles, weigh 20% less, and have just 5% of the embodied emissions.

Unfortunately, it looks as though Biomason is funded with more socially *destructive* uses in mind: according to their website, the company works "with support from the US Department of Defense" towards the obvious marine applications of this technology, and for land-based uses in "forward operating positions", "where native, non-engineered surfaces prevent safe vertical take-off and landing".

All such uses should be non-proprietary, and available for use in *civil* engineering projects.

A similar but seemingly inferior approach, pursued by scientists at the University of Colorado Boulder, uses microalgae to grow "biogenic limestone". The microalgae capture CO_2 via photosynthesis in the growth phase; this is released again during the calcination process: net-zero as far as the process emissions are concerned.

Apart from cement *manufacture*, there are some indications that cementitious materials, such as concrete, could be artificially and *rapidly* recarbonated with CO_2 after manufacture. Part of the natural curing process of cement involves it reabsorbing CO_2 over its lifetime, as mentioned in Part 7. However, that process is slow when it occurs naturally, and can lead to structural problems when it occurs in an uncontrolled fashion.

Research recently reported in the architectural press, by Tunley Environmental (a sustainability consultancy) suggests two methods of *controlled recarbonation*: (1) injection of CO_2 into precast concrete; and (2) embedding CO_2-rich materials into the concrete mix. They also propose that controlled recarbonation could be performed on waste concrete, before recycling it into fresh concrete as recycled concrete aggregate (RCA). The controlled nature of these processes, they say, would avoid the structural degradation that can result from natural recarbonation.

Noting that the *theoretical maximum* carbonation capacity of cement is 50%, Tunley point out that, were all the world's production of concrete recarbonised in this way, it would sequester around 77% of CO_2 emissions from cement manufacture.[6] Setting aside that *theoretical* figure, they suggest a more modest 17.3% of cement-related CO_2 emissions re-sequestered annually through method (2) above. Again, though, that is if *all concrete produced globally* were recarbonised in this way. So there are plainly practical constraints of scale, and of effectiveness.

In short, controlled recarbonation can presumably play some role. However, it seems *hugely unlikely* that such processes could be applied at sufficient scale to make a meaningful impact, *within the necessary timeframe* for decarbonising the built environment. Indeed, stories like this risk encouraging complacency.

There are also options for changing the way *concrete* is made. Again, a very simple approach is to reduce the amount of cement used to what is structurally necessary. For example, concrete roadside kerbs have very different structural requirements to the high strength grades of concrete used in bridges and skyscrapers.

CarbonCure, a company using similar technology to Seratech, injects captured CO_2 into *concrete* during mixing. This takes advantage of the usually very slow natural process of cement carbonation (recarbonation), producing nano-sized particles of calcium carbonate in the concrete that help to strengthen it.

Perhaps more promisingly, it is possible to make concrete without cement at all, by using a different binder. One example of that is "Earth Friendly Concrete", produced by the Australian materials firm Wagner, which apparently has up to 70% less embodied carbon than regular concrete made with cement.

Earth Friendly Cement has been licensed for use in the new Silvertown Tunnel under the Thames in London. Needless to say, reducing the embodied emissions in the construction of that road tunnel will do nothing to mitigate the much larger energy-based emissions arising from greater induced traffic flow.

And note the word "licensed". While some of these techniques are now operational or close to maturity, they all seem to be based on *closed proprietary systems*.

That is fine, perhaps, for decarbonising cement and concrete production where the technology is available, and where the costs are deemed commensurate to the benefits. But it is highly doubtful that a broader rollout of such technologies internationally could work on that "cost premium" basis.

In my view, the technologies to decarbonise cement and concrete manufacture should not – *and must not* – be subject to intellectual property restrictions.

If it is technically available and economical, then it should be *actually* available to all. As with essential drugs, off-brand "generic" versions must be produced, and made available at a price competitive with, or cheaper than, dirt-cheap bog-standard materials. By subsidy or regulation, that seems to me the only real solution to decarbonising cement and concrete manufacture on a world scale.

The IEA says that these emergent technologies are most unlikely, on their own, to be competitive on price against old-school cement, with its process emissions unabated. For them to become price-competitive, carbon pricing would have to be introduced globally. However, cement is mostly produced locally to where it is used (see part 3), making it hard to police.

8.6. Decarbonising steel

The steel industry now relies almost entirely on thermochemical processes that use coal. Recycling is already a big thing, and producing steel from scrap only requires about one-eighth of the energy used to produce steel from iron ore. But there is not nearly enough scrap to meet present market demand for steel products. Recycled steel only comprises 30% of total global supply.

The international steel industry is focused on reducing CO_2 emissions within the thermochemical paradigm, by

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[6] Based on the reported 2011 emissions, the authors estimate ~2 Gt CO_2 sequestered annually

using "green" hydrogen or biomass, instead of coal, to produce pig iron. The industry talks a good talk about decarbonisation along this route, and so do supportive states.

In Europe there's the HYBRIT demonstration project in Sweden, intended to "demonstrate a complete industrial value chain for hydrogen-based iron and steelmaking", and produce 1.2 Mt of crude steel a year.

China is developing Zhangjiakou as a "hydrogen energy pilot city", with a plan to open a zero-carbon steel plant there. But as a whole, China's steel decarbonisation plans do not go far or fast enough to meet the 1.5°C Paris target.

However, most industrial hydrogen is presently made using fossil fuels, and that is unlikely to change anytime soon. Hydrogen production itself is also incredibly energy intensive. "Green" hydrogen at any scale – or kindred alternative "flavours" of hydrogen – seems a long way off, if indeed they can *ever* be a practical eco-friendly reality.

Biomass combustion, meanwhile, carries its own problems: entailing significant on-site emissions, potentially colonising valuable agricultural land, and encouraging deforestation.

Innovations in steel manufacturing also face large economic barriers – from the capital intensity, long life, and sunk costs of industrial steel-making facilities; and from the low margin, fully globalised, highly competitive international market in steel products. Outside of boutique prestige projects, a universally-applied and enforced carbon price would seem to be necessary to encourage the necessary shifts in the industry at large.

Greening the international steel industry requires not just billions of dollars of investment, but trillions, according to Nathaniel Bullard, writing for Bloomberg. That's *thousands of billions* of dollars, just to get to low-emissions steel, globally.

The main future promise for low-emissions steel manufacture, however, lies further from the status quo: switching from thermochemical processes to electrochemical processes – and in particular, low-temperature electrolysis. This is less capital-intensive than the alternatives, is suited to intermittent power, and produces steel in a single process, so that it does not require further refining.

Crucially, electrochemical processes use electricity, so they can be run wholesale from renewable sources of energy.

However, electrochemical steel production at scale is also still a long way away. Such a widespread shift in technology would seem to require severe economic sanctions, or universally-applied regulations, to become *economically* justified.

Another issue is the centrality, in proposals for decarbonising both the cement and steel industries, of carbon capture, utilisation and storage (CCUS) and/or carbon capture and storage (CCS).

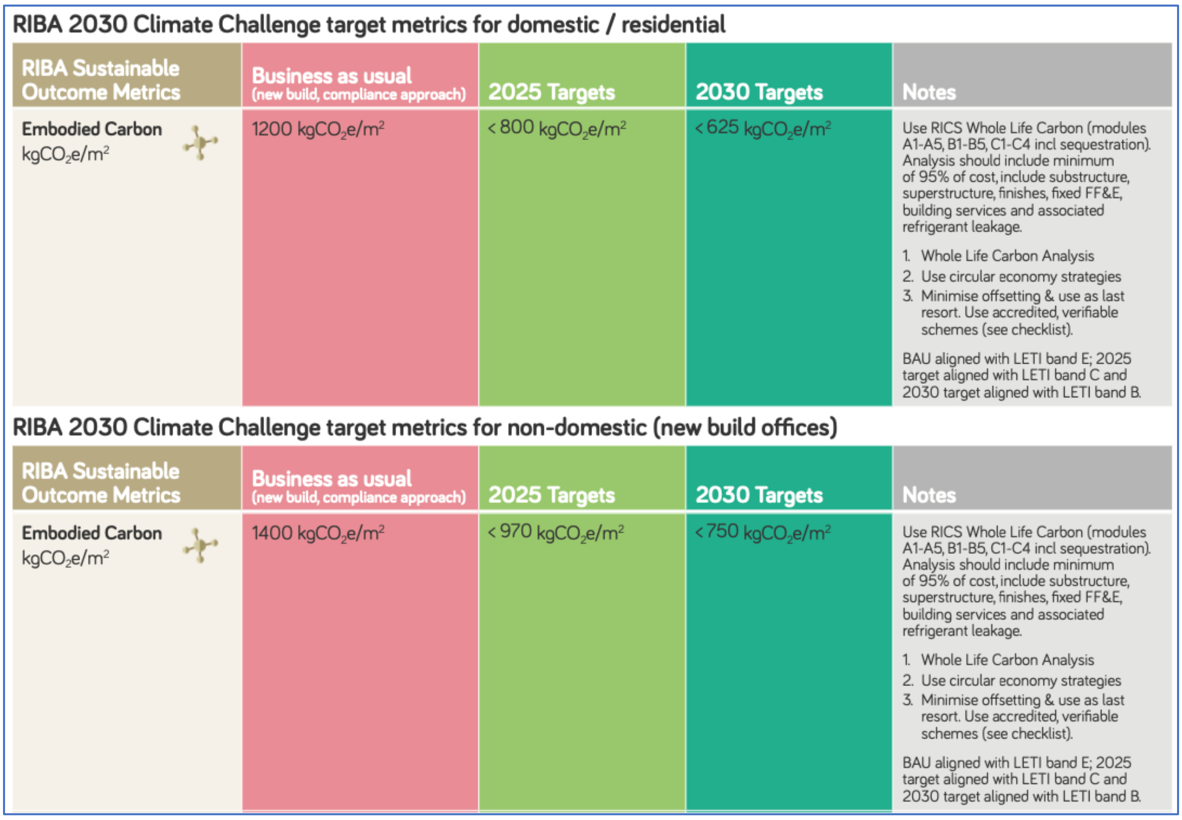
Reaching "net zero" will be "virtually impossible" without the mass roll-out of CCUS, according to the IEA, especially in the case of "hard to abate" emissions, i.e. those of heavy industry and long-distance aviation.

However, CCUS at sufficient scale *and energy-efficiency* to course-correct existing levels of greenhouse gas emissions, let alone draw down historic emissions, *in anything like the requisite timeframe*, is a total pipe dream.

In the minds of corporate and state high-ups captured by fossil capital, as the IPCC's Working Group III point out, "CCS can allow fossil fuels to be used longer", and this reduces the degree and speed at which fossil reserves become de facto stranded assets –a necessary economic lever for limiting warming to 1.5°C or even 2°C.

The Working Group also notes that, regardless of its supposed promise, the "global rates of CCS deployment are far below those in modelled pathways limiting global warming to 1.5°C or 2°C".

A highly critical report on CCS, published by the Institute



RIBA 2030 Climate Challenge target metrics for domestic / residential

RIBA Sustainable Outcome Metrics	Business as usual (new build, compliance approach)	2025 Targets	2030 Targets	Notes
Embodied Carbon $kgCO_2e/m^2$	1200 $kgCO_2e/m^2$	< 800 $kgCO_2e/m^2$	< 625 $kgCO_2e/m^2$	Use RICS Whole Life Carbon (modules A1-A5, B1-B5, C1-C4 incl sequestration). Analysis should include minimum of 95% of cost, include substructure, superstructure, finishes, fixed FF&E, building services and associated refrigerant leakage. 1. Whole Life Carbon Analysis 2. Use circular economy strategies 3. Minimise offsetting & use as last resort. Use accredited, verifiable schemes (see checklist). BAU aligned with LETI band E; 2025 target aligned with LETI band C and 2030 target aligned with LETI band B.

RIBA 2030 Climate Challenge target metrics for non-domestic (new build offices)

RIBA Sustainable Outcome Metrics	Business as usual (new build, compliance approach)	2025 Targets	2030 Targets	Notes
Embodied Carbon $kgCO_2e/m^2$	1400 $kgCO_2e/m^2$	< 970 $kgCO_2e/m^2$	< 750 $kgCO_2e/m^2$	Use RICS Whole Life Carbon (modules A1-A5, B1-B5, C1-C4 incl sequestration). Analysis should include minimum of 95% of cost, include substructure, superstructure, finishes, fixed FF&E, building services and associated refrigerant leakage. 1. Whole Life Carbon Analysis 2. Use circular economy strategies 3. Minimise offsetting & use as last resort. Use accredited, verifiable schemes (see checklist). BAU aligned with LETI band E; 2025 target aligned with LETI band C and 2030 target aligned with LETI band B.

Source: adapted from RIBA (2021), 2030 Climate Challenge for Energy Economics and Financial Analysis (IEEFA) in September 2022, specifically takes aim at the IEA's advocacy for the technology.

I have commented in more detail on the IEA's approach in Appendix 5.

8.7 Actions by architects

I began this series with reference to some worker-led groups and professional bodies across architecture, design and engineering that have become prominent advocates for decarbonising the built environment. In the UK, these include the Architects Climate Action Network (ACAN), Low Energy Transformation Initiative (LETI), Architects Declare (AD) and the Royal Institute of British Architects (RIBA).

Each of those has published a stream of pamphlets, petitions, guidance documents, case studies, regulatory and policy advice, and benchmarking objectives, all aiming to shift the built environment professions internally, *and* shift external norms and expectations.

They consider not just emissions, but also the built environment's direct impacts on other aspects of the natural environment, such as wildlife habitats, biodiversity, water systems, soil health, and people's health and wellbeing.

The *intellectual* momentum behind these proposals is significant. What they amount to *practically and at scale* remains to be seen.

In architecture, there are political tensions that need to be worked out. One of these is that large architecture firms usually get paid to design *new* buildings and shepherd them through construction. But what if one of the climate-aware architect's main tasks is to halt most new construction? What if the only way to be a climate-responsible architect is to *dis*courage, not encourage, large projects with high rates of material use and large carbon footprints?

What if the world needs architects and engineers to divest from surplus projects in rich countries, and be redeployed delivering services to the global poor?

In 2020, the famous architect Norman Foster, an early signatory to Architects Declare, withdrew his firm's support, because of his enthusiasm for airports.

The prestige buildings mentioned above for their novel use of low-carbon materials were *all new builds,* with stated tonnages of embodied carbon. Few people actively want to see an end to construction – and indeed new construction is necessary to meet urgent social needs.

But the onus needs to be on those new buildings causing emissions in the built environment proving their social worth, both in terms of redressing inequalities, and in an international context of limited and shrinking carbon budgets. Certainly this is the case in rich countries, but also wherever capital pours into construction.

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In this respect, it was nice to see Anne Lacaton and Jean-Philippe Vassal win the prestigious Pritzker architecture prize in 2021, for their spatially generous, and beautiful, retrofitted expansions of existing social housing blocks in France. Retrofits like that, which improve buildings' operational performance, at minimal cost in terms of embodied emissions – should be the model.

Most buildings construction worldwide is designed with little regard for the climate, and with more of an interest in catering to architects' clients – whose agendas will not often be led by environmental concerns. For that reason, compulsory regulations on embodied and operational carbon are essential, internationally.

Voluntary benchmarks set by RIBA and LETI give a sense of scale, when thinking about what reasonable legal limits on embodied carbon might look like, on a per-project basis.

However, legally-binding hard limits on the carbon footprints of new construction *as a whole* are needed, on a per-country, or regional basis. Plus tough benchmarks for the carbon intensity of the delivery of services, with *legally-binding obligations prioritising the collective provision of essential and universal social goods, such as housing*.

In its *2030 Climate Challenge* (version 2, 2021), RIBA proposes to almost halve embodied carbon for new buildings in the UK by 2030. The target is for an embodied carbon performance of less than 625 $kgCO_2e/m^2$ for domestic buildings, and less than 750 $kgCO_2e/m^2$ for non-domestic office buildings. There are interim targets for 2025, and additional targets for school buildings (see table on page 57).

LETI has published more stringent targets for 2030: less than 300 $kgCO_2e/m^2$ for domestic buildings (over 6 storeys), schools, and retail; and less than 350 $kgCO_2e/m^2$ for offices.

For comparison, 15 Clerkenwell Close, the (deluxe) residential and office building mentioned above, had declared embodied emissions of 335 $kgCO_2e/m^2$.

For a new home of 70 m^2, according to the RIBA 2030 benchmark, the embodied carbon would have to be under 43.75 tonnes CO_2e. For the LETI 2030 benchmark, it would be under 21 tonnes CO_2e.

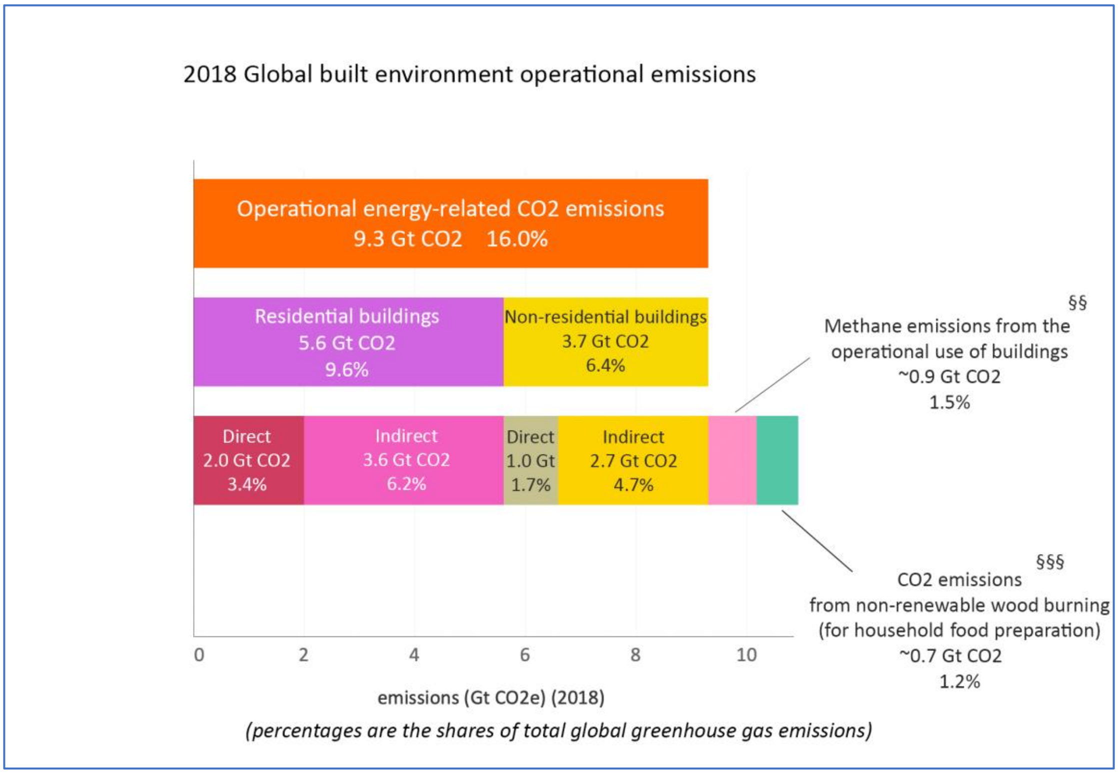
But in the UK, "business as usual" residential construction, under current regulations, produces an embodied carbon footprint of 84 tonnes CO_2e for the same floor area.

The architects' associations are saying this footprint needs to be slashed by nearly half (RIBA), or more than three quarters (LETI).

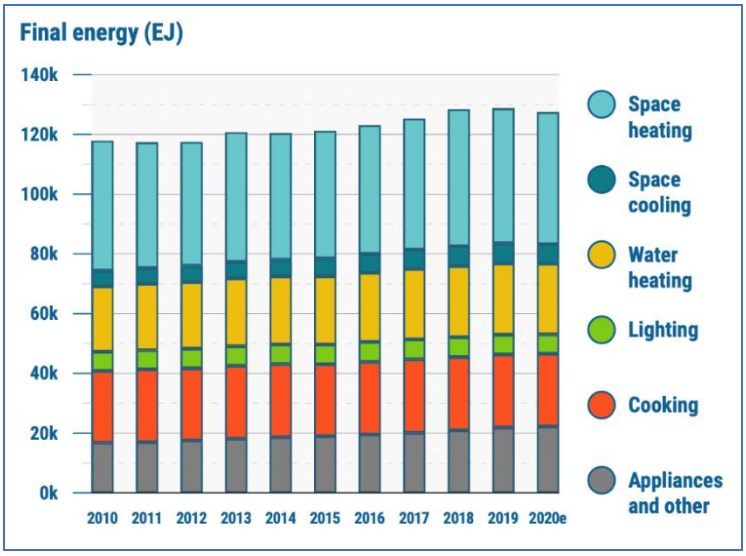
Part 9: Operational emissions and the thermal performance of buildings

In this part, I cover the operational energy used in buildings – that is, mainly, the energy used for heat, light, cooking and electricity – and the greenhouse gas emissions from this energy use.

I will provide an overview (section 9.1), a focus on space heating and cooling, the biggest user of operational energy (section 9.2), and a note about the effect of global warming on that (section 9.3). Then I look at what determines the thermal performance of buildings, i.e. how well they keep out winter cold or summer heat (section 9.4), and end with some points about Passivhaus standards (Section 9.5), which forms a link to the tenth and final part on how operational greenhouse gas emissions can be cut.



Source: IEA / UNEP (2019); §§ Global Carbon Project / Jan C. Minx et al (2021), IEA (2020a), IEA (2020b), IEA (2020c), IEA (2021a), IEA (2021b), IEA (2022). §§§ Alessandro Flammini et al (2023). For more details, see Appendix 3



Final operational energy consumption in buildings globally, by type. Source: IEA/UNEP (2021). Note: judging from the IEA's commentary, and a similar graph in the 2022 version of the report, the 'k' kilo prefix of the vertical axis is an error. The range extends up to 140 exajoules (EJ) – ie, 140 x 10^{18} joules

9.1. The operational energy of buildings

The chart above shows the global built environment's *operational* energy-related emissions for 2018.

This is an excerpt from the chart in part 5 that showed both operational and embodied emissions of buildings.

All three rows show different breakdowns of (i.e. different ways of looking at) the same emissions. The third row shows the direct and the indirect energy-related CO_2 emissions of residential and non-residential buildings. Additionally, I have included my rough estimate for the methane emissions associated with heating buildings, worldwide; and a recent estimate for the *non-renewable* CO_2 wood combustion emissions associated with household cooking (see Appendix 3).

As I mentioned in part 5, CO_2 wood combustion emissions are a component of the category "land-use, land-use change and forestry" (LULUCF). They are *not* included in the IEA's "energy-related CO_2 emissions" data.

The percentages here are proportions of all global sociogenic greenhouse gas emissions for 2018.

Excluding wood combustion emissions, the energy-related operational emissions of buildings worldwide were ~10 Gt CO_2e, or 17.5% of all greenhouse gas emissions. That compared, for example, to energy-related CO_2

emissions of global transport of 7.6 Gt CO_2 (13.1% of all greenhouse gas emissions).

Buildings' operational energy-related emissions comprise: space heating and cooling, water heating, lighting, cooking, and the use of various electrical equipment and appliances.

In part 5, I noted that globally, operational carbon from buildings comprises ~75% of the lifetime emissions associated with buildings, versus ~25% from buildings' construction.

In the chart, residential and non-residential CO_2 totals are divided into direct and indirect emissions. Direct is basically in-situ fossil fuel combustion, e.g. with a gas boiler. Indirect is mostly emissions associated with the production of electricity. (Again, direct emissions under the heading "energy-related CO_2 emissions" *do not include wood combustion*.)

However, "direct" emissions *do* include the CO_2 emissions upstream of in-situ combustion, in the energy supply chain.[1]

The chart shows that residential buildings are responsible for around 60% of buildings' operational CO_2 emissions worldwide, and non-residential buildings for 40%.

The level of buildings' operational energy use is, broadly speaking, determined by the number of buildings, and the scale of energy consumption in each of them.

The second graph on page 59 shows the level of operational energy use for the world's buildings, broken down by end-use. These are quantities of energy, including all fossil-based and non-fossil-based sources.

Many low-income households across the world depend on non-fossil fuel sources of energy.

For example, in Nigeria, roughly half of final energy consumption across the economy as a whole comes from household operational energy consumption. But around 65% of that comes from biomass – wood, charcoal, animal dung – mostly used for home cooking. In Nigeria, only about 60% of the population have access to electricity.

Biomass combustion in the home is enormously damaging to public health. According to the IEA, almost 500,000 people died prematurely in sub-Saharan Africa in 2018 because of cooking with solid biofuels – "a figure that equals the combined death toll of malaria, tuberculosis and HIV/AIDS".

Biomass combustion also produces more CO_2 combustion emissions per unit of energy than coal does. The fact that that CO_2 originally came from the atmosphere, and can eventually be reabsorbed by new plant growth, hardly recommends most biomass combustion as a useful "net-zero" energy source. Wood combustion in homes is a major cause of net forest loss. Moreover, most methods of biomass combustion are incredibly inefficient at transferring the chemical energy stored in biomass into a useful form.

Of the total final energy consumption in buildings, 35% – ~45 EJ in 2018 – is devoted *just to heating interior space*. That is, more than a third of all of operational energy use in the world's buildings is used *just to keep their interiors warm enough when it is cold outside*. ~7 EJ (~5% of total operational energy use) is used for space cooling.

So, taken together, space heating and space cooling comprise around 40% of buildings' operational energy use, followed by water heating and cooking; then use of appliances; then lighting.

So long as a great deal of the world's energy generates greenhouse gases, all of these uses of energy need to be minimised, to as near to zero as possible.

9.2. Space heating and space cooling

There are broadly two different kinds of energy efficiency connected to the heating and cooling of buildings:

a. Fabric efficiency: what the fabric of the building on its own does to mitigate operational energy use. For example, how good is a building at maintaining thermal comfort without additional energy being applied?

b. Supplemental heating efficiency: the efficiency of whatever technology provides the supplemental space conditioning that is required.

The fact that so much energy is used in heating and cooling interior space globally tells us that – whatever the technologies involved – buildings must be pretty poor at maintaining comfortable interior temperatures in the first place, without the application of energy.

In the rest of this post I will focus on those issues of thermal comfort and fabric efficiency. Then in part 10, I will turn to the topic of supplemental heating and cooling.

Thermal performance and fabric efficiency

Put simply, the thermal performance of a building is its capacity adequately to maintain steady, comfortable indoor temperatures, even as the weather and the climate vary outside, and with minimal outlay of supplemental energy.

Ideally, the building achieves this as far as possible without the use of additional energy – that is passively – through the physical properties of the building fabric itself. Such buildings have high fabric efficiency.

When poor thermal performance is combined with an energy system built on fossil fuels, the result is fossil dependency and high levels of emissions.

You might think that buildings requiring energy to heat and cool them is only natural – and it can seem so, when we are used to thinking about buildings that way.

However, from an engineering perspective, this need not be the case. Very high levels of thermal performance are, for the most part, entirely within reach, at comparatively low cost.

Some effective building strategies for mitigating heat and cold have been available for millennia. Other more recent techniques and innovations are now well-established and economically competitive, compared with the operational costs of leaving them out.

The problem is that the legacy building stock worldwide is under-performing, while new buildings are often poorly

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[1] This is my understanding of information on the IEA website here: "Indirect CO2 emissions result [only] from upstream generation of electricity and heat used in buildings." Indirect emissions also include the emissions associated with district heating and cooling (see Part 10)

and negligently designed, and poorly constructed from a thermal perspective.

As a result, the world's existing buildings are *needlessly and profoundly inadequate* to the task of delivering shelter and maintaining comfort and good health for their occupants, without the constant use of energy.

Often, thermal performance is so bad that, even with the option of constant supplemental heating or cooling, the amounts required to maintain thermal comfort are so large that thermal discomfort has been normalised. This happens in the UK, for example – a country rich in accumulated resources.

Meanwhile, the prevalence of heating and cooling systems has tended to disguise, and excuse, tremendous levels of thermal inefficiency in buildings' physical structure. The upshot is that buildings have been specified, designed and built to a lower expectation, and a lower thermal standard. They then *require* the additional heating and cooling paraphernalia, and energy to power it, just to remain habitable and functional.

In parts 3 and 7, I mentioned how *aesthetic* considerations have helped drive the use of high-emissions steel and concrete in much modernist architecture and contemporary buildings design. The building aesthetics also depended on a degree of historical and ideological *blindness* to the material and environmental effects of energy use – and produced an international style of climate-insensitive and context-inappropriate design.

Unquestionably, an aspect of that concerns supplemental heating and cooling systems – an almost universal affliction. Large embodied *and* operational emissions have been typical throughout the post-second-world-war period of fossil capital.

The Seagram Building in New York City, mentioned in part 7, is a good example. It has enormous operational emissions.

Barnabas Calder and Florian Urban note how the building's brass mullions and spandrels "radiate the warmth of the building out into the winter cold of New York, or collect the sun's heat in summer, making them among the main causes of the building's exorbitant energy consumption for heating and cooling", that task performed by vast forced-air servicing.

That servicing, in turn had "liberated the building's envelope from its traditional obligation to keep out the winter cold or the summer sun". Ludwig Mies van der Rohe, a prominent architect, could instead "make his glazing an artistic meditation on transparency, clarity and elegance".

Even now, the Seagram Building's operations produce ~15,400 tonnes of CO_2 annually – and that is not even including other greenhouse gases besides CO_2. That is equivalent to the per-capita consumption-based emissions of about 1500 people living in the UK.[2]

The Seagram Building is a particularly egregious example, but it is *just one of* New York City's most energy-hungry office buildings.

The ideological disinclination to think about energy use and its environmental consequences has been an epochal mis-step in the built environment.

This disinclination unfortunately still remains, in widely-shared expectations about what a "modern" building is like: what it looks like, how it feels inside.

Poor thermal performance is perhaps forgivable in old buildings. It might be that traditional, pre-war and even some post-war building types can be excused over poor thermal performance – depending on the historical availability of effective engineering knowledge, or the obscuring power of ideology.

However, when new buildings are built that way today, it amounts to professional malpractice – given the collective material resources and the engineering expertise at the world's disposal, and the narrow sliver of time that remains to mitigate worldwide climate disaster.

And existing buildings can also be retrofitted to improve their thermal performance greatly, and improve their occupants' thermal comfort.

In my view, existing buildings should be retrofitted wherever possible, (a) if it will mitigate the combined embodied and operational emissions of the building over something like a 30-year timeframe; and (b) if it will meaningfully lift the comfort, and improve the health, of occupants.

This means keeping the embodied emissions and material footprints of retrofit as low as possible, and making all retrofit decisions according to an independent assessment of the likely lifecycle emissions and material and environmental footprints, when compared to no retrofit.

More broadly, there is a case for appraising real needs, and redistributing the use-values associated with the built environment, in the context of a global need for contraction and convergence.

New buildings should be built only when strictly necessary from the point of view of needs, and when lower-emission retrofit options are unavailable.

Data from the IEA/Tsinghua University buildings model suggests that, since at least 2010, the rapid increase in constructed floor area worldwide has been the leading driver of the growth in buildings' combined operational energy-related CO_2 emissions.

Economic growth has tended to bias the construction of more and larger buildings, and – given a disinclination to specify for fabric efficiency – these expanded floor areas and enlarged volumes of internal air have all needed to be heated, cooled, and lit.

Economic demand has been the main driver of those floor area constructions, and the increases in space conditioning have likewise been based on an ability to pay.

In any case, the health effects for occupants of buildings of poor thermal performance, or an inability to pay for space conditioning – fuel poverty – should be evident. So too the climate impacts of the emissions that follow from space conditioning being powered overwhelmingly, still, by carbon-based fuels.

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[2] Author's estimate. That is consumption-based UK emissions including all greenhouse gas emissions, not just CO_2 (CCC, 2018 data)

Thermal comfort

Thermal comfort can be difficult to define. I think we all know from experience that it can be highly subjective – ultimately it is a physiological and psychological state of being. It also varies according to things like your age, health and level of physical activity.

Thermal comfort plainly varies with ambient temperature – but it varies, too, with the level of ambient humidity and ventilation. These are physically related to ambient temperature, and are themselves important factors when it comes to securing thermal comfort and health.

Nevertheless, we are all familiar with thermal *dis*comfort. It can seriously impact people's quality of life, and can be deadly. People's degree of risk from exposure to extremes of temperature also varies – for example, the elderly will tend to be more vulnerable, with less physiological capacity for dealing with heat or cold.

I mentioned in part 6 that international human rights law has codified adequate housing as an intrinsic human right, and that all states have committed themselves to this principle in one form or another. An important part of adequate housing, alongside things like security of tenure and affordability, is a *habitability* provision.

As well as things like sufficient living space for all, this also includes "protection against the cold, damp, heat, rain, wind, other threats to health".

In the UK, there are no laws over temperatures in the workplace – only statutory guidance that suggests temperatures be roughly between 16°C and 30° – though 13°C is considered OK if work is physically strenuous. Of course at home people tend to be physically inactive, but thermal performance is not regulated across the housing stock.

In relation to keeping out cold, LETI say that a good metric for thermal comfort indoors is when the internal surface temperature is "greater than 17°C, when outside temperatures are at a minimum". The Royal Institute of British Architects (RIBA) define "overheating" in the home as "25-28°C maximum for 1% of occupied hours".

So, presumably, reliable indoor ambient temperatures of ~17-23°C in the daytime could be taken as the outer range of thermal comfort in a home, *wherever you are in the world* – going down to 16°C at night time.

In 2021, the Welsh Government published a report, Tackling Fuel Poverty 2021 to 2035, in which they defined a "Satisfactory heating regime". In homes without elderly or disabled people, it would be "21°C in the living room and 18°C in other rooms for nine hours in every 24 hour period on weekdays, and 16 hours in a 24 hours period on weekends". For homes with older or disabled people, on every day of the week it would require temperatures of "23°C in the living room and 18°C in other rooms achieved for 16 hours in a 24 hour period".

In any case, one of the main ways to secure thermal comfort, and protection from the elements – especially in the context of costly commodified energy and climate change – is by ensuring that all homes perform well thermally, and have good to excellent levels of fabric efficiency.

What that looks like will vary, depending on where a building is. When it is cold outside, you want your building to capture and retain heat effectively. But when it is hot outside, you want your building effectively to shade its interior from the sun, and efficiently dissipate the heat that does enter.

9.3. Buildings in a changing climate

Climate change is also now having *accelerating effects* on the habitability of buildings. 2023 is "virtually certain" to be the hottest year on record – the hottest year in "millennia" – with 2015-2022 already the eight warmest before that.[3]

However, the need for thermoregulation in buildings is becoming more acute at both ends of the temperature scale, alongside an increased need for flood and storm protections. Many existing buildings are becoming ever more inadequate to the task of providing comfort without massive, and sometimes impossible outlays of energy.[4]

Urban population growth and construction in warmer climates are compounding the effects of heat for urban dwellers via the "urban heat island" effect – the tendency for urbanised areas to be warmer due to the presence of heat-absorbing urban materials instead of vegetation, and the heat-producing effects of various domestic, retail, transport and industrial activities.

The quantity of electricity used for space cooling internationally doubled between 2000 and 2018. And heatwaves across China in 2022 drove widespread use of air conditioning, and took China's electricity demand to an all-time high (see also part 4). With hydropower reservoirs out of action, and with as-yet inadequate renewables and power storage capacity, this was one of the factors that led to increased recourse to coal. Even retired coal-fired capacity was brought back online. These events seem also to have reinforced coal as the backstop of China's energy transition.

A further turn of the screw is that the refrigerants used in cooling systems – the fluorinated gases or F-gas – have high global-warming potential, and a tendency to leak. So their increased use, like the Chinese coal burned to cool people

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[3] There have been severe heatwaves in both 2022 and 2023 on several continents. In 2022, South Asia experienced an unusually early and long heat wave; Pakistan suffered deadly heat and deadly floods from rapid glacial melt. In 2023, Phoenix in Arizona, USA, had a record 19 days in a row with temperatures above 110°F (43°C). Rome in Italy had its hottest ever day in 2022, at 41°C – but that was exceeded in 2023, with temperatures reaching 43°C.

[4] *A note about methodology.* In relation to buildings' operational emissions in a changing climate, metrics of "temperature adjusted" emissions are often used. These "adjust" the historical record for analytic purposes, "correcting" for temperatures deemed to be anomalous to the historical norm. This is useful for tracking, say, year-on-year progress in reducing home heating emissions through measures such as insulation. The UK's Climate Change Committee, for example, refers to UK temperatures in 1981-2020 as a baseline. The "adjustments" to emissions can go up or down; in the UK they have tended to be on the order of 2-7% of buildings' operational emissions.

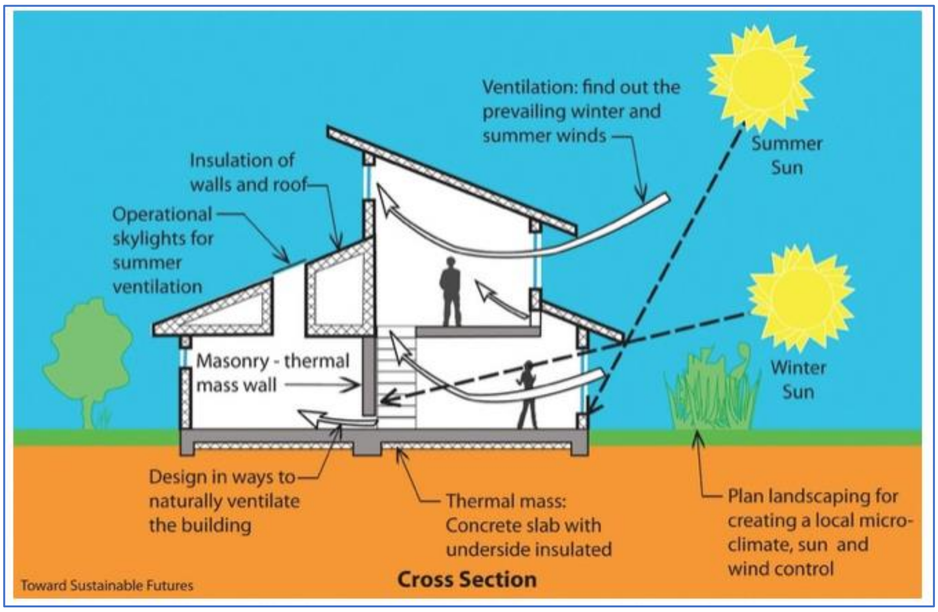
But outside of that specific analytic use, we of course want to see "unadjusted" data. We want to see *how* living in a changing climate, and *outside* the historical norm, might increase or decrease fossil combustion.

Note that, in the UK, winters are set to become moderately warmer and wetter, due to global warming. However, that hardly helps the millions of people suffering *now* from fuel poverty in winter.

down, has further added to the burden of greenhouse gases in the atmosphere.

And at the other end of the scale, we have more frequent and severe extremes of cold. Fossil-fuel dependency and price rises, combined with buildings' poor thermal performance, are also exposing people to heightened risk from winter cold.

The technical challenges of ensuring people are warm or cool enough at home cannot be overcome without *also* overcoming the social causes of inadequate housing.



Passive solar design. Source: Getting Off Grid

9.4. What determines buildings' thermal performance?

What makes buildings perform well, or badly, thermally? The following basic principles of architectural design all play a role – but they are too often poorly implemented or left out of new buildings entirely, and absent in older buildings.[5]

Readers may know, or recall from school physics classes, the three main ways that heat transfers across a medium: by radiation, conduction, or convection.

Radiation is the transmission of energy in the form of waves or particles – and any object that is warmer than its surroundings transfers heat from itself to its surroundings by radiating heat from its surface. Conduction works instead by physical contact, with heat energy propagating from one molecule to the next through a given substance. Convection transfers heat through a fluid, like air or water, via the movement of the particles themselves.

Much about a building's thermal performance is determined by the physical qualities of its outer walls, windows, floor, roof and outer doors. These comprise the building *envelope* – where the building meets its environment. In thermal terms, the envelope serves either to block, or to permit, the transfer of heat into or out of a building – by radiation, conduction or convection.

An important concept in this regard is *bioclimatic design*: the principle by which buildings passively *work with* local climatic conditions to take advantage of whatever natural daylight, heating, cooling, and ventilation effects are available. The aim is to maximise comfort and health for a building's occupants, with minimal use of supplemental energy.

Solar gain means that a building's interior is heated by radiation in the form of light from the sun – the original "greenhouse effect". As we all know, when it is sunny outside you will often want to shade buildings' interiors from the sun, to prevent overheating and maintain comfort; when it is cold outside you will often want to capture that heat instead, to passively heat a building's insides.

Optimal thermal performance, with respect to solar gain, therefore means tailoring the building to strike the best balance between these two requirements, depending on the variations in incident sun at a particular site, both over the course of a day, and over the course of the year.

Two of the most important ingredients in this respect are the orientation of a building in its surroundings, and the arrangement of the windows. In the UK, for example, according to LETI, the optimum glazing ratio for a building, on the average, is a maximum of 25% glazed surface on its south-facing side, up to 20% glazing on its east- and west-facing sides, and as little glazing as possible on the north-facing side. Getting these things wrong can have enormous costs in terms of thermal performance, and the resulting operational efficiency of a building overall.

Long eaves and brise soleil are also very simple, effective ways to manage solar gain. They allow low-level sunlight to enter and warm a building during winter months and in the mornings and evenings, while shading windows and exterior walls from high-level midday and summertime sun. Similarly, deciduous trees adjacent to a building can screen the sun in the summer, while allowing sunlight to warm a building in the winter.

One fairly high-tech way to manage solar gain through windows is with high-performance glass that has coatings to reflect away certain wavelengths of light, selectively. The *G-value* of glass (in Europe), or its *solar heat gain coefficient* (in the USA), quantify (in different ways) the solar heat gain through that glass, per unit of incident solar radiation.

Low-e coatings on glass reflect a larger proportion of long-wavelength infra-red light. When used on the outside of a window, this minimises the greenhouse effect indoors. External shutters are a lower-tech alternative, that does something similar by entirely blocking the light.

In terms of overall heat gain and heat loss, the *form factor* of a building – the ratio between external surface area and

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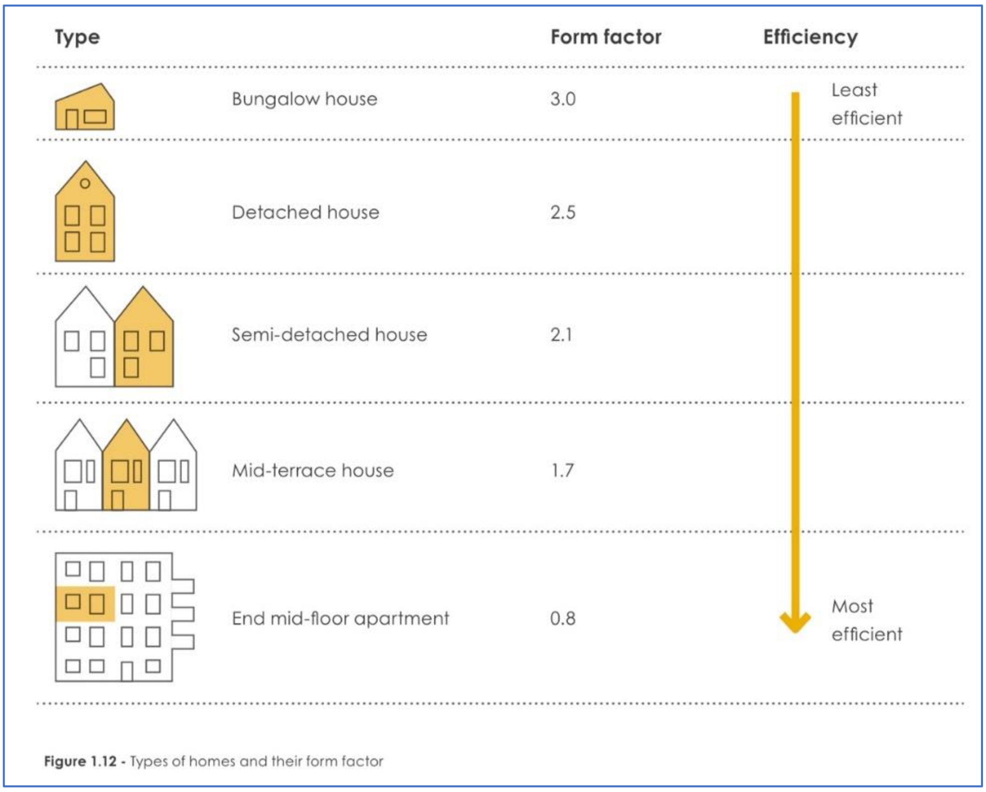
[5] This is a brief outline; the Designing Buildings Construction Wiki is a great resource if you want to learn more



Type	Form factor	Efficiency
Bungalow house	3.0	Least efficient
Detached house	2.5	
Semi-detached house	2.1	
Mid-terrace house	1.7	
End mid-floor apartment	0.8	Most efficient

Figure 1.12 - Types of homes and their form factor

Types of building, form factors and efficiency. Source: LETI (2020)

internal floor area –is important. It can also be measured for any individual part of a building, such as an apartment. (See the illustration above.)

The key mechanisms here are radiative heat loss/gain and conduction. Heat can be lost to the surrounding environment, or gained most readily from it, if there is a larger external area of the building exposed to outdoor conditions.

All other things being equal, this means that a detached bungalow will typically gain or lose heat easiest (it has a high form factor ratio); whereas a mid-floor apartment will typically gain or lose heat more gradually (it has a low form factor ratio). In overall thermal performance terms, that makes a mid-floor apartment more thermally efficient, as it is sheltered like a penguin between its neighbours.

For those areas of a building's envelope that *are* exposed to the outside, the most effective way to prevent heat loss is thermal insulation. This also works to insulate buildings from *gaining* heat from outside, and can double as sound insulation on exterior or interior walls. Thermal insulation minimises conduction, convection and radiation across a building's envelope.

One way to quantify the thermal insulation qualities of a material is with an *R-value*. This measures its thermal resistance, and is the product of its conductivity and its thickness. High resistance means a substance very effectively frustrates the transfer of heat energy, and therefore is a good insulator.

However, the insulating qualities of building materials are more usually given by looking at things the other way round – with a measure of the rate at which heat energy flows across a given material. U-values (heat transfer coefficients) are the reciprocal of R-values, and they quantify the thermal conductivity of materials. A good conductor is a poor insulator, and a good insulator is a poor conductor – so a low U-value means a low rate of thermal conductivity, and a high level of thermal insulation – generally a good thing.[6]

Wall insulation can be provided by many materials. They are usually classified as *open cell* or *closed cell*, depending on their physical structure.

Open cell insulation typically consists of strands of fibrous material, such as sheep's wool, hemp, or mineral wools like glass fibre or rock fibre. As such, the material is *breathable* – air can migrate through it, but only very slowly – so heat loss by convection is minimal, provided the material remains dry and not contaminated with water vapour. Meanwhile, the fibres themselves are poor conductors of heat, and therefore also ineffective at absorbing and radiating heat energy outwards from the structure.

Closed cell insulation consists of a denser structure of small, self-enclosed cells – usually containing a gas with lower thermal conductivity than air. Convection cannot occur from one cell to another, and the cell walls are sufficiently thin that conduction is also minimal. The closed structure means such materials are more impervious to the passage of water vapour.

Typically these are solid foam-board products, sold as sheets. Their insulating qualities are very good within the confines of a single board, but can be compromised quite easily at cut-points and at the joins if poorly installed.

Hemp (see also part 8) is an open call fibre, and performs averagely compared to mineral wools, but not as well as synthetic products like aerogel board and evacuated panels.

Cavity walls, where a cavity is created between two layers of brick or masonry, became common in the UK in the 1920s, as a way to prevent the transmission of moisture across the building envelope. But cavities also give a space

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[6] *Technical note. R-values* quantify thermal resistance in m²K/W (metre-square kelvin per watt). *U-values* quantify the thermal conductivity of materials, and are more widely used in materials specifications, and building design and construction. They are measured in W/m²K (watts per metre-square per kelvin).

One watt means that one joule of energy passes per second (1 J/s). One kelvin here is functionally the same as 1°C, and refers to the difference in temperature on either side of the material. So, for example, if a material has a U-value of 1 W/m²K, it means that, when there's a temperature difference of 1°C across the material (say, inside and outside of a building), 1 J of heat energy flows across each 1m² of the material every second.

The U-value of an insulating material generally decreases in proportion to its thickness. From the perspective of providing insulation, a low U-value is best.

for thermal insulation. According to the Designing Buildings Construction Wiki, some typical U-values for walls are:

Single layer of brick	2.0 W/m^{2}K
Cavity wall with no insulation	1.5 W/m^{2}K
Insulated cavity wall	0.3 W/m^{2}K or less

Then there is window insulation. As we are all aware, windows can be insulated by the use of two or more panes of glass, often separated by an air-tight gap filled with a gas such as argon. This minimises heat loss by conduction, while allowing visible light to radiate through the window. Three panes of glass instead of two is better operationally, but three versus two panes also increases the embodied carbon of a window. Yet the embodied carbon is also affected by what the frames are made of – wood, PVC, or aluminium.

A triple-glazed window unit with wooden frames will likely have lower embodied emissions than a double-glazed aluminium-framed window. In any case, the wisdom of double- or triple-glazing largely depends on climate. When *low-e* coatings are used on the inside of a window, this also serves to decrease the amount of infrared light *re-radiated back outside* from a building's interior, therefore preserving heat on the inside. Curtains and shutters perform a similar function.

Like all building specifications, the choice of glazing warrants a whole-lifecycle approach to emissions, to balance the trade-offs in embodied versus operational emissions, and money cost.

In all kinds of insulation, one important aim is to avoid weak links in the insulating barrier, where there is either direct exposure from the inside to the outside, or a more thermally conductive passage through which heat can pass.

Weaknesses like these form *thermal bridges*, which tend disproportionately to shuttle heat energy, as well as damp, across the building envelope. They are very common in older buildings, but are also found in poorly designed or poorly constructed modern buildings.

Heat loss by convection is also a problem. The best way to prevent it is to make the building airtight. But this needs to be balanced with ventilation, which is needed to maintain comfort and thermal integrity. Ventilation removes stale air and introduces fresh air into the interior, thereby moderating the temperature and humidity, replenishing oxygen, venting CO_2, and preventing the build-up of damp or various air-borne contaminants.

Airtightness, though, is about *controlling* the inflow and outflow of air. It is the opposite of air leakage, such as uncontrolled draughts, which can introduce all of those things that good ventilation is meant to control: the passage of damp air, and loss of regulated interior temperature, and so on. The motto is: "build tight, ventilate right".

Ventilation, in turn, can be *natural* – that is, passively achieved through wind, cross-ventilation, or the stack effect, where cool air enters at the base of the building, is heated by the interior, and is vented out the top. Or ventilation can be achieved mechanically, or with a combination of passive and mechanical means.

Ventilation can also include a heat recovery mechanism, to transfer up to 98% of the heat from vented stale air, to warm the incoming fresh air – in which case, the net operational energy savings over even just a few years will likely outweigh the upfront cost and the embodied carbon of a device's manufacture.

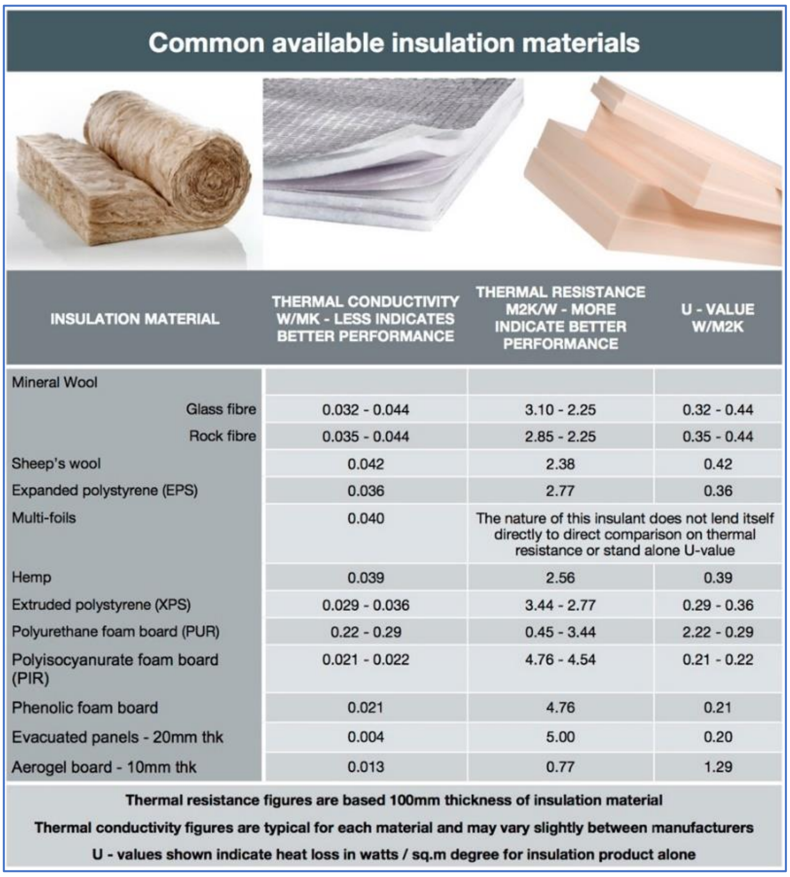
Similarly, you can have a water-based heat recovery mechanism for outgoing waste water. With those, hot water from a kitchen sink, washing machine, shower or bath, helps to heat hot water ready to use.

Looking beyond the envelope, to a building's inner fabric, *thermal mass* describes the ability of a given material to absorb, store, and later release heat energy – and it is therefore an important way to transfer, and to moderate, variations in external temperature.

For example, masonry or concrete have high *specific heat capacity*, which means that they very effectively absorb and store heat. A trombe wall made of one of these materials can be used to collect solar radiation from a sun-facing window during the day, which it then slowly radiates back into the building over subsequent hours.

9.5. Passivhaus standards

The Passivhaus certification standard combines all of the above design principles and more, to achieve maximum operational efficiency for buildings *passively* – with the minimal use of additional energy. The standard includes



Common available insulation materials

INSULATION MATERIAL	THERMAL CONDUCTIVITY W/MK - LESS INDICATES BETTER PERFORMANCE	THERMAL RESISTANCE M2K/W - MORE INDICATE BETTER PERFORMANCE	U - VALUE W/M2K
Mineral Wool			
Glass fibre	0.032 - 0.044	3.10 - 2.25	0.32 - 0.44
Rock fibre	0.035 - 0.044	2.85 - 2.25	0.35 - 0.44
Sheep's wool	0.042	2.38	0.42
Expanded polystyrene (EPS)	0.036	2.77	0.36
Multi-foils	0.040	The nature of this insulant does not lend itself directly to direct comparison on thermal resistance or stand alone U-value	
Hemp	0.039	2.56	0.39
Extruded polystyrene (XPS)	0.029 - 0.036	3.44 - 2.77	0.29 - 0.36
Polyurethane foam board (PUR)	0.22 - 0.29	0.45 - 3.44	2.22 - 0.29
Polyisocyanurate foam board (PIR)	0.021 - 0.022	4.76 - 4.54	0.21 - 0.22
Phenolic foam board	0.021	4.76	0.21
Evacuated panels - 20mm thk	0.004	5.00	0.20
Aerogel board - 10mm thk	0.013	0.77	1.29

Thermal resistance figures are based 100mm thickness of insulation material

Thermal conductivity figures are typical for each material and may vary slightly between manufacturers

U - values shown indicate heat loss in watts / sq.m degree for insulation product alone

Source: Designing Buildings Construction Wiki benchmarks for aspects of a building's structure and services. Good thermal performance is crucial to it.

Passivhaus certification is not just a matter of design, though.

All of these building methods depend too on *high standards of fabrication and construction*. What is good in theory may not work as it is meant to, if it is poorly implemented, or if the materials themselves underperform, giving rise to a *performance gap*.

Only in-situ testing can tell you what is really going on, once a building is made. There are diagnostic tools for testing thermal performance. For example, you can test the air tightness of a building using a blower door, and detect paths of thermal leakage using infrared thermography (IRT).

Building techniques also vary technologically, from low-tech to high-tech and industrial; the above is not a prescriptive list. Different human needs, environments,

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economies and traditions all suggest different paths to thermal efficiency.

Yet such is the scale of thermal wastage and the poverty of effective buildings construction worldwide, that anything and everything should be done – as with infrastructures of renewable energy – to prioritise the improvement of buildings' thermal performance, *in the context of a diminishing global carbon budget but a ballooning demand for energy*. This is certainly the case wherever *new* construction is needed to ensure people's wellbeing.

The political aim should be to improve the use-value of buildings for the bulk of humanity, while minimising the impact on the environment, through operational emissions, embodied emissions, material footprints and other impacts.

And wherever existing homes lack decent thermal performance – as in the UK – we need to retrofit and update them urgently, to the highest standards possible within a limited budget for embodied carbon.

Part 10: Decarbonising heating and cooling

The importance of only building those buildings that are really needed was explained in part 8. Making sure that buildings keep out winter cold and summer heat – that is, improving their thermal performance – was dealt with in part 9. Nevertheless, supplemental heating and cooling, hot water, and energy for cooking, will always be needed: this final part looks at how these can be provided without fossil fuels.

The most common sources of such energy are fossil fuels and biomass, for the most part directly combusted on site, in buildings. This results in high levels of emissions – and, in much of the world, hazardous fumes associated with cooking indoors. (See part 9 and Appendix 3).

These emissions and indoor pollutants can only be dealt with by changing the energy source. Decarbonising cooking, hot water and space conditioning means switching out all of that fossil fuel and biomass for other, greener, sources of energy – ideally, relayed by electricity.

Notwithstanding recent findings on the toxicity of gas stoves, cooking with gas is much cleaner than cooking with biomass, and gas is widely pushed as a comparatively clean-burning "transition fuel" for poor countries. But in my view, the case for gas in such circumstances is often over-stated, with a view to providing fossil fuel companies with a new source of revenue. The best alternative to biomass is electricity – for example, in an electric pressure cooker or induction stove.

In this part, however, I will focus on space conditioning and hot water. I will outline the main alternative technologies: heat pumps (section 10.1) and district heating and district cooling (section 10.2). I will then assess the potential role of hydrogen (section 10.3). I will discuss how such technological changes can be approached in a socially just way (section 10.4). Finally there are some Conclusions (section 10.5), from both this part and the whole series.

Crucially, heat pumps, district heating and (to a lesser extent) district cooling, are *very* mature and established technologies. They have industrial manufacturers and supply chains ready to expand, to fill an enormous potential – and necessary – market.

Local installation expertise is also crucial, and that varies enormously: in the UK, for example, a historical failure to train sufficient numbers of engineers, fitters and other tradespeople is a massive bottleneck. Nevertheless these technologies exist – they are not technofix dreams.

That expansion in turn requires the right support from states, both domestically and internationally: direct funding, regulation, technological transfers, and skills training.

10.1. Heat pumps

Apart from when they are used in industrial Combined Heat and Power (CHP) plants and similar settings, heat pumps are powered by electricity. So decarbonising heating and cooling for buildings with heat pumps is additionally dependent on decarbonising *electricity* – whether it is locally generated, or comes from a national or regional grid.

A heat pump is essentially a device for transferring thermal energy from one place to another.

And because it simply transfers existing thermal energy, it can be used for space heating, hot water *and* space cooling, simply by changing the direction of heat flow.

Heat pumps use electrical energy to pump a refrigerant (F-gas) through pipes, say from the outside of a building to the inside. The refrigerant transfers thermal energy in the process, and then loops back to do the same all over again.

There are a few different kinds of heat pumps: they vary e.g. by the source of heat and by typical output temperature. Most heat pumps used in buildings are air-source (ASHP) or ground-source (GSHP). When heat pumps are used in district heating and cooling systems (see below), the source (or sink) for heat might be water (sea, lakes, rivers, water treatment networks) or sewage.

Usually, water serves as an intermediary ("hydronic") carrier of thermal energy, once the heat has been transferred. So most heat pumps send hot water through hot water pipes and radiators, or into underfloor heating pipes, as does a gas boiler: these are air-to-water heat pumps or "wet heating systems". There are also air-to-air (A2A) heat pumps that send out hot air (or cold air). A heat exchanger heats water directly, to provide hot water.[1]

Even when it is very cold outside, heat pumps are able to extract thermal energy from the air, from the ground, or from a water source. In the case of space cooling, an air-source pump simply transfers heat from the interior to the outside.

Historically, ground-source pumps have had better performance, but have been more expensive. However, air-source heat pumps are now almost or just as good.

Crucially, heat pumps are massively more efficient at providing thermal energy than gas boilers. This is because *they transfer thermal energy that already exists in the surroundings*, rather than producing heat from scratch through combustion.

You therefore get more energy usefully *transferred* in the form of thermal energy (that is, heat gained or expelled) than you *use* in the form of electricity to power the process. Heat pumps function *as if they were more than 100% efficient.*

This *effective efficiency* of a heat pump is known as its Coefficient of Performance (COP). For example, a heat pump with a COP of 2 will transfer 2kW of heat for every 1kW of electrical power used – effectively as if it were 200% efficient.

The COP depends on environmental conditions. When the "thermal gradient" is steeper, and the difference greater between the interior target temperature and the exterior

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[1] You can read a useful overview here, from a 2021 report by the UK's Department of Business, Energy and Industrial Strategy (BEIS) on the electrification of home heating

ambient temperature, a heat pump has to do more work, and the COP is lower – but typically the COP ranges between 2 and 4.

A “SCOP” is a *seasonal* COP, meant to quantify year-round efficiency in a given locale for a given heat pump.[2] In the UK, any heat pump on sale after March 2016 is meant to have a minimum SCOP of 2.5, i.e. should be effectively 250% efficient or more over the course of an average year.[3]

The typical difference in efficiency between a gas boiler and a heat pump is illustrated below. Here, the blue “C” values stand for the quantity of energy consumed (“energy in”), and the red “U” values stand for useful thermal energy transferred (“energy out”).

The arrow from C→U shows the efficiency of the energy conversion. According to LETI, 85% is the average efficiency of gas boilers installed in the UK, although a typical new boiler has an efficiency of 90% or more.

Home energy consumption and use are widely measured in kilowatt-hours (kWh). One kWh means 1,000 Watts of energy used for one hour. For a sense of scale: the power of a typical electric kettle is 3 kilowatts (3 kW); it holds 1.7 litres of water, and typically takes about 230 seconds to boil 1.7 litres of cold tap water. Boiling a full kettle therefore uses about 0.2 kWh.

The average gas-consuming household in the UK used ~12,000 kWh of gas in 2020, according to the BEIS.

So, returning to the graphs on the right: in the case of a typical gas boiler, if you burn 100 kWh-worth of gas, you will get 85 kWh of useful thermal energy out. For the same 85 kWh out, you only need 34 kWh-worth of electricity powering a SCOP 2.5 heat pump – only 34% of the energy consumed by a gas boiler!

Heat pumps in the UK are effectively about 3x more energy-efficient than a gas boiler.[4]

That picture is complicated, however, by the price of electricity. In the UK, *electricity presently costs at least 4x as much per kWh than gas does* (see here). In 2021, the price of electricity for households was 5.59x that of gas. The reason for the disparity is that gas receives an effective subsidy, and – perversely – electricity consumption receives a much higher *environmental levy* than gas consumption does. The result is that, for UK households, the energy efficiency gains of heat pumps are outweighed by the operational costs – and that is on top of the higher upfront costs of installing a heat pump.

Heat pumps are vastly more efficient than gas boilers when it comes to reducing greenhouse gas emissions. In the UK, to get the same amount of heat, about one-third of the volume of emissions are produced. And, as electricity is decarbonised, that volume of emissions from electricity will go down, *without any changes to the heat pump*.[5]

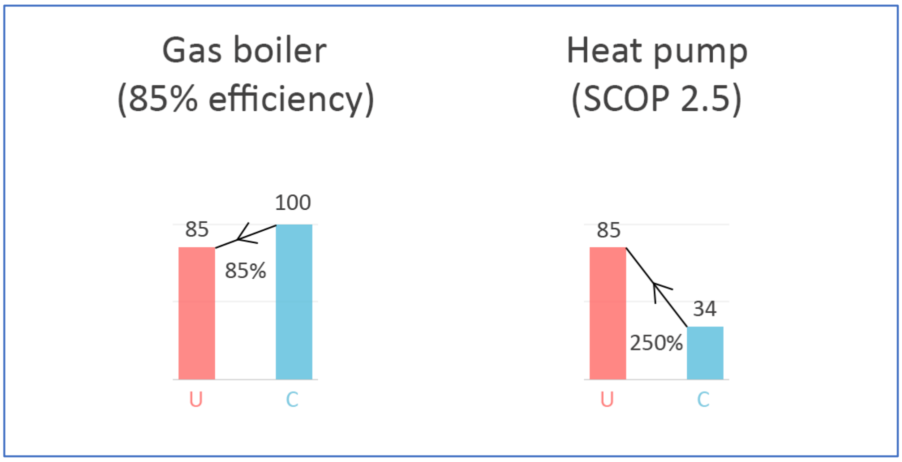
Here is the upshot:

☐ *The efficiency gain alone* of heat pumps means that the energy consumption per unit of useful heat out (or transferred) goes down massively.

☐ Even while the emissions intensity of the national grid is not much below that of a gas boiler (see footnote 5), *the efficiency of a heat pump alone drives down emissions very effectively*. And as the grid is decarbonised, so are heat pumps.

☐ This means that, *so long as the source of electricity is decarbonised, it is not necessary - for purposes of decarbonisation alone – to reduce the amount of heating or cooling required*, by adding insulation and other thermal efficiency improvements.

☐ Reducing the amount of required supplemental heat or cooling nevertheless has its own benefits – in terms of



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[2] You can read more on this from the UK’s Carbon Trust here

[3] Here is some test data from 2021, from the UK Department for Business, Energy & Industrial Strategy (BEIS).

[4] See here for a similar example from LETI

[5] When natural gas is burned in a gas boiler for home heating, on average it directly releases 180 grams of CO_2-equivalent emissions for every kilowatt hour of energy consumed (180g CO_2e/kWh): these are its “scope 1” emissions. For gas consumption in the UK, an additional 31g CO_2e/kWh are associated with extraction, refining and transportation (“scope 3” emissions), including vented and fugitive emissions. (These are the 2022 estimates assembled by the BEIS.) So the total emissions factor for natural gas combusted in UK homes is ~211g CO_2e/kWh.

Note that, for methane’s “scope 3” emissions – specifically, the warming effects of deliberately vented and fugitive methane – BEIS use a 100-year global warming potential (GWP) of 25 (ie, 25g CO_2e per g methane emitted). However, in the view of many experts, a 20-year GWP for methane is more appropriate – in which case, the IPCC recommends a GWP of 84-87.

In any case, by those 100-year emissions factors, a gas boiler burning 100 kWh-worth of natural gas in the UK, to deliver 85 kWh of heat, is responsible for ~21.1 kg CO_2e of emissions.

Heat pumps, on the other hand, are usually powered by electricity from the national grid, which has an emissions intensity (indirect “scope 2” emissions) of about 190 gCO_2e/kWh for power generation (2022 figure, BEIS). (This fluctuates greatly and varies regionally: see the National Grid’s “Future Energy Scenarios” 2022 data workbook, and here.) Additional (“scope 3”) emissions of ~18 gCO_2e/kWh are associated with the electricity transmission and storage network (for example through energy lost between generation and end-consumption). So that adds up to an emissions intensity of ~208 gCO_2e/kWh in 2022 – not that much different from burning gas directly.

However, 85 kWh of heat transferred by a heat pump in the UK, will on average be powered by just 34 kWh of electricity. That means only ~7 kg CO_2e of emissions, in 2022 – so about 33% the emissions from a gas boiler, for the same amount of useful heat energy transferred.

security of thermal comfort, and energy efficiency. Efficiency savings across the energy system also means that less infrastructure is required, which produces savings in the associated embodied emissions, materials, and land-use.

□ And finally, depending on where you are in the world: as far as your average existing building is concerned, the input-output efficiency gains of a heat pump, compared to fossil fuel or biomass, will likely *reduce your overall energy consumption for space conditioning far more than most retrofit options*, apart from the very deepest retrofits on offer.

Something to beware of, however, is that if they break or are poorly installed, heat pumps can leak their refrigerant – usually, one form or another of F-gas. F-gases tends to have high global warming potential (GWP), so heat pumps that use refrigerants with lower GWP are preferable. Heat pumps will potentially move from F-gases to propane, CO_2 (!), or other coolants in the future.

One very important thing, additionally, is the lifespan of a heat pump. Recent estimates range from 15 years to 25 years.[6] The consensus by researchers is that the lifespan of the average heat pump is now longer than it was in the past – and that heat pumps generally last a few years longer than gas boilers.

Heat pumps, in any case, are expensive– much more costly than a gas boiler. That cost will go down as the market for them expands and (presumably) benefits from economies of scale, and becomes more competitive. But the mainstream uptake of consumer-scale heat pumps will for the foreseeable future require substantial financial assistance from governments.

10.2. District heating & district cooling

District heating (DH) provides hot water and space heating to many buildings from a centralised source, by pumping hot water through insulated pipes.

Buildings in a heat network receive hot water from the network into a heat interface unit, which uses a heat exchanger to deliver hot water to taps, and space heat via radiators, underfloor heating and air-handling systems.

District heat is a familiar and established technology in many countries, although less common in the UK.[7]

Like electricity, the fuel source for district heat is flexible and "hot swappable". It can be generated from a mixed variety of sources: residual heat recovered from industrial processes; fossil fuel, waste (trash), or biomass combustion; or renewables-powered heat pumps. Heat pumps are the main option for decarbonised district heating and cooling networks. [8]

Similar principles to district heat can also be applied for district cooling systems.

District cooling *deposits* heat – for example into a river, so that the network's water is cooled. Whereas heat networks transfer heat, district cooling is said to transfer "coolth".

District heating and cooling networks are best suited to feeding buildings and homes clustered close together, in towns and cities and suburbs. They are not suitable for isolated dwellings.

District heating and cooling networks can be combined to increase efficiency, as district heating and cooling (DHC). London's Olympic Park has a DHC network.

Cooling networks are less physically efficient than heat networks, and they have greater upfront costs, so building-based cooling may be more practical and economical.

"Swappability" means that a network can switch between different sources or sinks of heat depending on the time of the year, for efficiency. The Helsinki DH network is warmed by seawater in the summer, and sewage water in winter.

These systems are generally amenable to gradual shifts in the energy mix. This "future proofs" district heating and cooling, as opposed to locking homes and other buildings into just one fuel source for heat.

Additionally, heating and cooling networks combine well with thermal storage to buffer demand. Examples of thermal heat stores are water tanks, tanks of molten salt, boreholes (rocks) and aquifers (water). Coolth can also be stored: for instance, Paris has a district cooling network that includes 30 MWh of ice storage.

Heat and coolth storage are an important way to buffer fluctuations in use – and crucially, these thermal stores reduce dependence on electricity and carbon-intense sources of "dispatchable" power during periods of peak use.[9]

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[6] The UK's Climate Change Committee (CCC) said (in 2020) that – as with gas boilers – the lifespan of a domestic air-source heat pump is generally around 15 years, and that a ground-source heat pump lasts perhaps 20 years before it needs to be replaced. The UK's Energy Saving Trust (2021), said much the same. The IEA (2022) estimates a 17-year lifespan for the average gas boiler, 15 years for air-to-air heat pumps, and 18 years for air-to-water heat pumps. One 2013 study, citing earlier data, suggested that "30 years [...] is a standard estimated lifetime for GSHP systems".

Jan Rosenow, an energy systems researcher with the Regulatory Assistance Project (RAP), says that heat pumps can indeed last longer than 15-20 years, if they are properly maintained. The RAP base their projections for the cost of heat pumps on a 20-year timespan of operation.

Meanwhile, the heat pump industry in the UK says that recent technological developments mean that the lifespan of a new heat pump is now 20-25 years. Publicly-accessible evidence for that seems to be thin on the ground. However, one manufacturer estimates that 80-90% of their heat pumps last longer than 20 years – dependent on proper installation, "reasonable conditions", regular servicing, and prompt repair when problems arise.

[7] This section draws on research commissioned by the UK's Climate Change Committee

[8] Alongside the heat source, heat networks can also be classified by temperature. Early DH networks in the late 1800s and early 20th century tended to be steam-based, with network temperatures over 120°C. Second and third generation networks were hot water-based. More recent (4th generation) DH technologies tend to use lower temperatures, of ~60°C or below. Building-scale heat pumps can be used to "top up" the temperature of incoming water from a heat network.

[9] The modelling for 2015 research for the CCC indicated that periods of peak heat use nevertheless required "dispatchable" sources of heat, in the form of combustion – even when the "baseload" heat source is fully renewable. The authors model a remarkable 35% of annual heat "demand" for such networks coming from gas combustion. One would assume lower temperature baseloads could mitigate that need. And, contrary to those 2015 assumptions, two heating sites in Helsinki apparently now use heat storage to meet peaks of heat dispatch, and for the most part forego boiler use entirely.

I mentioned the high cost and comparatively short useful life of a consumer-scale heat pump. If you are looking to reorganise the way that heating and cooling are delivered to buildings, it seems absurd to swap one piece of short-lifespan heating equipment for another. District heating and district cooling for the most part get rid of that concern.

When complex heating or cooling equipment is placed in centralised facilities, they can be serviced, replaced, and updated as needed, but the capital cost and the hassle of that do not devolve onto individual households.

District heating and cooling also imply a *materials* saving, on the embodied materials and emissions of manufacture, compared to using millions of consumer heat pumps.

Sure, there will be the odd pipe or pump that needs fixing across the network of buildings supplied – but that is minor, compared to wholesale replacement of heat pumps every 15-25 years. I see little reason – from the position of use-values – to have heat pumps all over the place, whenever district heating and cooling are the more efficient option.[10]

To summarise: in my view, district heating powered by decarbonised heat pumps should be the priority, wherever they are feasible within the necessarily urgent timeframe of decarbonisation. Heat pumps in individual homes are next best, for example for isolated dwellings – and can function for cooling, too, if need be.

10.3. Hydrogen

You often hear about the potential for hydrogen to displace gas for home heating in a "green" way – and the fossil fuel industries are pushing this.

A hydrogen-based energy system would use hydrogen as an energy store (like a battery), or an energy carrier (like natural gas). Energy is applied to produce the hydrogen in a chemical reaction – either from fresh water or methane (CH_4). The hydrogen is stored or transported, and then is either directly combusted to release energy again (as would be the case for home heating), or its chemical energy is released through a "redox" reaction in a fuel cell (e.g., in a car). Either way, the direct waste product is just water (and maybe some nitrogen oxides).

It sounds good, but there are numerous substantial problems. Not least is the source of energy.

Almost all hydrogen used at present (~95%) is produced from fossil fuels: coal ("black" hydrogen), lignite ("brown" hydrogen), and methane ("grey" hydrogen).

Much is pinned on generation from methane with carbon capture and storage (CCS),"blue" hydrogen. However, a recent life-cycle analysis by Robert Howarth and Mark

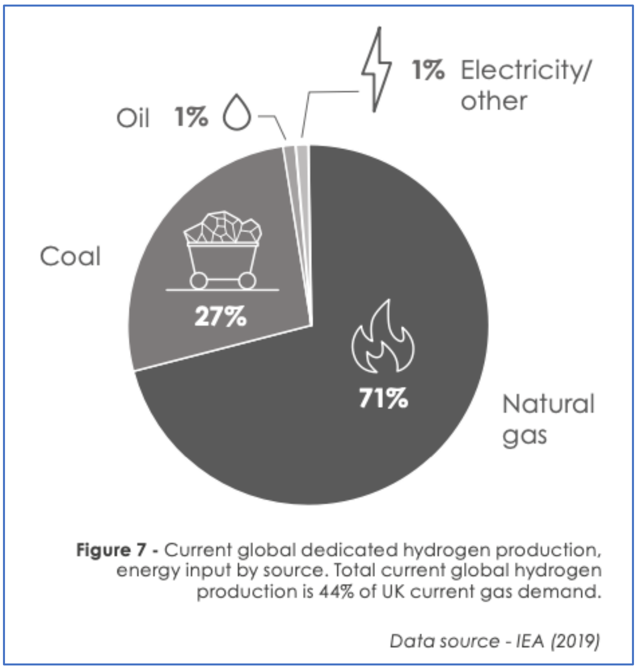

Figure 7 - Current global dedicated hydrogen production, energy input by source. Total current global hydrogen production is 44% of UK current gas demand.

Data source - IEA (2019)

How hydrogen is produced. Source: LETI (2021), Hydrogen. A decarbonisation route for heat in buildings?

Jacobson found that the total emissions associated with the production of blue hydrogen are only 9%-12% less than for grey hydrogen. This is because methane is also used to power the CCS, which means that vented and fugitive methane emissions are higher.[11]

Yet, even purely "green" hydrogen – produced using electrolysis of water, powered by electricity from renewables – is not a viable or desirable replacement option for heating in homes, according to a recent review of the scientific literature focused on the UK.[12]

Additional problems include: sourcing fresh water for electrolysis; the necessity of pressurised storage; the fact that water freezes below zero– a problem for fuel cells; hydrogen has a tendency to chemically "embrittle" storage tanks; and the cost and location of natural sources of platinum and iridium, which are used in fuel cells.[13]

One of the main arguments for hydrogen is as both a medium-term and "interseasonal" store of energy, to buffer fluctuating flows of renewable power – an alternative to mechanical stores of energy such as reservoirs. However, this argument does not apply to hydrogen for heating.

A recent report by the House of Commons Science and Technology Committee concluded that, in the UK, hydrogen "does not represent a panacea" in the path to "net zero". They reckon that hydrogen will likely only have "specific

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[10] Notably, a recent paper in the journal *Applied Energy* surveyed options for decarbonising heating systems in the UK, and found that district heating fed by heat pumps would be the cheapest option overall because of its economies of scale – about 11% cheaper than fitting heat pumps in every home.

[11] Jacobson and Howarth estimated that emissions from "blue" hydrogen production are ~486-500 gCO_2e/kWh, against grey hydrogen's ~550 gCO_2e/kWh. Note that – correctly, in my view – they used a 20-year global warming potential (GWP) of 86 for methane, instead of the more usual 100-year GWP of 28-36. They think that the emissions associated with blue hydrogen could be reduced to ~200 gCO_2/kWh, if the CCS was powered solely by renewables. But that's still barely less than the emissions factor for natural gas (see above) – and would only come after enormous build-outs in infrastructure.

[12] See here for more on this from Fiona Harvey in the Guardian.

[13] Youtuber Sabine Hossenfelder has a really good explainer video, from which I can only conclude that the notion of a "hydrogen economy" of any scale is absurd. She points out that green hydrogen production looks likely to remain very expensive for a while. Without very steep carbon tariffs and regulation in place, why would anyone use renewables to make hydrogen instead of using methane, or instead of storing green energy by other means?

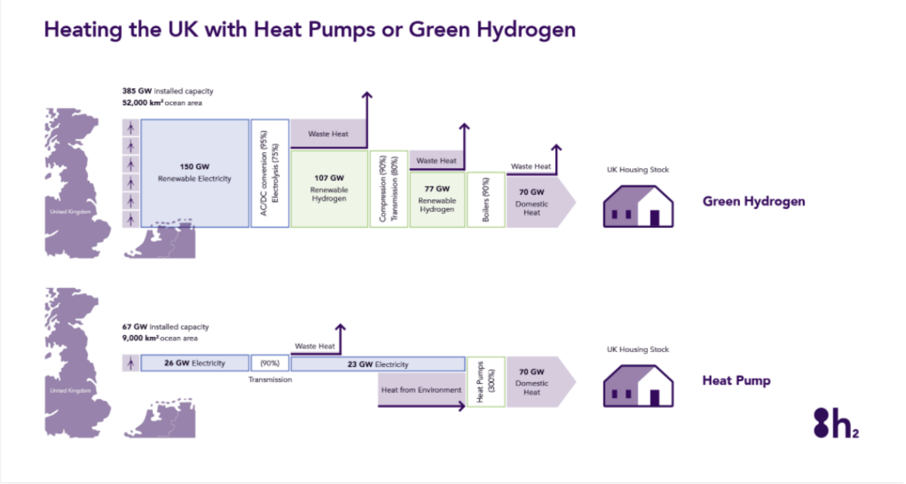

Figure 1: Providing domestic heating in the UK using either Green Hydrogen or Heat Pumps. The colours of the arrows indicate the type of energy: electricity, green hydrogen or heat. The widths of the arrows are proportional to the power flows (in units of GW). The blue boxes show scaled areas of wind turbine farms on the maps.

Source: Hydrogen Science Coalition

but limited roles to play across a variety of sectors to decarbonise where other technologies – such as electrification and heat pumps – are not possible, practical, or economic."

For some time the idea of a green hydrogen economy has looked like a ploy by the fossil fuel industry and their friends in government, to maintain dependence on a centralised fossil-fuel infrastructure, while retaining market access for "blue" and "grey" hydrogen – with a branding arsenal of cutesy colours like "pink", and "turquoise" hydrogens.

There is still talk, in the UK at least, of making gas boilers "hydrogen ready". However, as far as I can tell, the thermal efficiency of new domestic hydrogen-combustion boilers is the same, or a bit worse, than a gas boiler. The UK's Climate Change Committee (CCC) "assume that the efficiency of hydrogen and gas appliances is identical" (or indeed, worse: ~80% in 2020 for residential boilers, or ~86% for non-residential boilers).

There has also been talk, including from the CCC, of "hybrid" heat pumps featuring a hydrogen boiler for "back-up" power.

In terms of efficiency, more consequential than the poor performance of hydrogen boilers are the enormous energy efficiency losses *upstream* of final hydrogen combustion. The illustration above, from the Hydrogen Science Coalition, is instructive. For "green hydrogen", each unit of useful heat *out* of a domestic hydrogen boiler requires about 6x more electrical power going in upstream than a SCOP 3.0 heat pump – and that's assuming a hydrogen boiler with 90% efficiency.[14]

More than anything, the energy inefficiency of the hydrogen supply chain means that, even with an inflow of entirely renewables-generated hydrogen, a hydrogen-based heat network fed to individual homes could needlessly dominate demand for electricity, and – in a commodified market for energy – likely cost much more for end-consumers than the alternatives. All while keeping the door open to nastier flavours of hydrogen.

Additionally, very recent evidence points to new concerns over the risks of *hydrogen gas itself* as an "indirect greenhouse gas" in the stratosphere – where it increases the warming effect of methane. In light of those findings, updated guidance from the CCC suggests that "greater attention may need to be given to hydrogen leakage and its role, offsetting some of the benefits of a hydrogen-based economy."

Indeed, the UK CCC now (2023) say that hydrogen for home heating looks like a needless drain on a finite resource – green hydrogen. With a clear supply squeeze in the pipeline, they give every indication of wanting to "narrow the space" for hydrogen dependency, by further diminishing hydrogen's role in home heating, or removing it entirely.

For all the above reasons, and with additional concerns around safety, campaigns against hydrogen – and against the fossil industries pushing it – have been gathering force.

In the UK, the government's formal position remains that it will pursue community trials for hydrogen as a means of home heating.

However, recently (July 2023), plans for one such trial have been successfully defeated by residents of Whitby, Merseyside. After that defeat, energy minister Grant Shapps said that hydrogen for home heating in the UK as a whole now looks "less likely" – good news, and a considerable victory for campaigners.

Even more recently, there has been some indication that geological sources of hydrogen gas may be economically available ("white hydrogen"). That could be good, to the extent that it would provide a ready-made source of clean-burning chemical energy, side-stepping the energy-inefficiencies of hydrogen production, along with the associated greenhouse gas emissions.

However, the environmental and social side-effects of white hydrogen extraction remain unclear. All the drawbacks listed above would also still apply: the problems

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[14] The paper that I cited on district heating gives a smaller differential than the Hydrogen Science Coalition estimate, but still a large one: x4. Either way, hydrogen does terribly compared to a heat pump, just on energy efficiency grounds, before you factor in emissions. LETI make similar comparisons in their own report.

The UK 6th Carbon Budget (6CB) (2020) recommended that only *surplus* ("curtailed") renewable power be used for hydrogen production. But it still saw hydrogen as a plausible supplier of home heating. The 6CB's middle-road "balanced net zero" (BNZ) pathway envisaged it being used in 11% of homes by 2050. However, all of those boilers would be "hybrid" heating systems, in which most heat still came from heat pumps. The 11% translates to ~2.2% of year-round domestic space heating UK-wide.

with storage, the indirect greenhouse effects of hydrogen itself, and the material constraints in the fuel cell supply chain – and the likelihood that *any* continuation of a hydrogen economy simply maintains the economic viability of *dirty* sources of hydrogen.

For home heating, and not just in the UK, it is clear that, compared to heat pumps and district heating, hydrogen combustion is a dead end.

10.4. Just transitions

So, heat pumps combined with district heating and cooling, are the best ways to decarbonise space conditioning and hot water. Heat pumps in individual homes are the next best thing. Hydrogen for heating buildings is a dud.

Decarbonising electrical grids will require ultra-high voltage DC lines, and diverse systems of power storage so that electrical power can be effectively dispatched on demand, instead of relying on fossil-based sources of energy, and the dead-end of hydrogen.

Green electricity can and should come from distributed, community-controlled mini-grids. Nevertheless, it seems that national, regional, or at least local, grid access will be necessary for most people, in order to buffer fluctuations in local green production and end-demand. This is the case for home heat.

Alongside the full decarbonisation of energy and heat, I think that we should be fighting too for the *decommodification* of essential electricity, globally. I would like to see public ownership of 100% renewable power-generation, power-storage, heating and cooling systems, and the electricity system – all managed democratically in the public interest, locally and nationally. And I think that all households should have "universal basic energy", free at the point of use, to cover an agreed quota of energy needs.

Decarbonising transport, manufacturing industry, and the economy as a whole means that everything presently powered by something other than electricity needs to be transferred *onto* electricity.

This is "energy transition" as normally conceived, and it brings with it the need for a massive *expansion* of the generation of electricity, wherever fossil fuels presently function. This "crowding in" to electricity is one reason why the in-built efficiencies of heat pumps are so important – providing much more useful energy out per energy in than the alternatives.

But *we should also want to massively expand access, globally, to socially-necessary use-values* powered by green electricity: to power basic, and more than basic, needs.

At the world scale, I have referred throughout to the 2018 paper by Arnulf Grubler and his colleagues, modelling a "contraction and convergence" Low Energy Demand (LED) scenario for world energy usage.

In their LED scenario, global access to electricity and standards of living would increase, while global total energy consumption would go *down* to about 60% of where it is today, reaching ~245 EJ/year in time for 2050.

I pointed out that the authors envisage the global north narrowing on its current per capita residential floor area of 30m^2. They see the global south's mean per capita floor area rising from 22m^2 in 2020 to 29m^2 in 2050, and being more evenly distributed. (See part 6.)

All of that indoor living space for ~9.2 billion people in 2050 also needs to be habitable – so they see it built or retrofitted to be energy and thermally efficient.

They have the world total for useful thermal energy (that is, roughly, the heat energy used in the world's buildings) in 2020 at ~12,200 terrawatt-hours (TWh) – that's 12,200,000,000,000 kWh. But that useful energy comes from ~19,200 TWh of final energy: that is, ~40% is lost between energy-in (mostly coal, gas and biomass) and energy-out (mostly heat, in leaky buildings).

Grubler et al project, in 2050, a world total of useful thermal energy available at ~5,500 TWh, and final energy at ~4,400 TWh (16 exajoules). That is, mostly electricity goes in, and *~25% more useful thermal energy comes out* (or is transferred), worldwide. How is that done? Heat pumps and insulation.

In any case, all of the world's buildings – and especially homes – should be able to perform their essential functions of providing shelter and comfort, including sufficiently warm or cool interior space.

Plainly, principles of contraction and convergence should mandate *significant constraints on consumption by the world's largest consumers.*

Just looking at space conditioning: even with dramatic efficiency savings from heat pumps, space conditioning should be constrained – if only to limit the quantity of embodied emissions, and the quantities of materials like rare earths, needed to produce solar panels, wind turbines and the like.

That in turn means rationalising the *use* of buildings to socially-necessary and egalitarian ends, and improving the thermal performance of those buildings, where that is able to constrain lifecycle emissions over (say) a 30-year period of building use.

In part 6, I went into the enormous build-outs in *new* buildings floor area forecast by the IEA and other international organisations– and pointed to the enormous unmet need *right now* in global housing. Decent housing is a basic need, and must be expanded as a matter of political urgency. So operational inefficiencies and inadequacies of buildings cannot be replicated.

That means updating and strictly enforcing building codes. New, aggressive thermal efficiency standards should be applied to new buildings internationally – covering fabric efficiency, and energy systems such as heat pumps.

That is especially important *in locations of rapidly expanding building stocks*. States should mandate the use of heat pumps for supplemental space conditioning and hot water; and/or provide, and be helped to provide, district heating and cooling as a municipal service.

Operational energy is increasingly being regulated, as I mentioned in part 6. Viet Nam and Papua New Guinea are moving solidly in the right direction, according to the UNEP, as are the countries involved in the Caribbean Regional Energy Efficiency Building Code (CREEBC), and the EU, Colombia, Lebanon, Maldives, Montenegro, Panama and Vanuatu.

Those regions that do need to construct more new buildings over the coming decades have – or *should be* *allowed to have* – all the benefits of "late developer advantage". They are in a position to bake in high operational efficiencies in new buildings, to secure standards of thermal comfort, and mitigate the danger of fuel poverty, from the get-go.

Yet those (poorer) countries forecast to experience the most rapid and significant increases in population and building stocks over the coming decades – Nigeria, Bangladesh, India – have weaker measures in place to tackle operational or embodied emissions.

In many such places, there is also *already* a dramatic under-supply of adequate housing, and a lack of *affordable* housing. For example, 54% of Nigeria's urban population are presently defined as living in slums, informal settlements or inadequate housing. Nationwide, *even now*, Nigeria has 16-20 million too few homes for its population.

Evidently, Nigeria needs many millions of new residential buildings. These need to be hyper energy-efficient operationally, and especially thermally. They need to be flood resilient, and need to be fed with stable infrastructures of electricity, heating and cooling, that are equally sustainable, and cheap if not free at the point of use.

With regard to the world's *existing* buildings, there are important conversations to be had globally about the best way, politically, to bring buildings' operational energy and operational emissions into an appropriate "contraction and convergence" pathway.

Heat pumps *alone* bring enormous energy efficiency savings compared to fossil fuel boilers and biomass combustion, as I have shown above – whether they are used in individual buildings, or as part of district heating and cooling networks.

Depending on the thermal performance of existing buildings, *energy conversion* savings like these may be the largest efficiency saving available, even when compared to quite substantial retrofit improvements to fabric efficiency. Fabric improvements are often challenging, can entail disruption, and carry risks if done badly.

Yet, when thermal performance is poor, *significant but shallow* fabric improvements, e.g. draught-proofing and additional loft insulation, can often be made easily. Such
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measures can be enough to greatly improve thermal comfort while avoiding the downsides.

Different pathways will be appropriate according to location and circumstance. Different countries and regions will have different baselines to work from. One important consideration will be how to pace decarbonising space conditioning and hot water, alongside any necessary improvements to the thermal performance of existing buildings through fabric retrofit.

10.5 Conclusions

There are no immovable *social, political or economic* constraints on the people of the world to solve whatever problems they collectively choose to solve. Among those should be sustainable energy and sustainable buildings for all – to address the real needs people have, like decent housing.

But those problems cannot be solved through a system centred on the profit motive alone.

In this series, I have outlined where greenhouse gas emissions come from in the built environment, globally – and many of the means available for decarbonising it. I have also situated decarbonisation in the context of a "contraction and convergence" approach to international development. In this last post I have addressed all this from the perspective of home heating and cooling.

Just transitions are essential in relation to heating and cooling. They are also essential with respect to the built environment as a whole, globally. This means decarbonising *both* embodied emissions, and operational emissions.

In my view, all of that requires the global economy to be rebuilt, and made autonomous from the capitalist drive for profit – oriented instead on providing for essential human needs.

That requires an enormous political effort on the part of the *working* class, globally. It means freeing *national* economies from the directive control of the *capitalist* class. And it means steering the economies of the world in another, more liberatory, direction.

Appendices

Appendix 1. Capital goods: a blindspot in emissions footprints

Materials accounting and emissions accounting can have many blindspots, as I have noted in the main text. A significant blindspot of consumption-based accounting concerns capital goods. This brings the built environment centre stage again, and highlights a problem of defining end-consumption.

Three conventions of consumption-based emissions accounting are discussed in the main text: (a) allotting all end-consumption emissions to individuals, assuming they account for an equal share in national emissions; (b) partitioning end-consumption-based emissions into five mutually-exclusive divisions; and (c) allotting all end-consumption emissions to individuals on the basis of their income-derived share in national consumption.

In (a) and (c), the emissions associated with developing all capital goods – *which include all buildings and infrastructure* – are folded into national production-based *and* consumption-based emissions.

In convention (b), on the other hand, "gross additions to capital formation" are treated only as final products. This category in standardised databases folds together "private capital" (i.e. all commercial fixed capital investments) and "public capital" (i.e. construction and infrastructure undertaken by a state).

However, "private capital" at the very least constitutes *factors of production*. And as such, it is a material input to consumption downstream. Any consumption-based footprint analysis should therefore instead count private-sector "gross additions to capital formation" *not* as a form of end-consumption, but as a form of indirect (intermediate) consumption, part of a necessary supply chain of production upstream of its end-products, and *embodied in what goes on to be end-consumed*.

Furthermore, if private companies' activity is intermediate consumption, surely the same could be said of much government and NPISH consumption.

Treating capital formation as a form of end-consumption is especially a problem in the case of international trade, because this means that all associated material and environmental costs are pegged to the producer state – or, per-capita, to its citizens – instead of being attributed to the end-consuming state or individuals, or to capital. Consumption-based footprint indicators of this kind are effectively just a "trade-adjustment of the production account".

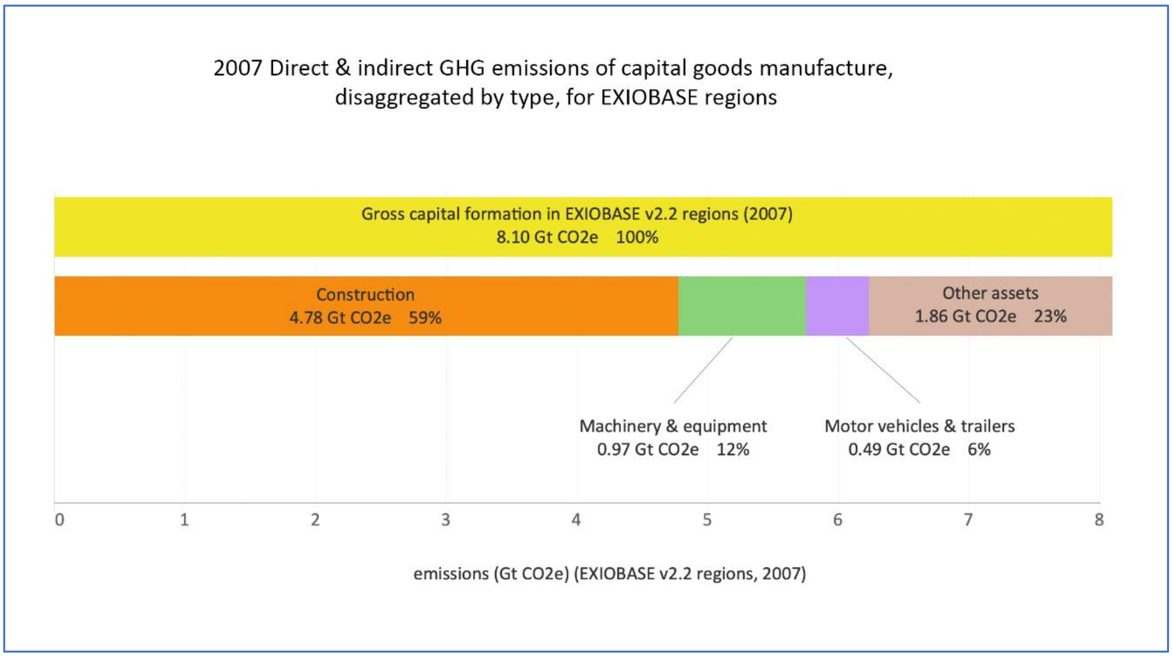
Conversely, in properly-kept *money* accounts, the convention is for the economic costs of fixed capital to be amortised to capital: drip-dripped as a fractional cost of production, "paid for" through revenue as a deduction from profits.

Treating capital goods as a form of end-consumption also means that consumption-based footprint indicators tend to underplay the considerable material footprints and carbon footprints of the service sector, and by extension the consumption-based material footprints and carbon footprints of their customers – since services rely so extensively on stocks of buildings and electronics, which tend to impose a very large embodied impact. Think of hotels or financial services.

Some studies (like this one and this one) have addressed this ambiguity, by seeking to "endogenise" the sum of "private capital" and "public capital" formation to the other end-use consumption categories: household consumption, consumption by governments, and so on. In doing so, they are able roughly to reconcile domestic consumption to exports and imports.

Such studies help us to update our understanding of various products' embodied emissions, and the resulting carbon footprints of different end-consumers. This has been done for some individual countries, and lately using global consumption-based indicators.

Carl-Johan Södersten and colleagues calculated that out of the category "gross capital formation", 38.3% of the embodied emissions was consumed as services, 30.6% was consumed as manufactured goods, and 31% was consumed as shelter. They used data from the EXIOBASE data set, covering most of the world's economies, put together by



Source: Carl-Johan Södersten et al (2017) researchers who analysed the emissions, water, land and materials embodied in trade and final consumption.

Another useful way of slicing the data is to look at the different *varieties* of capital goods produced. These are different kinds of *intermediate products*, used by various branches of the economy to produce end-use goods and services.

The illustration on page 74 is based on previous work by Carl-Johan Södersten and colleagues, which uses the EXIOBASE regions for 2007. Recall that "gross capital formation" for the EXIOBASE regions in 2007 stood at 8.1 Gt CO_2e, or 24% of total GHG emissions (see part 2).

Here we see the carbon footprints of construction (59% of the carbon footprint of all capital goods), machinery and equipment (12%), motor vehicles and trailers (6%), and miscellaneous other assets (23%). (For a similar breakdown for 2011, see here.)

That means that construction comprised around 14% (59% x 24%) of total greenhouse gas emissions for the EXIOBASE regions in 2007. It also comprised 49% of gross fixed capital formation by money value.

However, there remain various technical and methodological challenges in this kind of analysis, and in establishing agreed conventions for it. Among those is that private and public "capital" are tangled up with one another in national accounts data.

Both theoretically and *morally*, it may also not be possible "objectively" to disentangle gross economic gains from capital gains and end-consumer gains, when it comes to capital goods – all the more so where import and export are concerned.

Presumably, it is for those reasons that the most widely-cited indices still do *not* "endogenise" the material footprints and carbon footprints of capital goods to other categories of final consumption. Nor do they break capital goods down by type, as above. Capital goods footprints tend instead to be simply folded into producer state material footprints and carbon footprints.

In any case, we can see that the global emissions of *the construction of the built environment* comprise, firstly, around 59% of the emissions of all capital goods, and, secondly, a significant portion of global emissions, around 14%, based on the 2007 EXIOBASE data.

Buildings and infrastructure are a crucial part of material flows, and material stocks worldwide – but the role of the built environment is often obscured. Buildings and infrastructure are a fundamental part of fixed capital stocks. They are also a crucial mediating factor driving the consumption of resources, and the production and reproduction of the forms of society we live in.

More broadly, the ways that you trace the movement of materials locally and globally always imply a particular politics, a way of seeing.

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Appendix 2. China's climate policies

China's Nationally Determined Contribution (NDC) under the Paris agreement has to some extent been informed by research at the Institute of Climate Change and Sustainable Development (ICCSD) and at the Institute of Energy, Environment and Economy (3E) at Tsinghua University.[1]

At least for the ICCSD, 2060 "carbon neutrality" meant zero-carbon and net-zero greenhouse gas emissions – passing through net-zero CO_2 by around 2050.

According to Xie Zhenhua, China's special envoy for climate change, that is also the case for the 2030/2060 vision announced in 2021: peak CO_2 emissions by 2030, then net zero for all greenhouse gas emissions by 2060.

However, according to the Climate Action Tracker, the Long-term Low Greenhouse Gas Emission Development Strategy (LT-LEDS/LTS) that China submitted to the UNFCCC in October 2021 as part of its updated NDC still "strongly suggests that the carbon neutrality target covers carbon dioxide only". And because of the scale of China's emissions, this makes a big difference, adding or subtracting 0.1°C to overall global warming by 2100.

In China, the 2030/2060 agenda is now contained within the CCP's 14th Five Year Plan (14FYP), which covers 2021-2025. The energy plan component of the 14FYP was announced in late March 2022.

Key words throughout the English-language Outline of the wider 14FYP are "development", "rational", "orderly" and "harmonious". And the Chinese Communist Party (CCP) apparently wants wiggle room in its emissions pledges before 2030 to secure all that.

New installations of wind and solar for 2021-2025, totalling 570 GW, were provided for in the 14FYP (see charts in section 4.2). These plans updated and seemingly accelerated the 2030/2060 targets. Whereas the 2030/2060 timeframe had more than 1200 GW of installed wind and solar by 2030, the 14FYP version has capacity reaching 1100 GW by the end of 2025.

As of early 2023, the Chinese government had upgraded its installed capacity targets for wind and solar during the 14FYP. The 570 GW target of new wind and solar installations, foreseen for 2021-25, has been upgraded to ~870 GW of new installations. This implies a combined capacity 1,400 GW by the end of 2025.

The scale of these plans is enormous, *as it should be*.

Yet, such is the growth in the size and energy demand of China's economy, that planned gains in non-fossil energy sources (renewables + nuclear) are insufficient to keep up with growing energy demand. Any balance to 2025 will be met by coal.

Specifically, China-based Guosheng Securities forecast in March 2022 that annual energy consumption in China would rise by nearly one fifth by 2025, from 4.98 billion tonnes of coal equivalent (tce) (or ~40 *million* gigawatt hours) in 2020, to 5.92 billion tce (~48 million gigawatt hours). They forecast non-fossil energy consumption would rise from 0.79 billion tce (~6.4 million gigawatt hours) in 2020 (15.9% of total consumption), to 1.18 billion tce (~9.6 million gigawatt hours) in 2025 (19.9% of the total).

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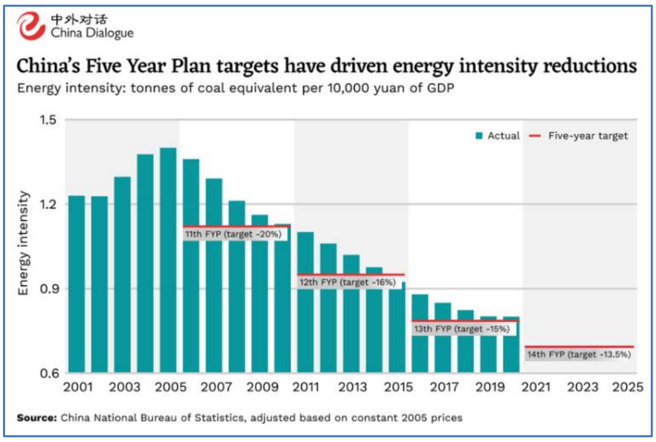
[1] See a summary on Carbon Brief, by Lauri Myllyvirta, here

This is a 49% increase in the scale of non-fossil energy capacity – again, definitely a good thing. But if the Guosheng forecasts are borne out, that will *only cover 41% of the increase in overall energy demand*: 59% of the increased demand would be met by fossil fuels, mostly coal.

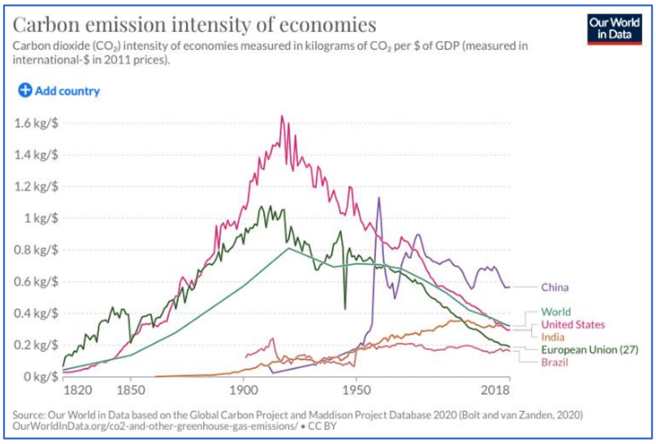
This is the basic dynamic behind the fact that China's greenhouse gas emissions continue to rise year-on-year, and have yet to peak – although odds-on they will peak before the CCP's 2030 deadline. As I mention in the main text, updated analysis by Lauri Myllyvirta now suggests that China's emissions *could* peak in 2024.

During the 14FYP, there remains a perennial focus on lowering the energy intensity of GDP growth – which is good. Even if the energy source is as dirty as coal, it is better if the intensity of its use per unit of GDP falls over time – that will help steer emissions downwards.

Thanks in part to those reductions, China's *carbon*-intensity per unit of GDP is likewise tracking downwards – although as it is based on coal, it is descending from a comparatively high level – as you can see in the second graph below.



Source: China Dialogue / China National Bureau of Statistics



Source: Our World in Data / Global Carbon Project & Maddison Project Database

In any case, the Climate Action Tracker finds China's present efforts to still be far *less* than the highest possible ambition demanded by the Paris agreement. They define even China's modified 14FYP pathway "insufficient", and "highly insufficient" based on a "fair share" appraisal of the pathway China should be targeting. They give China an overall rating of "highly insufficient", with its net zero target judged to be "Poor".

That basically rests on a judgement that China is still simply not moving fast enough – at least as far as its official declarations are concerned. Though decarbonisation does genuinely seem to be the CCP's end goal, and there seem to be the beginnings of a "realist" roadmap for getting there, for now the problem is that the government seems to be *positively embracing* increased emissions from coal in the short term.

The original 14FYP also *backloads* the heavy lifting of decarbonisation to *after 2030*. Rapid and deliberate cuts in emissions before 2030 seemed to be regarded as a bridge too far.

Coal in the post-Covid economy

As the world emerged from the first phase of Covid shutdowns in 2021, a jump in manufacturing orders brought a commensurate spike in the demand for electricity across China. With inadequate "peak" supply in place, China experienced widespread power outages.

Then, in summer 2022, widespread use of air conditioning – spurred by record-breaking heatwaves – took China's peak electricity consumption to a record high. At the same time, droughts and low rainfall put hydropower reservoirs out of action. With as-yet insufficient methods of energy storage to even out variations in supply, this caused electricity shortages, as it had done in 2021.

The upshot was an increased recourse to coal as a ready source of dispatchable power. Previously closed coal-fired power stations were brought out of retirement to bridge the energy gap. From the CCP's point of view, these power shortages brought a threat of social upheaval, and potential political upset.

These cautionary experiences in energy insecurity cemented coal in place as a flexible, backstop energy supply for China's energy transition. Accordingly, by the summer of 2022, the 14FYP enunciated a twin focus: large build-outs in new renewables on the one hand, partnered with a continued reliance on and expansion of coal.

The CCP further speaks of a "coordinated and orderly" energy transition. It wants a "single game" conducted nationwide, without scattershot or chaotic "campaign-style" local efforts in emissions reduction.

The CCP say they are now moving away from coal as the "mainstay", towards coal as the "support". But in performing this pivot there is also a move to *transfer most of China's existing coal-power capacity to western China*, away from population and manufacturing centres in the east.

The twin renewables-plus-coal energy infrastructure is being packaged in many cases as so-called "clean energy bases" – enormous, multi-gigawatt-scale facilities, mostly located in China's deserts, and connected to centres of energy demand by long-distance DC power lines. In these, according to Lauri Myllyvirta, "typically one gigawatt of new coal power is built for every six gigawatts of wind and solar".

By 2022, the bottlenecks in renewables installation in China were no longer economic or technological, according to Jiang Yifan, Gao Baiyu and Sam Geall, writing in China Dialogue. The challenges concerned the ability of electricity grids to absorb and relay power, and the political economy of managing uneconomic coal installations, with the various regional fluxes of coal development and deindustrialisation.

Planned coal capacity grew dramatically through 2022. Yet Xi Jinping pledged in 2021 that coal *consumption* would decline during the next five-year plan period of 2026-30.

China's 2060 "carbon neutral" vision therefore seems to depend on seeing *new coal as an economic loss-leader and stranded asset* – only ostensibly operating by market imperatives, meant for mothballing before its lifetime of use is up, and made possible entirely by government finance. One piece of supportive commentary (quoted by Carbon Brief) characterised the policy in terms of coal providing "drip irrigation".

In 2023 this strategy seems even more clear. According to Carbon Brief, the CCP's energy plan for 2023 includes studying capacity payments for coal – that is, utilities will be paid simply for *maintaining dispatchable coal capacity*, instead of for the actual electricity generated from coal-power. (See here for a policy outline document from the EU on such schemes.)

However, as Carbon Brief also notes, the danger remains that local utilities could go ahead and use coal power *beyond* peak necessity. Coal interests may prove unwilling to forego profits, and to be demoted to their support role. Local lobbying could likewise stimy central government's efforts to throttle unnecessary coal output – as happened before in 2015 – with the effect that demand for the market in new renewables could be curbed.

Nevertheless, the rollout of new coal-fired power capacity *need not entail continued reliance on coal-fired power*. And more coal power *could* still remain compatible with peaking emissions by 2030 or before.

There are critics within China who think this path of coal dependency unwise. Simply from within the governing class in China, Carbon Brief cites Wang Zhixuan, a former general secretary of the China Electricity Council, and Zhou Dadi, former director general of China's Energy Research Institute.

In 2023, the focus among observers of China's economy was on the causes of China's apparent economic downturn. Some saw them as related to China's difficulty in managing the Covid-19 pandemic, others attributed them to deeper-going factors.

Any stagnation and its causes are enormously salient for the future trajectory of fossil capital and of a potentially green capitalism. They would also be salient to the urgent task within China of reconfiguring the form of the economy and its built environment for a zero-emissions future.

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Appendix 3. Counting the built environment's greenhouse gas emissions in six steps

There are various ways of counting the greenhouse gas emissions from the built environment. Here I will lead you through the data that I have drawn on, in six steps.

Step 1. Estimating the total global greenhouse gas emissions in 2018.

I use 2018 as the reference period, because at time of writing, that is the most recent year for which I have found published data for world greenhouse gases emissions (the EDGAR dataset).

As the following graph shows, in 2018, the *entirety* of sociogenic greenhouse gas emissions was about 58 gigatonnes of carbon dioxide equivalent (Gt CO_2e). CO_2 and methane (CH_4) are the main climate-forcing gases. 65% of the total is CO_2 from fossil fuels combustion and industrial processes (CO_2 FFI); 10% is CO_2 from land-use, land-use change, and forestry (CO_2 LULUCF). 18% is methane (CH_4).

There is a controversy among researchers about how to count the climate-changing effect of methane. It stays in the atmosphere a much shorter time than carbon dioxide, but pushes global warming much faster while it is there. In the following steps, in line with common practice, I have assumed that the global warming potential of methane is 28 times greater than carbon dioxide. One alternative approach, noted by the IPCC, would count the effect of methane as 81.2 times greater than that of carbon dioxide – and this would increase the role of methane further.[2]

Step 2: assessing the built environment's share of the total

In section 5.4, I presented an overview of the built environment's embodied and operational emissions by combining data from the IEA and other sources. It is shown in a panel of bar charts. [3]

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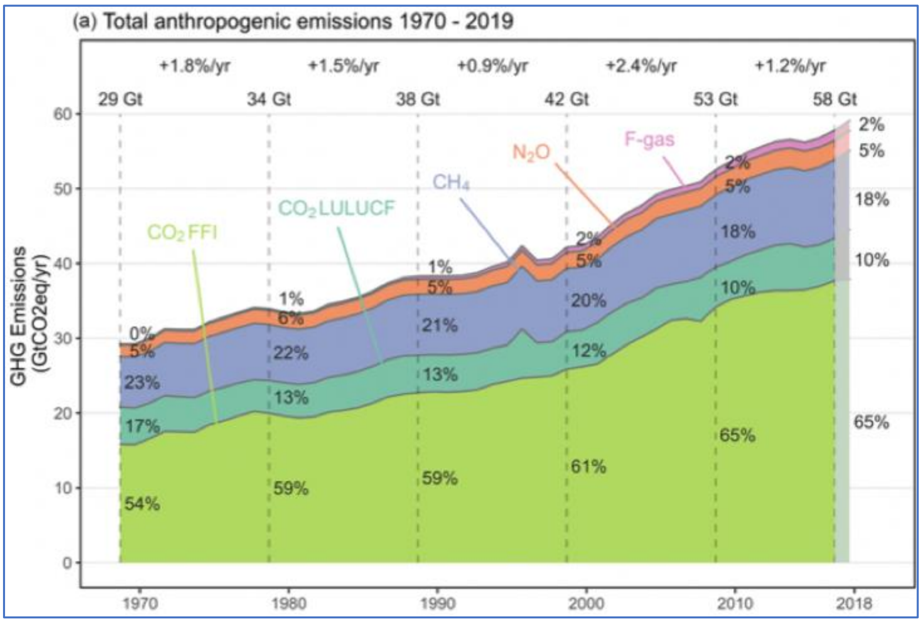
[2] Quantities of methane and all other non-CO_2 greenhouse gases are often expressed in terms of their global warming potential (GWP) relative to CO_2. Here, that is using a 100-year time horizon (GWP-100), and without consideration of climate feedbacks. On that basis, methane's GWP is 28 (i.e., 28 x the warming potential of CO_2), and this accords with the IPCC's Fifth Assessment Report (AR5, 2014). (See the parallel Global Methane Project.)

Methane, "has a short lifetime in the atmosphere […] about 9 years for the year 2010" – but it is an incredibly potent greenhouse gas for that short time. In the view of many experts now, a 20-year GWP (GWP-20) for methane is therefore more appropriate – and the IPCC's Sixth Assessment Report (AR6, 2022) suggests a GWP-20 of 81.2 if a GWP-20 is used. On that modelling basis, methane emissions in 2018 would *roughly triple* – from ~10 GtCO_2e to ~30 Gt CO_2e. Overall emissions would be ~78 GtCO_2e, of which methane would comprise ~38%.

[3] *Here is a note about methodology.* In the bar chart, I made a couple of small substitutions. Only in 2020 did the IEA / GlobalABC start quantifying the energy-related carbon footprint of the construction industry beyond buildings construction – i.e., for infrastructure as well. They estimated that each sector produces about 10% of energy-related CO_2 emissions – these were estimates for the portions of industry's overall energy-use devoted to manufacturing building construction materials such as steel, cement and glass, plus the (marginal) direct energy-use in construction transport etc.

By contrast, their 2018 data had infrastructure construction bundled in with "other industry", with buildings construction at 11% of energy-related CO_2 emissions. For the 2018 data, I've applied the 2 x 10% figure. Correspondingly, I have switched "other industry" from 31% to 22%.

Note too that in bar chart (b) in section 5.4, the mass of CO_2 FFI (in light green), and the mass of all global energy-related greenhouse gas emissions



Source: Global Carbon Project / Jan C. Minx et al (2021) (EDGAR dataset). Note: based on global warming potentials with a 100-year time horizon from the IPCC Fifth Assessment Report (AR5)

Built-environment emissions are mostly captured by adding together the sector's energy-related CO_2 emissions, the process emissions of cement, and the process emissions of steel manufactured for the construction industry. Those data are compiled by the IEA, and widely cited. I supplement some additional data.

Step 3: operational emissions

In the bar charts in section 5.4, there is a conceptual skew. While the embodied emissions come from the construction of both buildings and infrastructure, operational emissions are shown *only* for buildings.

Infrastructure has no operational emissions here because many of the "operations" of infrastructure are conventionally regarded as distinct and outside the scope of the built environment – as with the operation of the transport and energy sectors. These have their own emissions footprints.

However, the energy-related emissions of services such as water and waste management are also not included here.

In line with the discussion in part 2, operational emissions will on the average be much higher where they cater to more energy-intensive lifestyles and production and consumption processes.

One important countervailing factor, however, concerns biomass combustion. Biomass combustion produces a lot of greenhouse gas emissions – per unit of energy released, wood combustion releases more greenhouse gases than coal. And it is mostly the world's poor who depend on burning biomass, instead of using fossil fuels or electricity.

Biomass combustion is, however, widely understood to be "renewable" – the assumption being that biogenic carbon released into the atmosphere is "balanced" by prior or subsequent plant growth. If that "flux" sums to zero, biomass combustion is said to be "net zero". However – as I noted in relation to plant-based construction materials – there is an important time component to the "flux". This is crucial in the context of a rapidly diminishing carbon budget for the world.

Moreover, a very large proportion of the CO_2 released into the atmosphere from biomass combustion is in any case *not* reabsorbed.

I show some of that *net gain* in atmospheric CO_2 in bar chart (c) in section 5.4. Here I include a recent estimate for the scale of the *non-renewable* CO_2 wood combustion emissions that are associated with "household food preparation" globally. Most of that combustion is for cooking.

To be clear, "non-renewable" here means that a "high extraction rate [of wood] does not allow time for the biomass to [ever] regrow". This leads to a sustained net loss in stored biogenic carbon – and a net gain in atmospheric CO_2.

As I note in the main text, CO_2 wood combustion emissions like these are a component of the category "land-use, land-use change and forestry" (LULUCF). They are *not* included in the IEA's "energy-related CO_2 emissions" data, and this is normal practice in emissions accounting under the UNFCCC and Kyoto Protocol. (The limited *non*-CO_2 emissions arising from biomass combustion – such as methane and nitrous oxide – *are* conventionally counted in energy-based emissions.)

Note that the study cited here looks only at *wood* combustion, and not the other types of biomass combusted, like dung. It focuses exclusively on tropical countries, where wood burning is taken to be 100% for food preparation, and 0% for space heating. The figure given here (~0.7 Gt CO_2) therefore *excludes* whatever non-renewable CO_2 emissions are associated with space heating in colder climates.

It also has a very large range of uncertainty: -63% to +64%.

I have said that, in my view, all biomass combustion for human use should be kept to an absolute minimum. The solution, in the case of cooking, is electrification – and economic assistance to provide electric cooking equipment for the world's poor. The solution in terms of heating is also electrification – heat pumps – alongside legislated bans on wood burning. For the most part, harvested wood should only ever be used for durable products, with a long useful life.

The "natural" incidence of forest fires is meanwhile dramatically increasing worldwide; and forest clearance by deliberate burning runs rampant.

The bar charts in section 5.4 also show my own rough estimate for the share of *operational* methane emissions related to the built environment.

(CO_2e, in red), are very similar. However, this is coincidental – they are different indices.

There were ~10.5 Gt CO_2e of anthropogenic methane emissions in 2018, according to the Global Carbon Project. Around another 5 Gt CO2e arise naturally each year from wetlands, the IEA estimates. Around 36% of anthropogenic methane comes from agriculture; and around 33% comes from fugitive and vented emissions in the energy sector – of which I estimate ~0.9 Gt CO_2e / year relates to the operational use of buildings globally.[4]

Note that this does not include the share of methane emissions associated with *construction.*

Step 4: embodied emissions

When you take a step back, it is incredible to think that the construction industry annually funnels something like 43 Gt of materials into the production of about 30 Gt of newly built stocks of buildings and infrastructure – *and* in doing so it throws 8 Gt of CO_2 emissions into the atmosphere.[5]

Putting that another way: *the mass of CO_2 emissions by global construction has around 25% of the mass of the finished built environment stocks produced* – while the total mass of sociogenic emissions outweighs the mass of new construction.

In itself, that is no particular indictment – it is just the nature of the materials, and the prevailing chemical processes of industry. But the physical facts are extraordinary.

In chemical terms, most of the mass of CO_2 emissions from global construction come from the mass of oxygen in the air. When carbon-based fuels are burned, oxygen reacts with carbon to produce carbon dioxide.[6]

However, in the case of cement's process emissions, the mass of the CO_2 derives from the limestone inputted.

Step 5: impacts not reflected in these data

The IEA data are not exhaustive. Aside the additions I've made, they exclude non-CO_2 energy-related emissions.

There are also plainly very many other environmental impacts caused by the built environment, apart from greenhouse gas emissions. For example, built-up areas displace natural habitats; and human habitation often brings many other varieties of pollution.

Step 6: comparison with the data in part 2

The 2007 data in part 2, and the 2018 data here, give us different analytic points of view on the same underlying processes of material consumption and emissions waste.

From the data in part 2, it is estimated that global construction (the built environment component of fixed capital formation) was responsible for around 14% of total greenhouse gas emissions (see Appendix 1). Here, for 2018, it comprises practically the same proportion of energy-related CO_2 emissions + process emissions for the world as a whole: 11.4% + 3%.

What is here placed under operational energy-related CO_2 emissions categories, in the 2007 data would have been subsumed within the household and government end-consumption carbon footprints that excluded capital formation: direct emissions through home heating, indirect emissions through consumed services, shelter, manufactured goods etc.

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Appendix 4. What drives floor area increases?

The building floor area growth projections discussed in section 6.3 are based on the IEA's Energy Technology Perspectives buildings model, which is itself based on collaborative work between the IEA and the Building Energy Research Centre of Tsinghua University (TU).

The researchers sought to understand the main drivers of the extent of residential and non-residential floor area per person. To do that, they drew on historical data from "more than 110 countries, dating back as far as 1950". Their thinking and methodology are outlined in a joint report from 2015 (and also here and here).[7]

Across regional and cultural variations, they understood that, as individual incomes have risen, people have tended to live in households of fewer people, and pay to live in larger dwellings.

These trends were seen to be in evidence for populations as a whole: as a country "developed" economically and GDP per capita increased, so dwelling sizes increased, and households became smaller – subject to the availabilities and vintages of suitable dwellings. In the UNEP's terms, there is a "reasonable correlation" between GDP per capita and *residential* floor area per capita.

Once regional and cultural differences determining household size were stripped away, per capita residential floor areas was basically understood to be a direct function of income. The *total* demand for domestic floor area in a country or region was likewise the product of the size of its population and its GDP per capita.

In short, the research concludes that *domestic floor area per person is just another form of material consumption that tends to increase with rising income and wealth*.

Greater economic activity also seems to have been correlated with increased *non-residential* floor areas. The researchers' data refer to "commercial [buildings], services, education, health, hospitality, public and other non-residential" buildings, but exclude industrial premises.

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[4] This is my own estimate, based on a 100-year global warming potential. I am not aware of a sectoral breakdown that establishes the proportion of those fugitive and vented emissions related to the operational use of buildings globally

[5] These amounts are based on the 2015 figures on material use cited in the main text, and 2019 emissions data

[6] The molecular weight of CO_2 is 44 grams per mole, and the molecular weight of oxygen (O_2) is 32 grams per mole. So ~73% of the weight of combustion CO_2 comes from O_2

[7] The population projections that the IEA/TU feed into their floor area projection models come from the UN Department of Economic and Social Affairs (UN DESA) Population Division. The GDP forecasts to 2050 come via the International Monetary Fund (IMF); and for GDP forecasts beyond 2050 the IEA applies its own projections

These are some observable effects of economic growth. However, the connection between GDP-per-capita and floor area needs to be questioned, and it needs to be broken.

I have said that urban populations *can* grow as a function of per-capita economic growth. But they can also grow in the total absence of any economic growth whatsoever.

What are those in poverty meant to do to acquire adequate shelter? And yet, such people can seem invisible when you read these floor area forecasts – or their material circumstances mistaken for something they are not.

A case in point is that there seems to be a common assumption that urban population growth – *in whatever economic context* – leads to economic growth and income growth. The one-way causality is routinely suggested, by researchers at the IEA, UNEP and other international agencies. Rarely is the alternative explored.

Take a report by UNEP (2018): "Urbanisation is associated with increases in overall and per capita income"; "cities tend to generate more income per capita as they increase in size"; "cities produce 80 per cent of global GDP and just 100 cities may account for 35 per cent of global GDP growth by 2025".

As far as floor area expansions go, the inference runs like this: population growth tends to spur increases in residential floor area – *because sufficient household economic resources are naturally made available* to meet the growing social demand for new housing, on a capitalist basis.

This is a "classical" model of urban growth familiar from European history. It is also familiar from the recent history of China. Rising incomes pay for new homes. But it is far from the only story.

If most rises in GDP globally are associated with cities and rural-urban migration, that hardly means that cities, urban population growth, and rural-urban migration *in and of themselves* bring income gains for those involved, and that these will pay for suitable new habitation in the prevailing economy.

Other forms of urban development occur, besides the "classical" one. "Urbanisation without growth" is a harsh reality that many in the world endure.

And as I noted previously, "natural" demographic expansion has been the main factor driving urban population growth among poorer countries, although migration into cities from also-more-populous rural areas has been significant too.

Where population growth continues to outpace economic development, the question is then whether sufficient economic activity – formal or informal – can be generated to *absorb* a growing population that lacks any other non-market means of subsistence. Often, it cannot.

That problem could get much more acute as climate change brings ever-greater scales of environmental degradation, driving more and more people to migrate.

Assuming that a "classical" narrative of urban growth will unfold seems hopeful at best, and potentially misleading. Instead, housing needs should be met, and building floor areas forecast, *on the basis of real needs*.

A second mistake here – or perhaps an ideological sleight-of-hand – seems to concern conflating per-capita GDP growth with income growth. But just because the overall value of transactions in an economy grows, it does not mean the share that goes to income rises, or that the gain is widely shared.

Yet perhaps the main factor is that, within a certain boosterish mindset, capital investment is often talked up to the degree that GDP growth is seen as inevitable; and there is a similar assumption – as much about the task of political persuasion – that income levels are bound to follow. According to this view, investment opportunities are the aim – from which social welfare will just *trickle down*.

European history, and China, are assumed to be the precedents that other countries can, will and should follow – whereas there are many other courses that urban population expansion can take and does take.

Other options are also available for improving the material conditions of populations – beyond an economy steered only towards capital returns, and premised on dramatic increases in volumes of material consumption.

It cannot be assumed that high levels of capitalist investment are the answer for urban populations already found "surplus" to the needs to capital.

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Appendix 5. Critique of the International Energy Agency's approach

There are big technological *and economic* obstacles to energetically retrofitting existing economies of construction – but continuing these economies in something like their present form seems to be *the* direction favoured by the IEA.

Tracking report
Cement
● Not on track
November 2021

Tracking report
Iron and Steel
● Not on track
November 2021

Tracking report
CCUS in Industry and Transformation
● Not on track
November 2021

Tracking report
CCUS in Power
● Not on track
November 2021

Tracking report
Tracking Buildings 2021
● Not on track
November 2021

The IEA's assessment of progress on decarbonisation. Source: adapted from the IEA website

Above all, the Agency – set up in the 1970s to coordinate action by rich oil-consuming countries against the challenge from producers in the Organisation of Petroleum Exporting Countries (OPEC) – seems to have accepted the role of advising governments to do only so much as they need to, in order to conserve the present state of things. Aside from begging for emissions-mitigation measures, they see the existing form of political economy continuing to operate as is.

In the IEA's view, for-profit investments should be deployed (fingers crossed!) to update the forces of production, on the basis of the existing *relations* of production, in order to grow still further the pie of world consumption, and maintain as far as possible the value of existing capital investments.

There is a form of "realism" here, which consists in accepting the economic balance of forces of the world economy as it stands; and seeking to steer the technical content of the relations of production in a decarbonising direction, simply by the power of good technocratic common-sense.

Certainly there is a role for that. For example, where liberal regulation can be brought to bear on rapidly decarbonising the energy sector.

However, it is also a form of idealism: expecting entrenched property interests to be moved by words, ideas and ideals alone.

There is also a good deal of contradiction. Fossil energy needs to be closed down over the next decade or so; states need instead to mobilise *and share* the forces of labour and technology, *via their own resources of capital* – outside of the irrationalities, misallocations, chaos, and short-term profit horizons of private capital.

And a good deal of cognitive dissonance: the IEA continually bases its recommendations on the assumption that technological solutions can be applied *as is*, at sufficient scale so as to magic away the emissions problem for energy-intense areas of the economy. Such is the case with their continual endorsement of pathways that depend on various forms of carbon capture and storage (CCS).

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For cement, the IEA models, for reference, a business-as-usual Stated Policies Scenario, in which global cement output rises slightly, from 4.1 Gt in 2019, to 5 Gt/year in the mid 2040s, and then declines to about 4.8 Gt in 2070. In place of that, they press their Sustainable Development Scenario, where annual use of cement ends up at about 3.5 Gt/year in 2070. Emissions in 2070 from cement production would be 2.3 Gt CO_2 in the Stated Policies Scenario, and just 0.2 Gt CO_2 in the Sustainable Development Scenario – but that success relies 80% on the use of CCUS.

To be fair to the IEA's researchers, they do see demand reduction and materials efficiencies as also key to this "net zero" cement pathway – to reduce process emissions at source, and the need for carbon capture.

As for steel, under the Sustainable Development Scenario, the IEA sees crude steel production levels remaining roughly the same in 2070 as they were in 2019 – kept at that level by materials efficiencies in end-use and through more effective recycling and secondary production.

By contrast, a recent report by E3G says that 1.5°C of warming means that steel sector emissions "need to fall by at least 50% by 2030 and by 95% by 2050", compared to 2020 levels. China needs to cut its steel emissions by 99% by 2050.

Surveying the sector, the IEA thinks that energy-related efficiencies in manufacturing of 20% may be possible by 2070. Electrification and renewable sources of electricity such as hydrogen count for a further 9% reduction in emissions, with direct fuel-shifting from coal to gas providing another 7%. CCS counts for about 30% of the envisioned reduction in end-use emissions.

But as things stand, the vast majority of the IEA's pathways to a Sustainable Development Scenario are "Not on track". These include their pathways for cement, for iron and steel, and for carbon capture, use and storage (CCUS). In fact, 34 out of 38 clean-energy technology pathways assessed by the IEA are so far failing to materialise.

Decarbonising the Built Environment: A Global Overview by Tom Ackers

A peoplenature.org pamphlet

Architects on a Fridays for Future day of action in London. From Architects Declare twitter feed

People & Nature
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Or email & ask for updates that way
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