The Role of Low Carbon and High Carbon Materials in Carbon Neutrality Science and Carbon Economics

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Abstract

Focusing on switching the energy inputs to economies from fossil fuels to renewable energy and neglecting material outputs gives an over-optimistic picture of achieving carbon neutrality. We propose a set of equations that integrate analysis of energy and materials, provide a framework for a new carbon neutrality science, and lead to three carbon neutrality conditions. The equations are applied to low carbon materials, such as metals, and high carbon materials, such as wood. Refining carbon is the key carbon dioxide (CO_2) emissions source to minimize for steel and aluminium, but slow technological change could create a 'carbon neutrality gap' by 2050. This will increase in size unless forest expansion is accelerated to offset remaining CO_2 emissions. Principles of a new carbon economics are proposed and applied. Policy priorities include integrating energy and materials in carbon neutrality strategies, strengthening carbon reporting standards, establishing national wood products databases, increasing afforestation rates, and controlling deforestation.

Key words: carbon neutrality; net zero carbon emissions; Life Cycle Analysis; materials; bio-based economy; carbon economics

Introduction

Carbon neutrality, in which emissions of carbon dioxide into the atmosphere are offset by its removal from the atmosphere, could become the leading global environmental goal of the 21st Century. Concern about changes in global climate caused by the rising atmospheric concentration of carbon dioxide (CO_2) (and other greenhouse gases) (1) has led a growing number of countries to commit themselves to carbon neutrality (2). In 2019 the UK pledged to achieve this goal, which is also called net zero carbon emissions, by 2050 (3). It was followed in 2020 by Japan (4), and by China, whose target is 2060 (5). Later in 2020 the Secretary General of the United Nations called on all governments to "declare a Climate Emergency in their countries until carbon neutrality is reached" (6).

One constraint on realizing this goal is that national strategies and academic research have so far focused on switching the *energy inputs* to economies from fossil fuels to renewable sources, and neglected the *material outputs* of these economies. Whereas 35% of the 49 Gigatonnes of CO_2 equivalent (Gt CO_2eq) of all annual greenhouse gas emissions are directly linked to energy production, industry accounts for 21% (7) and too little attention has been paid to reducing emissions from using fossil fuels in "energy-intensive industries" which produce iron and steel, aluminium, chemicals, cement and forest products (8-12). Society depends on these materials, e.g. to construct buildings and vehicles which account for another 6% and 14% of emissions, respectively (7). As these and other material uses influence *demand* for energy, concentrating on energy *supply* is rather one-sided, so integrating the analysis of materials and energy is crucial to gaining a better understanding of likely future trends in CO_2 emissions from using fossil fuels. Yet only 6% of the 2,265 journal papers that we analyse here focus on materials, and they have been published in multiple, weakly interacting, scientific literatures (13). To fill this gap, bridge these literatures and contribute to the carbon neutrality literature, in this paper we show how trends in producing and using materials could promote or delay the achievement of carbon neutrality.

Materials differ in how their manufacture depends on fossil fuels. *Low carbon materials*, such as metals, have a low carbon content but fossil fuels consumed in their production and use emit much CO_2, so this dependence must be changed to reduce total CO_2 emissions. Wood products, on the other hand, are *high carbon materials* that are rich in carbon sequestered from the atmosphere by forests and need less energy for their production. Forests, and carbon capture and storage technologies that store carbon dioxide in underground reservoirs or as carbonated minerals (14), are central to achieving carbon neutrality by offsetting CO_2 emissions (15). If forests are to be sustainable carbon sinks they should be managed sustainably, their trees regularly felled and replanted, and the carbon in harvested trees stored for long periods in wood products. To transfer large amounts of CO_2 from the atmosphere to the Earth the world will actually depend *more* on carbon, not less, so it is misleading to talk about a "low carbon economy" (16) – or even a "post-carbon economy" (17). Here we compare the main sources of CO_2 emitted in producing and using low and high carbon materials, and show how to reduce them.

Scientists have struggled to keep pace in conceptualizing novel environmental concepts (such as sustainable development) that originate in the government arena or outside it in civil society (18), and the same applies to carbon neutrality. By using physical variables and equations, a new *carbon neutrality science* could integrate energy and materials analysis, provide a common language for all carbon literatures, test hypotheses about alternative *carbon transition paths* (19-20), and support the political process of carbon neutrality by measuring progress towards achieving carbon neutrality (and later zero carbon emissions). This paper identifies ten existing equations in carbon literatures, and extends life cycle analysis (21) to propose eight more equations for the new science and three conditions for carbon neutrality. It also proposes seven principles of a new *carbon economics* which can explain how carbon transition paths arise and how to manage the emerging carbon economy.

This paper has five sections. The first reviews key literatures. The second proposes new carbon neutrality equations and conditions, which are used in the third and fourth sections to evaluate the roles of low carbon and high carbon materials, respectively, in achieving carbon neutrality. The last section proposes and applies some principles of carbon economics.

Key literatures

Research into reducing anthropogenic CO_2 emissions has grown rapidly since the year 2000 and is reported in seven literatures: decarbonization, low carbon economy, carbon transition, low carbon development, carbon neutrality, zero net carbon emissions and carbon footprint (Fig. 1). This section identifies equations published in these literatures and the relative priorities which each literature gives to energy and materials. Generic insights are provided by literatures on the circular economy and life cycle analysis, so these are reviewed too.

Global carbon budget

Empirical analysis in this paper is framed by two equations used by the Intergovernmental Panel on Climate Change to represent net CO_2 emissions into the atmosphere (C_n):

1. $C_n = C_{ffc} - C_{oc} + (C_{luc} - C_{terr})$

where C_{ffc} refers to emissions from fossil fuel use and cement production, C_{oc} ocean uptake, C_{luc} net land use change emissions and C_{terr} other terrestrial uptake (22); and

2. $C_n = (C_{end} + C_{eno} + C_{ind} + C_{tran} + C_{bld}) - C_{oc} + C_{afolu}$

where C_{end} denotes direct emissions from energy production, C_{eno} other energy emissions, e.g. in blast furnaces, C_{ind} emissions from industry, C_{tran} emissions from transport, C_{bld} emissions from buildings, and C_{afolu} net emissions from agriculture, forestry and other land use (7).

Decarbonization

Decarbonization is the process by which energy generation and national economies become less dependent on the fossil fuels whose use emits CO_2 (23). "Deep decarbonization" requires a sharp fall in emissions (24) or structural changes in some economic sectors (25).

A quarter of a sample of 2,265 papers published in international peer-reviewed journals between 1995 and 2020 that we found in a Google Scholar search have ‘decarbonization’ or related words in their titles. The shares of papers on energy (43%), transport (12%) and buildings (6%) are commensurate with their shares of all direct greenhouse gas emissions (7), but producing materials only accounts for 5% and other industrial processes 2% (Table 1).

Early research led to the “Kaya identity”, which “decomposes” the underlying causes of trends in carbon dioxide emissions from energy use (C_{en}) into several “drivers”, namely population

(P), gross domestic product (GDP), *energy intensity of GDP* (energy (E) used per unit GDP), and *carbon intensity of energy* (carbon emitted per unit of energy) (26):

3. $C_{en} = P \times (GDP/P) \times (E/GDP) \times (C_{en}/E)$

This identity is still widely used (27), but has been extended by including CO_2 emissions and sequestration linked to "non-energy factors" (28) to give net national terrestrial CO_2 emissions (C_{nt}):

4. $C_{nt} = C_{en} + (T_{ag} + T_{res} + T_{seq}) + (P_{sh} + P_{av}) + (C_f + C_{gs}) + (N_{non} + N_{seq} + N_{cr})$

These factors include "territorial emissions" within a country from agriculture (T_{ag}) and cement and fertilizer production etc. (T_{res}), and net sequestration from land use change (T_{seq}); "production emissions" from shipping (P_{sh}) and aviation (P_{av}); "consumption emissions" in imports of food (C_f) and other goods and services (C_{gs}); other aviation albedo effects (N_{non}), other forms of sequestration (N_{seq}), and sequestration funded overseas (N_{cr}).

Modelling research shows that, if decarbonization is rapid, the delay between the time when global CO_2 emissions peak (t_1) and the time when atmospheric CO_2 concentration peaks (t_2) is related to the ratio between the rates of change in CO_2 emissions before (m^*_t) and after (m^*_d) peak emissions (29):

5. $t_2 - t_1 = t_1 \left(\frac{-m^*_t}{m^*_d}\right)$

Low carbon economy

A *low carbon economy* is the outcome of a decarbonization process, and was first recognized officially by the UK government in 2003 (30). It initially described an ideal scenario for reducing national CO_2 emissions to a low level (16), and this definition is still used (31). Exactly how "low" emissions must become is rarely stated, but a more formal definition, an economy in which greenhouse gas emissions are "decoupled" from economic growth (32), implies that emissions eventually decline to zero.

A third of papers are economic studies and a quarter have a national focus (Table 1). Papers on energy (11%) again dominate those on materials (2%). The recent derivation in this literature of an equivalent to the Kaya identity (33) from the same original "IPAT" source model (34) illustrates the compartmentalization of carbon literatures.

Carbon transition

A *carbon transition* is the development path along which a shift is made from high to low carbon emissions. It begins at the Carbon Peak and ends with zero carbon emissions (Fig. 2). While it resembles decarbonization it links the change in carbon dependence to societal development and has a more specific ending.

A generic national *carbon transition curve* was proposed in 1997 to describe how over time countries pass from rising CO_2 emissions, as they depend on first wood and then fossil fuels for energy, to falling emissions as they increasingly rely on renewable energy sources (19-20).

The shift from fossil fuel to renewable energy dependence is also called an "*energy transition*" (35).

The carbon transition concept was inspired by the generic U-shaped *forest transition* curve, in which national forest cover declines as a country develops, and agriculture expands, switching from net deforestation (and CO_2 emissions) to net reforestation (and carbon sequestration) at a point called the 'forest transition' (Fig. 3). First seen in the present industrialized countries (36), it is rarer elsewhere in the world (37), so tropical deforestation remains a major source of CO_2 emissions (38).

In the various literatures which study the role of forests in global climate change (39), the stock of carbon stored above ground in a forest (C) is calculated by multiplying its area (A) by the volume per unit area (V) and density (D) of wood in trees, a factor (b) to convert this mass into total biomass and a carbon fraction quantity (f) to convert biomass into carbon (40):

6. $C = A \times V \times D \times b \times f$

The global net forest carbon flux (C_{nf}) is typically calculated as the sum of net fluxes in boreal forest (C_{nb}), temperate forest (C_{nte}) and tropical forest (C_{ntr}). As tropical forest is changing rapidly, C_{ntr} typically combines fluxes for sequestration by intact forest (C_{tri}), and the net flux for land use change (C_{trluc}), which combines emissions from forest clearance and sequestration by forest subsequently regrowing (41):

7. $C_{nf} = C_{nb} + C_{nte} + (C_{trluc} - C_{tri})$

The carbon transition and forest transition curves use time as the independent variable, but in the *Environmental Kuznets Curve* the concentrations of some air pollutants, such as sulphur dioxide, peak when countries reach a certain level of economic development represented by GDP per capita (42). Its application to CO_2 is controversial (43).

The largest share of papers (26%) focuses on energy, compared with just 5% on materials and 1% on forests (Table 1). Many papers use "transition" as a synonym for "achieving" a low carbon economy (44) or energy sector (45). Yet some take a "pathway" approach consistent with the original vision of a generic trend (19). A few of these papers equate "pathway" with a future strategy (46) or scenario (47). Most, however, use theoretical frameworks in which influences from regulations, markets and other sources link pathways in CO_2 emissions to underlying societal trends (48-49). Some decarbonization studies use a pathway approach too (50).

Low carbon development

Low carbon development is an equitable "development pathway which can achieve economic and social development while tackling global climate change" (51). It is particularly relevant to low and medium income countries (52), which face challenges in cutting CO_2 emissions but could "leap-frog" large-scale use of fossil fuels when they become less dependent on fuelwood (53), which still accounts for half of world wood production (54).

This literature is also dominated by energy (29% of papers). Just 7% of papers focus on economic development and poverty reduction. None covers materials (Table 1).

Carbon neutrality

Carbon neutrality is achieved when emissions of CO_2 into the atmosphere are offset by CO_2 removals from the atmosphere. It is a weaker goal than zero carbon emissions, but equally specific and easier to measure at global scale. As with the UN Sustainable Development Goal ("target") of land degradation neutrality (55), it combines control of environmental (in this case atmospheric) degradation and terrestrial restoration.

A country achieves carbon neutrality when its carbon transition curve is intersected by its *carbon sequestration curve,* so the *carbon neutrality gap* between the two curves becomes zero (Fig. 2). Even higher "negative emissions" (56) lead to *carbon negativity* (57), which can reduce atmospheric CO_2 concentration to a level where its warming effect is no longer a threat.

The concept of carbon neutrality originated when individuals purchased carbon offsets against their emissions (58). It was then adopted by communities and organizations (59), before spreading to national scale (60). Concise definitions are rather elusive.

Energy studies are again dominant, with 26% of papers, while materials only account for 7%. Consistent with how the concept originated, 24% have a local or urban focus (Table 1).

Zero net carbon emissions

While *net zero carbon emissions* is now a common policy goal (3), the term *zero net carbon emissions* has until now proved more popular in scientific studies, so it is used here as the name for this literature, though both are regarded as synonyms for carbon neutrality (61-62).

The two terms actually have different meanings when applied to buildings. In *zero net carbon* buildings "the amount of carbon emissions associated with a building's... construction [C_e = embodied carbon, discussed below] and... operational energy [C_o] on an annual basis is zero or negative", i.e. $C_e + C_o \leq 0$ (63). In *net zero energy* buildings, on the other hand, the focus is on operational energy, and energy imported from the electricity grid (E_{imp}) is less than or equal to energy supplied to the grid by renewable energy technologies attached to the building (E_{exp}) (64), or $E_{imp} - E_{exp} \leq 0$.

This is the smallest of the carbon literatures, even when including papers with 'energy', rather than 'carbon', in their titles. Some 70% of papers focus on buildings and only 14% on energy (Table 1). None focuses on materials, but their use in constructing buildings is evaluated.

Circular economy

The excessive transfer of carbon from the Earth to the atmosphere can be treated as a consequence of a "*linear economy*" (65), in which under the current market system human utility is equated with consumption. This makes it seem acceptable to deposit wastes like CO_2 into the atmosphere and the other *environmental sinks* of water and land, and to extract new natural resources without recycling old products to reduce depletion of remaining *resources stocks*.

A "*circular economy*" closes feedback loops left open in the linear economy; reduces material "throughput" to conserve natural resources and limits waste flows to those which the environment can assimilate; and gives the environment "three economic functions – as resource supplier, as waste assimilator, and as a direct source of utility" (65). It recognizes the prices of all three functions, so that, for example, any disutility resulting from CO_2 accumulating in the atmosphere should be corrected.

The political process of the circular economy has greatly expanded since the year 2000, as has its associated academic literature (66-67). It identifies normative actions to modify *biophysical* flows of resources, energy and wastes to increase prosperity and conserve the environment. Societal equity is rather neglected (68). The circular economy is a "contested concept" (69), so its political process has generated many indicator systems (70) and 114 definitions, though most of the latter combine "reduce, reuse and recycle activities" (71).

The parallel scientific process launched by Pearce and Turner (65) is still embryonic (72). Yet expanding its theoretical base, e.g. by including the frequency ("*circularity*") and length of time ("*longevity*") of resource use (73), should be more productive than trying to extract meaning from multiple definitions and indicator systems.

Life cycle analysis

Life cycle analysis evaluates the environmental impacts of products from their origin in natural resources stocks to their recycling or disposal as waste in environmental sinks (21). It can help to integrate materials and energy in carbon neutrality studies, having evolved from the "net energy analysis" method (74), and is consistent with flows of energy and materials in a circular economy (75). Studies with the most comprehensive "*system boundary*" include the energy "*embodied*" in a product, e.g. by mining, refining ores into metals, processing metals into products, and transport between these stages (E_e); the "*operating energy*" consumed in using the product (E_o); and the "*demolition energy*" (E_{de}) required for its recycling or disposal. Ramesh et al. (76) calculate overall *life cycle energy* (E_l) for constructing and using buildings by:

8. $E_l = (E_{ein} + E_{er}) + E_o + E_{de}$

where E_{ein} is initial *embodied energy* and E_{er} recurring embodied energy expended in repairs.

The embodied energy per tonne of metal (E_e) is expressed by Rankin (77) as:

9. $$E_e = \frac{E_m\,(1+w)}{(gR_mR_bR_{p1}R_{p2})} + \frac{E_b}{(gR_bR_{p1}R_{p2})} + \frac{E_{p1}}{R_{p2}} + E_{p2}$$

where E_m is mining energy; w the extra mass of waste per tonne of mined ore; g the ore grade; R_m the mass of ore sent from the mine for pre-processing (benefication); E_b the benefication energy per tonne of ore; R_b the fraction of ore recovered; E_{pi} the energy used in two chemical processing stages (i = 1-2) and R_{pi} the fraction of material recovered in each stage.

Life cycle zero energy buildings have an annualized life cycle energy (E_{la}) of zero. As they export more energy to the grid than they consume, mean annual net energy use (E_{oa}) offsets mean annual embodied energy (E_{ea}) over a building's life (78), or $E_{la} = E_{ea} + E_{oa} \leq 0$.

To estimate "global warming potential", "*embodied energy"* derived from fossil fuels can be converted into an equivalent amount of "*embodied carbon*", as can overall *life cycle energy*, though any product has other environmental impacts too (79).

Carbon footprint

The *carbon footprint* concept is framed by life cycle analysis and refers to the mass of CO_2 (or all greenhouse gases) emitted "directly or indirectly.. by an activity or.. accumulated over the life stages of a product" (80).

Carbon footprint (CF) is estimated differently from the *ecological footprint* index (80), and combines CO_2 emissions from all energy uses and other activities A_i (i = 1.....p):

$$10. \qquad CF = \sum_{1}^{p} A_i \text{ x } EF_i$$

where EF_i is the *emission factor* for activity i (81).

This literature has grown rapidly since 2005 (Fig. 1) and accounts for half the papers in our sample. It is alone in having similar numbers of papers on energy (10%) and materials (9%) (Table 1).

Conditions for carbon neutrality

A new carbon neutrality science could counter the neglect of materials in this field by using physical variables and equations to integrate the analysis of energy and materials - and renewable and non-renewable resources - and measure progress in achieving carbon neutrality. Here, using a circular economy framework (65), we build on life cycle analysis (21) to add more equations to those listed above and use them to propose three conditions for carbon neutrality (Table 2).

A circular economy framework

The use of natural resources to generate energy, manufacture and use materials and emit CO_2 as waste can be conceptualized by an ideal circular economy framework in which Human Capital (Labour, and more generally human skills and practices) and Human-Made Capital (productive Capital, such as machinery, and consumer goods) are linked to Natural Capital (comprising Renewable and Non-Renewable Resource Capital and Environmental Quality). A circular economy framework includes the full range of resource and waste flows, though contemporary "linear economies" deviate from this ideal because recycling within Human-Made Capital is limited, and so a lot of waste is deposited in environmental sinks in the Environmental Quality component (65). The flows in Figure 4 are aggregates of those for the life cycles of billions of products as they pass through the stages of resource extraction, refining, processing, operation, disposal and recycling etc. Recycling reduces the depletion of Non-Renewable and Renewable Resource Capital, but the latter is continually renewed through sequestration of CO_2 from the atmosphere and regular harvesting. Energy is expended in managing renewable resources sustainably so that harvests take full advantage of CO_2 inputs. The carbon flows on which this paper focuses are a subset of the larger number of flows of resources and wastes which determine whether an economy is circular or not.

Minimize carbon dioxide emissions at all life cycle stages of materials and energy resources

Our analysis of carbon neutrality begins with the *Energy Life Cycle Equation*. Expanding equation 8, the total amount of energy used per unit mass of a product containing material *i* during a single life cycle (E_{li}) - its *life cycle energy* - combines the: (a) *cultivation energy* expended in managing the growth of wood and other renewable resources (E_{ci}); (b) *extraction energy* needed to remove the material from its natural state, e.g. by mining mineral ores or harvesting trees (E_{mi}); (c) *refining energy* used to obtain the material in its pure form, e.g. by refining ores to produce metals or converting trees into sawnwood and other primary products (E_{ri}); (d) *processing energy* which converts a material into a product (E_{pi}); (e) *transport energy* expended in all stages from extracting the raw material to delivering products to end-users (E_{ti}); (f) *operating energy* consumed when using the product (E_{oi}); (g) *disposal energy* expended in disposing of a product (E_{di}); (h) *recycling energy* needed to recycle the material so it can be converted into a new product (E_{rei}); and (i) *heat energy* saved by using processing and other waste to substitute for other forms of energy (E_{hi}):

11. $E_{li} = E_{cij} + E_{mij} + E_{rij} + E_{pij} + E_{tij} + E_{oij} + E_{dij} + E_{reij} - E_{hij}$

The size of each category depends on the technology used (j = 1…m) (82).

If materials are produced using fossil fuels then each *energy category* has a corresponding *carbon category* in the *Carbon Life Cycle Equation* to represent its associated CO_2 emissions:

12. $C_{li} = C_{cij} + C_{mij} + C_{rij} + C_{pij} + C_{tij} + C_{oij} + C_{dij} + C_{reij} - C_{hij}$

Here C_{li} is *life cycle carbon*. Refining carbon (C_{ri}) can also include CO_2 emitted when refining raw materials, e.g. to convert limestone into cement. This equation integrates energy and materials using a common unit of carbon, rather than energy as in the *exergy* concept (83). It does not include CO_2 emissions associated with unsustainable management of forests and other renewable resources. These are included in C_{luc} in equation 1 and C_{afolu} in equation 2.

The ideal path to carbon neutrality, and later zero carbon emissions, minimizes *life cycle carbon* in a *Carbon Transition Path Equation* which applies to materials and energy resources and represents total CO_2 emitted annually in producing and using billions of products:

13. Minimize $\sum C_{li} = \sum (C_{cij} + C_{mij} + C_{rij} + C_{pij} + C_{tij} + C_{oij} + C_{dij} + C_{reij} - C_{hij})$

So the *first condition* for achieving carbon neutrality is that minimizing the sum of emissions at all stages of the life cycles of materials and energy resources is necessary to accelerate peaking of CO_2 emissions and then passage through the carbon transition (Fig. 2, Table 2).

National equations can be expanded, as in equation 4, to include imports and exports. Actual minimization of C_{li} along a development path will depend on how the *carbon intensities* of the technologies (j) used in each category decline (84) under "*lock-in*" constraints (85).

Materials differ in their natural and embodied carbon contents. "Low carbon materials", such as metals, are naturally low in carbon but high in embodied carbon. "High carbon materials", such as wood, are naturally high in carbon but low in embodied carbon. Cement is an "Extreme carbon material", as it is naturally high in carbon in its original form of limestone and high in embodied carbon too (so the 'natural' classification of cement refers to the natural raw material (limestone) before it assumes its commercial form) (Table 3). Grouping materials with similar properties in this way helps in estimating embodied carbon intensity in *carbon impact assessments* of new processes and products (86). While embodiment may seem like a virtual association it is physically very real, since each product is associated with a mass of CO_2 in the atmosphere.

Referring to C_{li} in equation 12, the life cycle carbon benefits B_{lc} of substituting one material (2) for another (1) in a product are expressed by a *Displacement Equation*:

14. $B_{lc} = C_{l1} - C_{l2}$

B_{lc} is 'normalized' by dividing by the difference between the masses of material 2 in the original product (m_o) and substitute product (m_s) to give a "*Displacement Factor*" DF_{12} (87-88):

15. $DF_{12} = \dfrac{(C_{l1} - C_{l2})}{(m_s - m_o)}$

The energy saved by recycling material i, rather than refining new ore, is indicated by the *Recycling Ratio* R_i between its recycling energy (E_{rei}) and refining energy (E_{ri}), i.e. $R_i = E_{rei} / E_{ri}$.

Maximize carbon dioxide removals

Since the present net terrestrial carbon sink is relatively small (see below), the *second condition* for carbon neutrality complements the first by requiring the maximization of CO_2 removals (C_s) e.g. through terrestrial sequestration (C_{sterr}), carbon capture and storage (C_{sccs}) etc. (Table 2):

16. Maximize $\sum C_s = \sum(C_{sterr} + C_{sccs} + ...)$

Offset carbon dioxide emissions by carbon dioxide removals

The *third condition* states that carbon neutrality is achieved by offsetting gross CO_2 emissions (C_g) by CO_2 removals (C_s) (Table 2). At global scale, for all countries k = 1….n:

17. $\sum C_{gk} = \sum C_{sk}$

Proximity to carbon neutrality can be measured by an absolute *Carbon Neutrality Gap* CNG = $\sum C_{gk} - \sum C_{sk}$, which equals 0 at carbon neutrality; and by a relative *Carbon Neutrality Index* CNI = $\sum C_{gk} / \sum C_{sk}$, which equals 1.0 at carbon neutrality.

The relative speeds of national carbon transitions can be compared by using the *Decarbonization Ratio (*D_i). This divides the number of years between the Carbon Peak year and the current year (Y_{post}), by the number of years between the Carbon Peak year and the historical Chordal Equivalent year, which had the same emissions as the current year (Y_{pre}) (Fig. 5):

18. $D_i = \dfrac{Y_{post}}{Y_{pre}}$

D_i is 1.0 for symmetrical carbon transition curves. It can complement cumulative CO_2 emissions (46) in comparing alternative future scenarios, and is related to the delay between the peaks in global CO_2 emissions and global CO_2 concentration (equation 5) (29).

Most industrialized countries have now passed their Carbon Peaks. A long-term international database (89) shows that a few have symmetrical carbon transition curves in which the rate at which CO_2 emissions rise before the Carbon Peak resembles the subsequent rate of decline, e.g. Romania (Carbon Peak 1989) has a D_i value of 1.0. Other countries have skewed curves (Fig. 6). Countries that reached their Carbon Peaks before 1990 generally have D_i values above 1.0, e.g. France's emissions peaked in 1979 and its D_i is 2.1, representing a right-skewed curve (Table 4). Many countries with later Carbon Peaks have left-skewed curves and D_i values below 1.0, e.g. Italy's emissions peaked in 2004 and its D_i is 0.3. This general decline in D_i with Carbon Peak year (Fig. 7) implies that transitions are more rapid in countries with recent Carbon Peaks. For example, France's emissions in 2014 were 57% of their peak value but this drop took 35 years, while Italy's emissions declined to 68% of their peak value in just 10 years. This confounds expectations that learning from experience (90) should accelerate emissions decline. Yet national *CO_2 half lives* are at least 20 years for most countries with Carbon Peak years before 1990, but below 20 years for countries whose emissions peaked more recently (Table 4). Most national carbon transitions, however, are far from complete.

Few evaluations have yet been made of the availability and quality of the statistical data needed to quantify the equations in this section reliably (91).

Low carbon materials

Metals are naturally low in carbon, but "embody" much more of it owing to the fossil fuels used to produce them and convert them into finished products. This section identifies the sources of CO_2 emissions in manufacturing and using metals which are critical to minimizing emissions to meet the first carbon neutrality condition (Table 2 and equation 13). It shows that constraints on changing technologies for producing metals could, by sustaining demand for fossil fuels, limit the rate of CO_2 emissions decline, regardless of renewable energy supply.

Steel accounts for 94% of all metal production and 70% of all greenhouse gas emissions associated with this. Producing steel and aluminium accounts for over 13% of all CO_2 emissions except for those from land use change. Copper and zinc are next in order of annual production (Table 5) (77). Steel, aluminium and copper are also used to make wind turbines, solar photovoltaic cells and lithium ion batteries for electric vehicles (92), so demand for them should remain strong in switching to renewable energy sources (93). We focus here on high longevity products, such as those used in vehicles, not low longevity products, such as beverage cans, many of which are rapidly recycled with high circularity (94).

Data available for analysis are limited. Our sample of 2,265 journal papers in the seven carbon literatures includes 17 papers on steel, but only 4 on aluminium, 2 on copper and none on zinc (Supplementary Table S1). Another Google Scholar search found 27 life cycle analyses for steel, 11 for aluminium, 19 for copper and 8 for zinc (Table S2), but none has a “cradle-to-grave” *system boundary* extending from extraction to recycling or disposal. Only 28% cover primary metal production, and not all of these include every stage from “cradle-to-[refinery] gate” (95), e.g. some focus on refining carbon and others on pre-processing ores. Yet most evaluate environmental impacts other than CO_2 emissions, e.g. emitting acidic gases such as sulphur dioxide (96), which together affect the overall sustainability of development.

Embodied carbon

An overview by the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia provides a set of estimates of *embodied carbon* in leading metals which, in our view, is uniquely comprehensive and internally consistent. Its estimates are also conservative, in having a common *emissions factor* for energy use (equation 10) based on using electricity derived from black coal at 35% efficiency. At 1 kg CO_2 eq /kWh this emissions factor is 27% greater than for oil, 2.3 times that for natural gas, 15 times that for nuclear power, and 100 times that for hydropower. Steel (an alloy of iron and other metals and up to 2% carbon) has the lowest embodied carbon per tonne of any leading metal: 2.2 t CO_2, or a tenth of aluminium's 21.8 t CO_2 (Table 6). Copper and zinc have intermediate values of 3.3 t CO_2 and 4.6 t CO_2, respectively, when produced using their most common pyrometallurgical and electrolytic processes, respectively (77). With the exception of aluminium, all CSIRO estimates of embodied carbon are in the middle of the range of other available estimates (Fig. 8).

Extraction carbon

Extraction carbon is only 0.2% of embodied carbon for aluminium and 2.5% for steel, but up to 59.4% for copper (Table 6), since much crushing and grinding ('benefication') is needed to concentrate copper ore before shipping it from the mine for smelting (101).

The range of estimates of extraction carbon helps to explain the spread of estimates of embodied carbon in copper in Figure 8, its main driver being the variation in ore grade. Copper from Australia's Mount Isa mine, whose current ore grade is 3.0% (96), has an embodied carbon of 3.0 t CO_2 t^{-1}, which is near the CSIRO estimate for the same grade (Fig. 8). The higher mean of 6.0 t CO_2 t^{-1} for all mines in Chile reflects the lower mean ore grade of 0.7% in that country (102). Another large Australian mine (Olympic Dam), which has a 2% grade, has an even higher estimate of 8.5 t CO_2 t^{-1}, but also a larger emissions factor (0.89 kg CO_2 eq /kWh) than Mount Isa (0.36 kg CO_2 eq /kWh) (96).

Refining carbon

Refining carbon accounts for over 99% of embodied carbon in aluminium, 98% in steel and 89% in zinc, but as little as 41% for copper owing to the dominance of extraction carbon (Table 6). The ranges of estimates for aluminium, steel and zinc in Figure 8 are mainly driven by the dependence of refining on fossil fuels.

CSIRO's estimate of 21.8 t CO_2 t^{-1} is the highest for aluminium, as it relies only on coal energy (77). In contrast, a global mean of 16.5 t CO_2 t^{-1} (103) is 56% dependent on fossil fuels; another global mean of 14.4 t CO_2 t^{-1} (104) is 71% dependent; and a European mean of 8.2 t CO_2 t^{-1} (105) is just 19% dependent.

The steel estimates in Figure 8 have a more compact distribution, near the centre of which is the CSIRO estimate of 2.14 t CO_2 t^{-1} (77). The others are 2.46 t CO_2 t^{-1} for Poland (106), 2.04 t CO_2 t^{-1} for China (107), 1.69 t CO_2 t^{-1} for Europe (108), and 1.60 t CO_2 t^{-1} for Italy (109). Only the last estimate includes extraction carbon, so for comparability the other values of embodied carbon in Figure 8 have been adjusted using CSIRO's estimate of 0.05 t CO_2 t^{-1}. All these estimates are for processes dependent on fossil fuels.

The zinc estimates are all for the leading hydrometallurgical process and influenced by fossil fuel dependency too. A Chinese estimate of 6.1 t CO_2 t^{-1} (110) is based on 100% coal energy, as is the CSIRO estimate of 4.6 t CO_2 t^{-1} (77), while a European estimate of 3.1 t CO_2 t^{-1} (111) is just 46% fossil fuel dependent. A lower global mean of 2.7 t CO_2 t^{-1} (112) covers a range of fossil fuel dependencies. This, as for other means in this section, made it difficult for the authors of these studies to reliably estimate emission factors.

Transport carbon

All the CSIRO estimates in Table 6 assume integrated mining and processing operations and so exclude transport carbon. Of the four metals reviewed here, transport energy is least crucial for aluminium, as its refining energy is so high. Until production expanded in China and the Persian Gulf (see below), most refining took place close to cheap nuclear or hydropower sources, to minimize refining energy. The UK now has only one small smelter at Lochaber, which uses hydropower. A larger smelter in Anglesey closed in 2009 when the nearby Wylfa nuclear power plant was decommissioned (113).

Reducing embodied carbon

The key to reducing embodied carbon in most metals is to cut their refining carbon by switching to improved technologies that use renewable electricity (shown in green in Figure 8).

Aluminium, copper and zinc are already produced by electrical smelting. The 'best available technology' estimate for aluminium smelters of 3.5 t CO_2 t^{-1} (104) in Figure 8 is based on hydropower. Improving anodes and cathodes could lower this value (114), but the Hall-Héroult smelting technology needs updating too (94). Before the year 2000, most aluminium smelters used hydropower or nuclear power, but the share of world production in China and the Persian Gulf based on fossil fuels has subsequently risen from 10% to 66%, and difficulties in replacing this new capacity are a "*lock-in*" effect (85) that will delay cuts in CO_2 emissions.

Switching to solar power could halve the European mean of embodied carbon for zinc from 3.1 t CO_2 t^{-1} to 1.5 t CO_2 t^{-1} (111). For copper, harnessing solar power in Chile's extensive drylands could cut its mean refining carbon of 6.0 t CO_2 t^{-1} more sharply to 2.2 t CO_2 t^{-1} (102), but reducing energy use in ore benefication is also needed to cut extraction carbon (96).

Switching to electricity poses the greatest challenge for steel production, since the widely used blast furnace method relies on fossil fuels to supply heat *and* reduce iron ore. The global dominance of steel is another "lock-in" effect that will limit the decline in total CO_2 emissions from all metal production if technologies change slowly. Blast furnaces could be replaced by hydrogen reduction and electric arc furnaces, using hydrogen derived by 'decarbonizing' fossil fuels (115) or electrolysing water, but this technology may not be operational until 2040 (116). It will take longer to spread worldwide, and since hydrogen reduction is expensive a high carbon price is also needed to make it economic (117). The same applies to electrowinning, an electrolytic process still under development (118).

Recycling carbon

Greater recycling of metals is therefore crucial to counter slow technological change in primary production, especially for aluminium (114), whose Recycling Ratio between recycling energy and refining energy (R_i) is only 0.05-0.08, depending on the scrap input (Table 6). Steel has a larger R_i of 0.43, though its recycling energy of 10 GJ/t resembles that of aluminium.

Reducing operating carbon

Minimizing CO_2 emissions will also require trade-offs between changes in *operating carbon* and embodied carbon. Operating carbon for steel vehicles can be cut by substituting lighter metals, such as aluminium, magnesium and titanium (119). These have higher strength to weight ratios (S) than steel - whose S value varies but is assumed here to be 80 kN-m/kg (Table 7) - but their refining carbon is higher too. Yet for a car made of 10% aluminium, for which S =130 kN-m/kg, the drop in lifetime operating carbon could be up to six times the refining carbon of aluminium (120). Higher refining costs make the lighter metals more expensive, e.g. a tonne of aluminium costs four times as much as steel, but the actual cost difference is less since the final product is lighter. Substitution will also be influenced by the carbon price and safety issues.

Legacy carbon emissions

This analysis shows that future CO_2 emissions scenarios for achieving carbon neutrality that are based solely on trends in renewable energy supply are over-optimistic, since they neglect delays in reducing fossil fuel demand by the metals industry. The lock-in effects of current technologies (steel) and fossil fuel-dependent refining capacity (aluminium), combined with the fossil fuel needs of new technologies, could leave a sizeable amount of *legacy carbon emissions* by 2050, and contribute to a substantial *carbon neutrality gap* (Fig. 2). If the metals industries are to become carbon neutral by 2050, all factories might therefore need their own carbon capture and storage facilities.

Data issues

Life cycle analysis has evolved considerably since Ayres (74) criticized the tendency for studies to use "non-comparable units of measurement": all of the studies reviewed here reported "global warming potential" in comparable units. Yet Ayres' other criticism, about the use of "data from unreliable sources that cannot be checked", is still relevant, since estimates for metals rely on large numbers of company and industry data sources to quantify multiple variables. Other constraints include basing emissions factors on regional electricity data (96), and (as noted above) the small number of life cycle analyses for manufacturing metals (95). International reporting standards for energy intensive industries would ensure greater transparency, but to be feasible this would require a general strengthening of the current weak international institutional framework of these industries (10). Intergovernmental Panel on Climate Change (IPCC) guidelines (121) are currently the leading international standard for reporting CO_2 emissions by industries, but so far they do not cover complete life cycles.

High carbon materials

Wood is naturally high in carbon, comprising half of carbon by weight, but compared with metals it needs less fossil fuel carbon to convert it into wood products. This section examines the feasibility of expanding global forest area to maximize CO_2 removals and offset CO_2 emissions to comply with the second and third carbon neutrality conditions (Table 2), and of converting the resulting extra wood supply into products to serve as long-term carbon stores.

Expanding forest area and carbon sequestration

Forests already remove a considerable amount of carbon from the atmosphere. Temperate forests are now net carbon *sinks* since most industrialized countries, such as the USA, passed through their forest transitions long ago, and are on the upward sloping arm of the forest transition curve (Fig. 3) (36). However, owing to continuing deforestation, most tropical countries, such as Brazil, are still net carbon *sources* on the downward sloping arm. Only a few, such as Vietnam, have undergone their transitions (37). It is currently estimated, based on equation 7, that forests are a small net carbon sink of 4.0-5.9 Gt CO_2 a^{-1} (1.1-1.6 Gt C a^{-1}) (38, 41). So forests and other terrestrial sinks only offset a fraction of the 32 Gt CO_2 eq a^{-1} of greenhouse gases emitted outside the land use sector (7).

Expanding forests is therefore necessary to maximize CO_2 removals to comply with the second carbon neutrality condition, and with the third condition by bringing the *carbon sequestration curve* nearer to the *carbon transition curve* (Fig. 2), yet forests only account for 1% of all papers in the seven carbon literatures (Table 1). At an IPCC conference in 1990 it was estimated that about 500 million hectares (Mha) of new forest could offset the prevailing net annual increment in atmospheric CO_2 of 10.6 Gt CO_2 a^{-1} (2.9 Gt C a^{-1}) from all sources, and so achieve carbon neutrality - though this term was not used then. Some 620 Mha of degraded tropical land were considered suitable for this "*carbonforest*" (122). While this estimate neglected economic and social factors, e.g. whether landowners wish to convert land to forest, this gap was tackled by research in the 1990s (15). The estimate also used poor quality statistical data, but a recent survey with very high resolution satellite images found sufficient land worldwide (123) to meet a new IPCC target of establishing up to 950 Mha of new forest by 2050 to limit global warming to 1.5°C (62). This area is twice as high as in 1990 since the net annual rise in atmospheric CO_2 has doubled. The Bonn Challenge is equally ambitious in aiming to establish 350 Mha of new forest by 2030 for this and other environmental goals (124).

If 10 Mha of new carbonforest had been planted annually from 1990, and CO_2 emissions remained unchanged, the world could have been carbon neutral within the present 2050 deadline. Yet CO_2 emissions have continued rising, and the rate of establishment of new tropical forest plantations fell from 1.8 Mha a^{-1} in the 1980s to 0.8 Mha a^{-1} in the 1990s, and from 2010 to 2015 was still only 0.9 Mha a^{-1} (125). Planting outside the tropics peaked at 4.7 Mha a^{-1} between 2000 and 2005, and the global rate of 2.5 Mha a^{-1} ha between 2010 and 2015 could not even offset the annual natural forest loss of 5.8 Mha a^{-1} ha (mainly in the tropics), despite temperate natural forest expanding at 1.4 Mha a^{-1} (Table 8). The 110 Mha of new forest plantations established since 1990 is a small proportion of the 500 Mha and 950 Mha targets, so a huge effort is required if forest expansion is to offset all remaining CO_2 emissions by 2050.

Most industrialized countries, even those with large forest areas, such as Canada, have large carbon neutrality gaps (the blue bars in Figure 9), because net terrestrial sequestration (C_{luc} - C_{terr} in equation 1) (green bars) cannot offset fossil fuel CO_2 emissions (grey bars). Many tropical countries, such as Indonesia, have large carbon neutrality gaps too, since CO_2 emissions from deforestation greatly outweigh forest sequestration. Only a few countries where deforestation has ended, such as Malaysia and the Philippines, have quite small carbon neutrality gaps (126).

Contrary to assumptions that allowing the carbonforest to grow indefinitely will maximize carbon uptake, research shows that more carbon is sequestered by adopting normal forestry practices, e.g. harvesting on specific rotations and thinning between harvests (127). The optimum rotation varies with tree species and ecological zone, but could be up to 80 years in temperate areas and lower in the tropics. Another finding is that carbon sequestration should be planned from the start to maximize total carbon storage in forests *and* wood products (Fig. 10), and that expanding existing uses of these products and substituting for other materials are both important (128). The current net annual sink associated with these "*harvested wood products*" is estimated at only 0.3 Gt CO_2 a^{-1} (0.09 Gt C a^{-1} (129)), but this is based on limited data since only in the last ten years have countries been required to provide statistics on these products to the UN Framework Convention on Climate Change (129).

Embodied carbon in wood products

Wood products compare favourably with metals in their values of the life cycle carbon categories in equation 12, leading to a mean Displacement Factor of 2.1 in equation 15 for the carbon benefits of substituting wood for other materials (87).

Few measurements of the *cultivation carbon* (C_{cij}) of wood in forest plantations are reported, but a recent estimate is 0.01 t CO_2 t^{-1} of Eucalyptus logs for both it and extraction carbon in China. The main source of emissions is using diesel oil in trucks and equipment (130).

The *extraction carbon* incurred in harvesting trees is itself only a small proportion of the total embodied carbon of wood products (131). A typical US mean of 0.04 t CO_2 t^{-1} of dry wood (Table 9) (132) is similar to the extraction carbon for steel (Table 6).

Total *embodied carbon* varies with the type of wood product, but is much lower than for metals, e.g. the 0.20 t CO_2 t^{-1} of sawn softwood (Table 9) (133) is a tenth of that for steel (2.1 t CO_2 t^{-1}) (Table 6). ‘Wood panels’, such as plywood, are more carbon intensive (134), e.g. embodied carbon is typically 0.45 t CO_2 t^{-1} for plywood, or twice that for sawn softwood (133). The estimates of embodied carbon in Table 9 all use an emissions factor of 0.06 t CO_2 /GJ, except that for particle board (0.05 t CO_2 /GJ), which is identified as 'uncertain" (133).

The embodied carbon of wood could be cut by using battery-operated equipment and vehicles in forest management, and electricity for processing. Forest industries have long generated heat from wood processing waste, and on average about half of the total embodied energy in wood products is *heat energy* (E_{hij} in equation 11) recovered in this way (Table 9) (133).

The number of life cycle analyses of wood products - like that for metals - is still relatively low (Table S1) (133). The first detailed evaluation for the USA, for example, was not published until 2005 (131). Estimates vary considerably with tree species and energy use characteristics (131) and also differ in their measurement units, which supports Ayres' (74) critique.

Using more wood in buildings

The top priority in expanding existing uses of wood is to increase long-term carbon storage in solid wood products, such as furniture (with lifetimes of 10-35 years), and those used in buildings (with lifetimes of at least 30-50 years) (127). We do not discuss low longevity products, such as paper, which are rapidly recycled with high circularity (135), or burning wood as fuel, the carbon neutrality of which is highly controversial (136-138).

Wood is a crucial part of "zero net carbon houses" designed to minimize embodied carbon and operating carbon (63), but the relative shares of these two categories are uncertain. In one estimate, embodied carbon only accounts for 10-20% of total life cycle carbon in buildings worldwide (76). Wood is already plentiful in buildings, and timber frame houses are the norm in Canada, Japan, New Zealand etc. A typical 2,074 m^2 timber frame house in Canada, for example, has twice as much wood as a brick house of similar size (139). Further reducing the non-wood content of buildings, e.g. by using wooden instead of concrete floors (140), can cut CO_2 emissions even more.

Substituting for cement and concrete is vital, as their manufacture accounts for a tenth of all CO_2 emissions except for those from land use change (Table 5). Cement is an 'extreme carbon material' (Table 3) since: (a) much CO_2 is emitted when limestone (calcium carbonate) is mixed with clay and heated to a high temperature to form 'clinker' – the intermediate material in manufacturing cement, which is then used to make concrete (141); and (b) more CO_2 is emitted when burning fossil fuel to provide the heat. Refining carbon (C_{rij}) in equation 12 includes both types of emissions.

No feasible complete substitute for clinker has been found, in attempts to cut CO_2 emissions described in 39 papers in the seven carbon literatures - ten more than for all metals combined (Table S1). Fossil fuels could be 'decarbonized' into hydrogen, to generate energy (115), and carbon, to substitute for concrete (142). Yet incremental reductions are more likely, e.g. fly ash from coal power stations and steel blast furnace slag can already account for up to 30% of cement, and as much as 15% of fine limestone can be added without heating (143). Slow technological change in the cement industry could leave a large amount of *legacy carbon emissions* to add to that of metals, widening the 2050 carbon neutrality gap even further.

Moving to a new wood economy

Owing to their lower embodied carbon, substituting wood products for metals, e.g. for steel in telegraph poles (144) and railway sleepers (145), can cut total CO_2 emissions. However, as global forest area expands and more trees are harvested, wood can also substitute for materials currently derived from fossil fuels, replacing the fossil fuel economy by a new *wood economy*. Glesinger published a blueprint for this, called "The Coming Age of Wood" (146), as early as 1949. Wood comprises cellulose, hemicellulose and lignin, three polymers that are separated when making paper. Goldstein showed again in 1975 how cellulose could be converted directly into polymers, such as rayon and cellophane, and broken down by hydrolysis and fermentation into ethanol, which can then be converted into ethylene and butadiene, the monomers used to form the polymers of polyethylene and polybutadiene (147).

These early visions have been reimagined for the 21st Century as a "*bio-based economy*", which is "the sustainable, eco-efficient, transformation of renewable biological resources into food, energy and other industrial products" (148). Just as oil refineries separate petroleum into fractions, "*biorefineries*" could convert wood and other forms of biomass into many products (149), e.g. degradable bio-plastics (150), and carbohydrates to serve as 'carriers' for generating hydrogen fuel (151). New plants are needed to convert cellulose and hemicellulose from birch wood into ethanol (152), but existing plants for manufacturing ethylene, propylene and butylene from fossil fuels can be "retrofitted" to take poplar wood instead (153). A transition metal catalyst method has been devised to depolymerize intractable lignin (154), as part of a new "green chemistry" initiative to use renewable feedstocks in chemical industries

(155). Wood might also be converted into other high carbon materials (156), such as graphene (157), carbon nano-tubes (158) and carbon fibre.

Wider political and commercial support is essential to realize the "bio-based economy" vision, since at the moment the European Union (EU) is virtually alone in having a strategy for this (159-160). In every country, new forests will compete with other land uses for each hectare of land (161). Yet support for bio-based economies should increase as the carbon price rises, and awareness grows of the competitiveness of new wood industries (153) and the potential to integrate these with climate change mitigation (162).

The emerging carbon economy

To achieve carbon neutrality it must be economically feasible to introduce new technologies to minimize the carbon embodied in low carbon materials and, by increasing the use of high carbon materials and other means, maximize the transfer of CO_2 from the atmosphere to the Earth. This will require the market economy to undergo a structural change to a new *carbon economy* that sets a sufficiently high carbon price. (For reasons stated above, the term “carbon economy” is preferred to “low carbon economy".) This section identifies three features of the emerging carbon economy and proposes seven principles of a new carbon economics to explain them.

Features of the emerging carbon economy

Three distinctive features of the carbon economy are that:

1. *It is evolving,* and so is not pre-planned.

2. *Its evolution is being shaped by a diversity of actors using various approaches*. Initially, *governments* tried to cut CO_2 emissions by introducing new *national* regulations, and ‘market-based mechanisms’, e.g. pollution taxes and marketable pollution permits (65). The 1997 Kyoto Protocol of the UN Framework Convention on Climate Change allowed industrialized country (or Annex 1) signatories to use both approaches to achieve binding targets for emissions reductions. Carbon taxes have been introduced in many countries but vary in their effectiveness, longevity and acceptability (163). Carbon emissions trading schemes began in the EU in 2005 and then spread to China and other countries (164).

While environmental economists regard market-based mechanisms as more efficient than policies in changing polluting behaviour (65), critics claim that carbon neutrality can only be achieved if these mechanisms are supported by new policies (165), e.g. to replace intransigent technologies, such as coal power stations (166), and improve government administration of emissions trading schemes to generate the higher carbon prices needed to cut CO_2 emissions sharply (164).

However, many “*sub-national actors*” are also changing their energy use and everyday practices, such as cycling instead of using cars (167), and this can be just as effective as regulations or taxes in reducing *demand* for fossil fuels (168). Carbon offset schemes began in the 1980s to allow individuals to reduce the impacts of their travel (58). They were later incorporated in the Clean Development Mechanism of the Kyoto Protocol, so that industrialized countries listed in Annex 1 of the Protocol could offset their CO_2 emissions by funding carbon sequestration projects in other countries (169).

3. *It is uneven in space and time*. A heterogeneous global mosaic of national policies and market-based mechanisms has formed as governments have failed to agree on a universal binding successor to the Kyoto Protocol. So carbon can "leak" as industries migrate from 'strong' carbon economies to 'weaker' ones, e.g. aluminium smelting has shifted to fossil fuel-dependent economies in China and the Persian Gulf (104). Policies can also be reversed, e.g. in 2012 the Spanish government ended renewable energy subsidies (170).

Seven principles of carbon economics

While 8% of papers in the seven carbon literatures are economic studies (Table 1) there is currently no specific literature on 'carbon economics'. To fill this gap, seven principles of a new *carbon economics* are proposed here to explain the evolution and operation of the carbon economy.

1. *Carbon economics studies the allocation of overabundant carbon in the atmosphere while other factors of production remain scarce*. This adapts a longstanding definition of economics as "the study of the allocation of scarce resources" - capital, labour and land - "which have alternative uses" (171). Carbon is allocated by sequestering atmospheric carbon and avoiding volatilization of terrestrial carbon.

2. *The ideal human economy is a circular economy*. In an ideal human (as opposed to ecological) economy, materials extracted from Resource Capital would circulate within Human-Made Capital through recycling, instead of being deposited as waste in environmental sinks (Fig. 4) (65).

3. *The human economy is an integral part of the biosphere*. This follows the *global ecosystem framework* of ecological economics (172), instead of an environmental economics framework which separates the human economy from the biosphere (65). Figure 11 therefore combines the global ecosystem and circular economy frameworks.

4. *A sustainable human economy should stay within the ultimate carrying capacity of the biosphere*. This is another principle of the global ecosystem framework, and once the critical upper limit is exceeded, "remaining Natural Capital [replaces Hu]man-Made Capital as the limiting factor" (173). This remaining Natural Capital is the "Critical Natural Capital", which is essential for human life support, e.g. global environmental cycles, like the carbon cycle, and ecosystem services provided by biodiversity (174).

The Earth's carbon carrying capacity threshold, measured by the level of CO_2 in the atmosphere, may have been passed in the 1970s (175), when the current steep rise in global temperature also began (176). In another estimate, which divides global carrying capacity into multiple "planetary boundaries", the biodiversity and nitrogen cycle thresholds have been passed too (177).

5. *New corrective economic institutions are needed when the scale of the human economy 'overshoots' ultimate carrying capacity*. Daly proposed in 1974 that to correct for overshoot the current institutions governing the market economy, e.g. those for contracts and property rights, should be supplemented by new institutions to stabilize human population, stop resource depletion, and limit social inequality (172). *Institutions* are not organizations but repeated practices, or "enduring regularities of human action in situations structured by rules, norms and

shared strategies, as well as by the physical world" (178). Daly implied that governments should impose the new institutions – as was common at the time. Since then, however, politics has changed dramatically, and studying institutional change has become a major research priority in various disciplines, including ecological economics (179).

Daly's proposal can be extended by using an approach, developed independently by Williamson and Ostrom, in which any society comprises multiple levels of institutions. Williamson proposed that institutions framing the market economy are structured hierarchically, with the institutions of resource allocation through *markets* being embedded in government institutions for *contracts*, which are nested in general "rules of the polity" that frame *property rights*, and are themselves embedded in *societal norms* (180). For a seamless shift to a carbon economy the arrangement of its institutions should be consistent with that of institutions governing the market economy. Ostrom's framework allows for this since it is more generic than Williamson's. "Operational institutions" - the everyday practices of *individuals* that are varied easily - are nested in the "collective choice institutions" of *groups* that change more slowly, and are framed by "constitutional choice institutions", complying with national and international *laws*, that vary even more slowly and are nested in "metaconstitutional institutions", such as *societal norms*, that rarely change (181).

6. *New institutions to govern the carbon economy can be created at all spatial scales*. According to Rhodes, following a shift in metaconstitutional institutions, in the 1990s many industrialized countries began switching from the conventional "government style" of governing, in which government steered society, to a new "*governance* style", in which society is "self-steering". So governing now involves decentralized, multiscalar and networked interactions between all groups in society; civil society has greater autonomy; and individual citizens and non-governmental organizations can create institutions with national and even global impacts (182).

Institutions governing the carbon economy are represented in Figure 11 by an *institutional matrix*, in which rows correspond to actors at global to local scales, and columns to different economic or policy sectors. Institutions are established when norms, rules and practices are initiated and reproduced at various spatial scales and spread to other scales. Multiple *levels* are not identical to multiple *scales*, so actors at any scale may be associated with multiple levels of institutions.

This explains the *second* (diversity) feature of the carbon economy, described above. New *operational institutions* are created and reproduced by the repeated practices of many individuals, e.g. when purchasing carbon offsets for their travel. *Collective choice* institutions are created when corporations redesign their operations to be carbon neutral. *Constitutional choice* institutions are created by governments which introduce market-based mechanisms, and by UN organizations which adopt new international agreements to tackle global climate change. These are all influenced by, and consolidate, the new global *societal norm* of carbon neutrality. A multi-level institutional approach is already used in carbon transition studies (49, 183)

Spatio-temporal unevenness, the *third* feature of the carbon economy, results from a diversity of actors creating different institutions at different scales, times and places. Some scales have a full complement of institutions while others have none. Each cell in the institutional matrix varies in its *density* of institutions (Fig. 11).

Unevenness can be reduced by filling gaps in the institutional matrix, e.g. by revising the Paris Agreement, or the World Trade Organization's international trade rules (184); and constructing partial sets of institutions, e.g. for energy intensive industries (10), or to prevent *carbon bias* in the carbon economy, so that conservation does not favour high carbon density forests over high biodiversity forests (185).

7. *Institutions within Human Capital co-evolve with changes in Natural Capital.* "Co-evolution" of the human economy and biosphere is fundamental to ecological economics (186), and explains the *first* feature of the carbon economy - its evolution. "Polycentricity" in institutional change, identified by Ostrom (181), is matched by polycentric change in Natural Capital. So incremental changes in the life cycle stages of materials to minimize CO_2 emissions into the atmosphere, and maximize CO_2 removals from the atmosphere, can occur in parallel with changes in carbon economy institutions, and carbon price changes resulting from these. Other adaptive changes should eventually occur in response to breaches of the other "planetary boundaries" (177) noted above as more rules of the ecological economy come into play.

Co-evolution is apparent in a *carbon economy box* in which products and processes become economic at carbon prices inversely proportional to their CO_2 emissions (Fig. 12). As in the *McKelvey box* of resource economics (187), low carbon intensity technologies should become more economic as the carbon demand curve shifts and the carbon price rises, e.g. increasing the present carbon price of \$28 tC^{-1} to \$67 tC^{-1} should make it economic to manufacture steel by hydrogen reduction (117).

The need for better statistics

Better statistical data are needed for carbon economics research, and for the transparent national reporting needed for fair international trade in carbon (188). This will be promoted if new international trade institutions set common standards to upgrade carbon accounting methods (189), and if all products carry *carbon barcodes* to record the categories of embodied carbon (equation 12) added at each life cycle stage.

Conclusions

Compared with other global goals, such as sustainable development (190), and other carbon strategies, such as decarbonization (23) and a low carbon economy (16), carbon neutrality is unambiguous and easier to measure at global scale. Yet achieving it is currently constrained since strategies and research have focused on energy (191) and neglected materials.

To fill this gap, we have extended existing equations in carbon literatures (76) by deriving more equations to integrate the analysis of the roles of energy and materials in achieving carbon neutrality. These equations can be used to establish a framework for a new carbon neutrality science; provide a common language for all carbon literatures; and monitor progress in realizing carbon neutrality. They also lead to three conditions for carbon neutrality: minimize CO_2 emissions at all stages of the life cycles of materials and energy resources; maximize CO_2 removals; and offset CO_2 emissions by CO_2 removals.

Applying these equations to low carbon materials, such as metals, shows that for aluminium, steel and zinc, refining carbon is the key source of CO_2 emissions to cut to minimize emissions to comply with the first condition. Extraction carbon is also important for copper. Trading off reductions in refining carbon and operating carbon will be another challenge. Yet owing to delays in introducing the best available technologies worldwide by 2050, a substantial amount of *legacy carbon emissions* could remain, and contribute to a sizeable *carbon neutrality gap*.

Wood is naturally high in carbon but low in embodied carbon, and so can reduce CO_2 emissions if substituted for metals. If global forest area is expanded, to comply with the second condition for carbon neutrality by maximizing CO_2 removals, more wood will become available to substitute for metals and other materials and provide new terrestrial carbon stores. So burning wood as fuel is indeed wasteful (138). Yet slow forest expansion since an Intergovernmental Panel on Climate Change conference in 1990 called for forest-based climate change mitigation (192) raises doubts about whether sufficient forest expansion can occur before 2050 to offset remaining CO_2 emissions and satisfy the third condition for carbon neutrality.

Insufficient minimization of CO_2 emissions and maximization of CO_2 removals could therefore leave a substantial carbon neutrality gap by 2050. However, carbon neutrality is sufficiently flexible to allow sub-optimal forest expansion to be compensated by: (a) faster than expected cuts in CO_2 emissions, and (b) greater use of carbon capture and storage, as the evolving carbon economy sets a higher carbon price to make carbon neutrality more economically feasible.

To fill another gap, this paper has proposed seven principles of carbon economics that build on circular economy, ecological economics and new institutionalism frameworks. These principles explain three features of the carbon economy: its gradual evolution, the various approaches adopted by a diversity of actors, and its spatio-temporal unevenness, which has led to 'carbon leakage'. The seventh principle - co-evolution of the human economy and the biosphere - suggests that the carbon price could eventually rise sufficiently to correct the imbalance between CO_2 emissions and removals, and counter critics of emissions trading (165).

Far more research is needed into the role of materials in carbon neutrality. Future research in carbon neutrality science could study actual transition paths to carbon neutrality and ultimately zero carbon emissions, and the role of harvested wood products as global carbon stores. More carbon neutrality equations could be devised to cover, for example, the carbon benefits of constructing vehicles using materials that are lighter and stronger than existing ones; the balance between longevity and circularity in different materials (73); and the impact of recycling alloys on the quality of materials (193). Research in carbon economics could expand its theoretical base, and study the spatial unevenness of the carbon economy in detail.

Our research leads to five policy recommendations for governments coming under pressure to publish detailed carbon neutrality strategies (194-196). First, these strategies should integrate the energy inputs to economies and materials outputs. Second, they should encourage stronger international carbon reporting standards for energy-intensive industries, to improve transparency in national reports of progress towards carbon neutrality. Third, they should establish national databases of carbon stored in harvested wood products, to improve estimates of terrestrial carbon stocks other than in ecosystems and agroecosystems. Fourth, they should promote faster forest expansion. Fifth, they should reinvigorate the Reducing Emissions from Deforestation and Degradation (REDD+) mechanism of the UN Framework Convention on Climate Change, so that deforestation no longer cancels out afforestation gains.

A new carbon neutrality science will have much to study in the coming decades as humanity strives to ensure the sustainability of Planet Earth. It also has much to contribute to planning effective strategies. We have set out some simple equations which can be used to assess the merits (or otherwise) of a range of proposed strategies for approaching carbon neutrality. If such basic metrics had been employed in the past, serious mistakes might have been avoided, for example in the case of the aluminium industry, and in the deployment of early-generation biofuels. We can only hope for better, more analytical, approaches in the future.

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Table 1. Numbers of papers in international journals in seven carbon literatures by principal categories 1995-2020.

	Decarbonization	%	Low Carbon Economy	%	Carbon Transition	%	Low Carbon Development	%	Carbon Neutrality	%	Zero Net Carbon Emissions	%	Carbon Footprint	%	Total	%
Energy	228	43	17	11	33	26	35	29	36	26	11	14	106	10	466	21
Transport	65	12	8	5	8	6	1	1	13	9	1	1	79	7	176	8
Buildings	34	6	0	0	6	5	6	5	11	8	55	70	59	5	171	8
Materials	26	5	3	2	7	5	0	0	10	7	0	0	98	9	144	6
Land Use	0	0	2	1	0	0	0	0	4	3	0	0	345	31	351	15
Forests	5	1	1	1	1	1	0	0	6	4	0	0	3	0	16	1
Economy	47	9	49	32	24	19	8	7	0	0	0	0	46	4	174	8
Development	7	1	0	0	3	2	8	7	0	0	0	0	3	0	21	1
Tourism	5	1	6	4	0	0	0	0	0	0	0	0	35	3	46	2
Decarbonization technology	50	9	0	0	0	0	0	0	0	0	0	0	0	0	50	2
Industry	12	2	15	10	3	2	7	6	0	0	0	0	90	8	127	6
Organizations	1	0	0	0	2	2	0	0	6	4	0	0	37	3	46	2
Urban	19	4	5	3	6	5	30	25	18	13	1	1	42	4	121	5
Local	2	0	4	3	3	2	4	3	15	11	6	8	4	0	38	2
National	9	2	37	24	22	17	12	10	11	8	2	3	32	3	125	6
Others	24	4	5	3	11	9	10	8	8	6	3	1	133	12	194	9
Total	534	24	152	7	129	6	121	5	138	6	79	3	1,116	49	2,265	

NB. All categories include synonyms, and zero net carbon emissions publications also include those on zero net energy.

Table 2. Three conditions for achieving carbon neutrality.

1. Minimize carbon dioxide emissions when producing and using materials and energy sources, to accelerate peaking of emissions and passage through the carbon transition.

2. Maximize carbon dioxide removals.

3. Offset carbon dioxide emissions by carbon dioxide removals.

Table 3. Classifying materials by their natural and embodied carbon contents.

	Embodied carbon content	
Natural carbon content	Low	High
Low	VERY LOW CARBON Non-carboniferous stone	LOW CARBON Metals
High	HIGH CARBON Wood products	EXTREME CARBON Cement

Table 4. National carbon transition curve characteristics of 17 countries.

	Carbon Peak Year	Chordal Equivalent of 2014	Decarbonization Ratio	Percent peak emissions in 2014	CO_2 half life (years)
Right skewed					
United Kingdom	1971	<1960	na	64	59
Sweden	1970	<1960	na	47	37
France	1979	1962	2.1	57	41
Belgium	1979	1961	1.9	67	25
Hungary	1984	<1960	na	46	28
Poland	1987	1969	1.5	61	35
Quasi-symmetrical					
Bulgaria	1987	1964	1.2	46	25
Romania	1989	1963	1.0	33	19
Left skewed					
Denmark	1996	1961	0.5	46	17
Portugal	2002	1992	1.2	67	18
Finland	2003	1972	0.4	68	17
Italy	2004	1971	0.3	68	15
Austria	2005	1976	0.3	79	22
Greece	2005	1988	0.5	68	14
Ireland	2007	1996	0.6	76	15
Spain	2007	1996	0.6	65	10
Croatia	2007	1993	0.5	70	12

Curves without peaks: Luxembourg, Netherlands, Norway, Slovenia, Switzerland, USA.

NB. Values of the Decarbonization Ratio are not available (na) for the United Kingdom, Sweden and Hungary, because the Chordal Equivalent Year precedes the beginning of the database that we used. Data were obtained from the World Bank (89).

Table 5. Carbon dioxide emitted in the production of five key materials in 2005[1] and 2015[2].

Material	Global Production (Mt/a^{-1})		Global CO_2 emissions[3] $(Mt.a^{-1})$		Percent all CO_2 emissions[4]	
	2005	2015	2005	2015	2005	2015
Zinc	10.5	13.7	47.0	61.3	0.16	0.17
Copper	15.6	23.0	60.0	88.5	0.20	0.25
Aluminium	38.0	57.5	830.0	1,255.9	2.81	3.49
Steel	924.0	1,620.0	2,000.0	3,506.5	6.78	9.75
Total	*988.1*	*1,714.2*	*2,937.0*	*4,912.2*	*9.95*	*13.66*
Cement	2,600.0	4,100.0	2,300.0	3,626.9	7.79	10.08

NB. [1]The 2005 estimates are from Rankin (77). [2]The 2015 production estimates are from the US Geological Survey (97-100), and emissions are calculated using the same conversion factors as in Rankin (77). [3]Conversion to emissions assumes that all electricity is generated by black coal. [4]CO_2 emissions apart from those for land use change are 29,508 Mt in 2005 and 35,977 Mt in 2015 (89).

Table 6. Key energy and carbon categories of four leading metals (77).

Metal	Extraction				Refining		Embodied				Recycling	
	Energy (GJ/ t metal)	Carbon (tCO$_2$/ t metal)	Production Process	Percent all production	Energy (GJ/t)	Carbon (tCO$_2$/ t metal)	Energy (GJ/t)	Carbon (tCO$_2$ t metal)	Percent Refining Energy	Input	Energy (GJ/t)	Ratio
Copper	19.60	1.93	pyro	80	13.42	1.32	33.02	3.25	40.6	Scrap No. 1	4.4	0.33
	18.17	1.74	hydro	20	46.29	4.42	64.46	6.16	71.8	Scrap No. 2	20.1	1.50
										Low grade	49.3	3.67
Zinc	5.46	0.52	electrolytic	90	42.98	4.09	48.44	4.61	88.7	New scrap	3.8	0.12
	4.96	0.46	ISP	10	30.89	2.88	35.85	3.34	86.2	Slab	22.0	0.71
Aluminium	0.36	0.04	electrolytic	100	211.15	21.77	211.51	21.81	99.8	Alloy	17.5	0.08
Steel	0.56	0.05	BF/BOF	70	22.14	2.14	22.70	2.19	97.5	Billets	9.7	0.44

NB. ISP = imperial smelting process; BF = blast furnace; BOF = basic oxygen furnace. The Recycling ratio (R_i) is calculated by dividing Recycling Energy by Refining Energy, and for copper the lower of the two Refining Energy values is used.

Table 7. The physical properties of three light metals and steel (119).

	Aluminium	Magnesium	Titanium	Steel
Density (Kg/m^3)	2,710	1,740	4,510	7,860
Strength to weight ratio (kN-m/kg)	130	158	120	80

Table 8. Trends in changes in the areas of natural forest and forest plantations 1990-2015 (125).

	1990s	2000-05	2005-10	2010-15	Total area change million hectares
		million hectares a^{-1}			
Forest plantations					
Non-tropical	3.36	4.65	3.81	1.60	83.87
Tropical	0.84	1.26	1.49	0.86	26.52
World	4.20	5.91	5.30	2.46	110.38
Natural forest					
Non-tropical	-1.08	-1.36	-0.61	0.61	-17.61
Tropical	-10.39	-9.13	-8.10	-6.38	-221.91
World	-11.47	-10.48	-8.72	-5.77	-239.52

Table 9. Typical values of extraction energy and carbon for forestry in the USA (132), and of the embodied energy and carbon of selected wood products in the UK showing total energy expended using fossil fuels and timber waste (133).

Product	Extraction energy	Extraction carbon	Embodied energy Total	Embodied energy Fossil fuels	Embodied carbon
	(GJ/dry t)	(t CO_2/dry t)	(GJ/t)	(GJ/t)	(t CO_2/t)
Sawn softwood	0.59	0.04	7.4	3.2	0.20
Sawn hardwood	0.59	0.04	10.4	4.1	0.24
Particle board	0.59	0.04	14.5	11.1	0.54
Plywood	0.59	0.04	15.0	7.9	0.45

Figure 1. Trends in journal publications on carbon neutrality, carbon transition, zero net carbon emissions, low carbon development, low carbon economy, decarbonization and carbon footprint in five year periods from 1995 to 2019, by initial year.

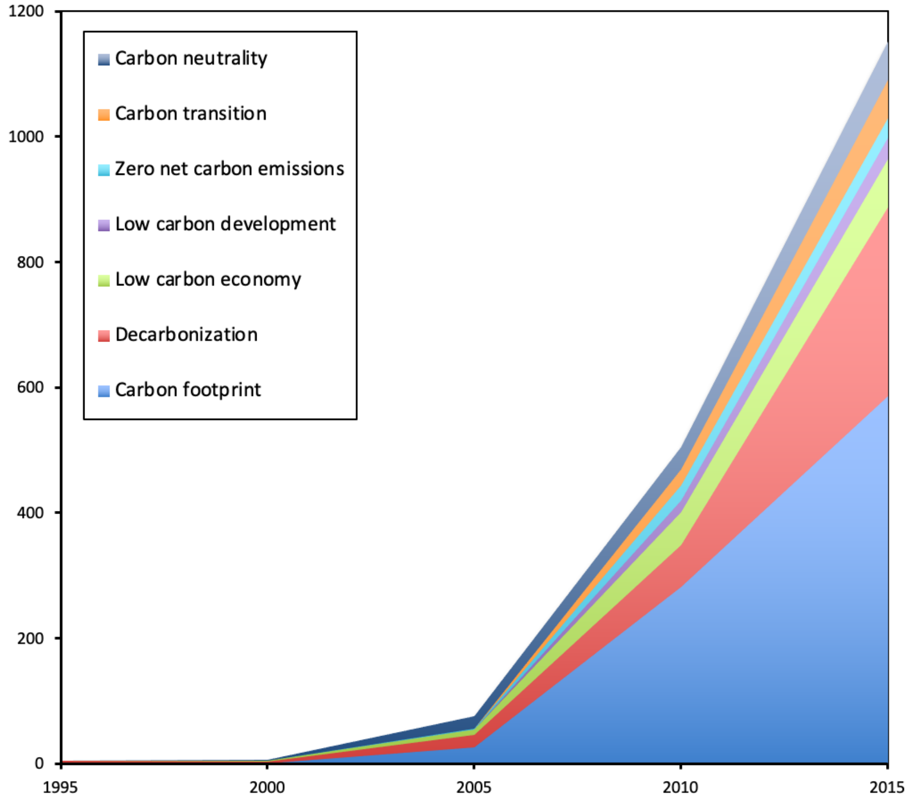


Figure 2. Carbon neutrality achieved at the intersection of the carbon transition curve and the carbon sequestration curve. The carbon transition begins at the Carbon Peak and ends with zero carbon emissions (based on (19)).

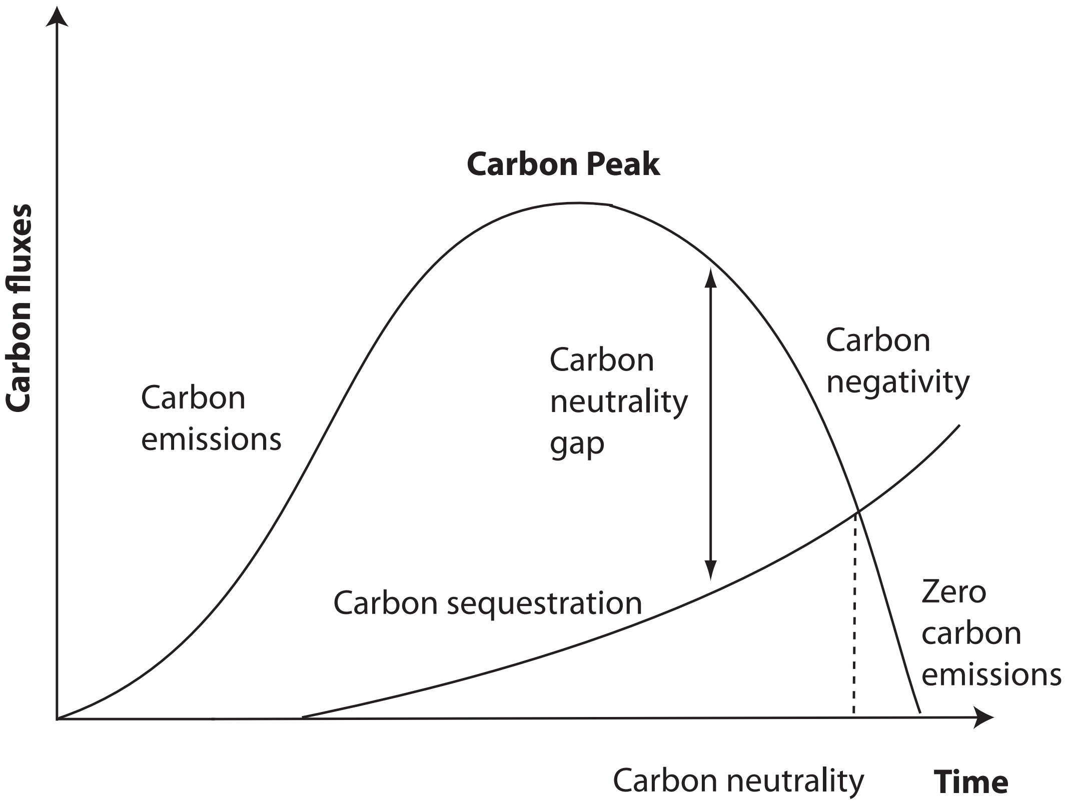


Figure 3. Forest transition curve (36), elaborated to show associated carbon fluxes, and examples of countries which are still to pass through their transitions, or close to doing so, and those that have passed through their transitions.

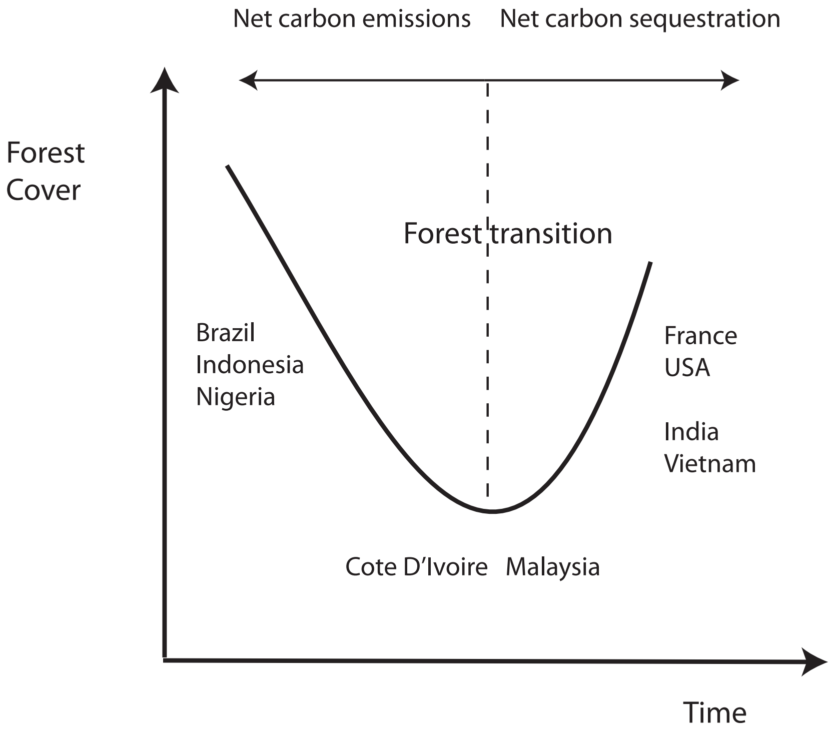


Figure 4. A circular economy framework (based on 65), which shows flows of resources between Renewable and Non-Renewable Resource Capital and (as energy resources and materials) the Productive Capital (P) and Consumer Goods Capital (C) in the human economy, together with CO_2 inputs from the atmosphere to Renewable Resource Capital and outputs of waste from using Productive Capital and Consumer Goods Capital. Flows are labelled using the names of the principal life cycle stages.

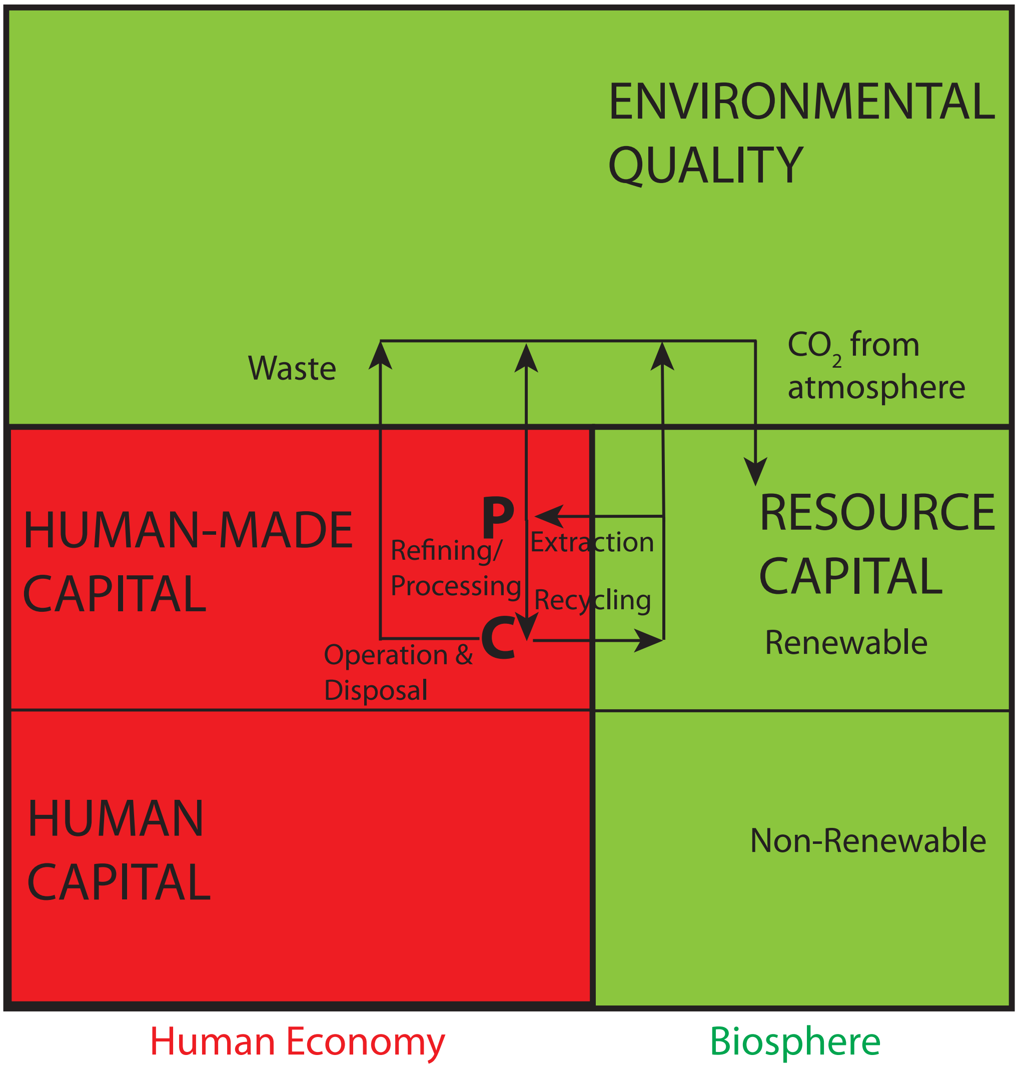


Figure 5. Evaluating the relative speeds of carbon transitions using the number of years before the Carbon Peak (Y_{pre}) and the number of years after the Carbon Peak (Y_{post}).

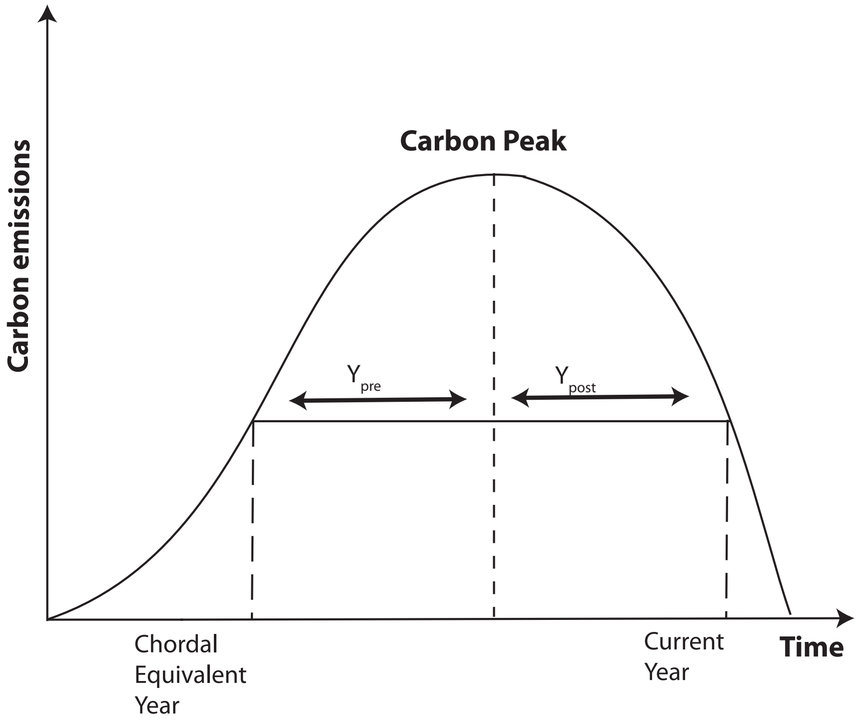


Figure 6. The carbon transition curves for four industrialized countries, showing trends in CO_2 emissions (Mt CO_2 a^{-1}) over time (89), to illustrate different degrees of symmetry: symmetrical (Romania), right-skewed (France), left-skewed (Italy) and minimal change (Switzerland).

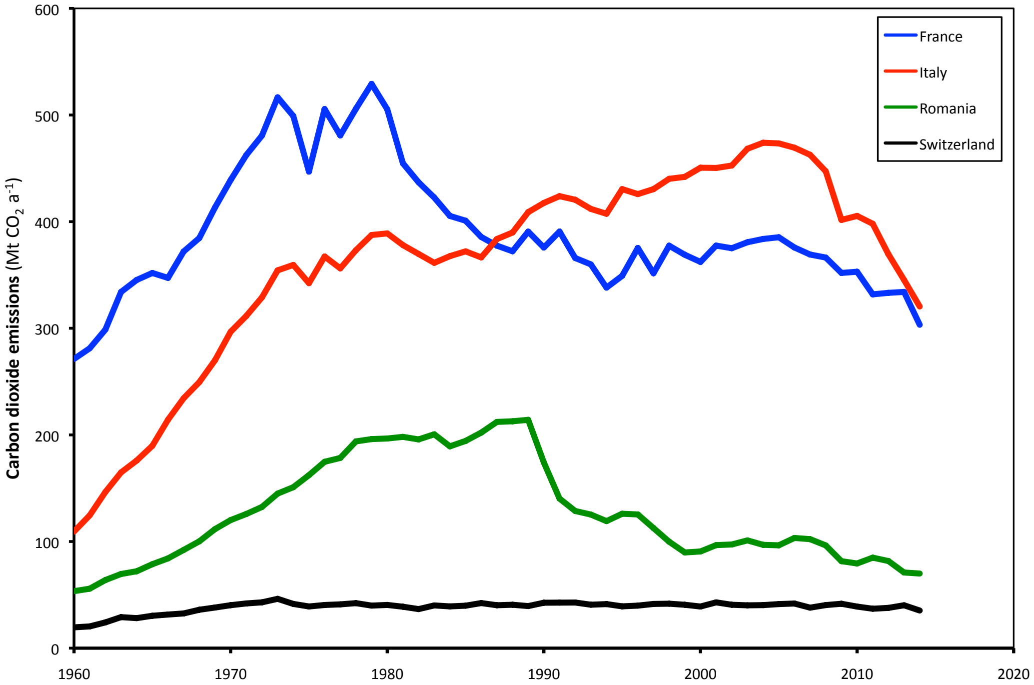


Figure 7. The relationship between the Decarbonization Ratio and the Carbon Peak Year for 17 industrialized countries.

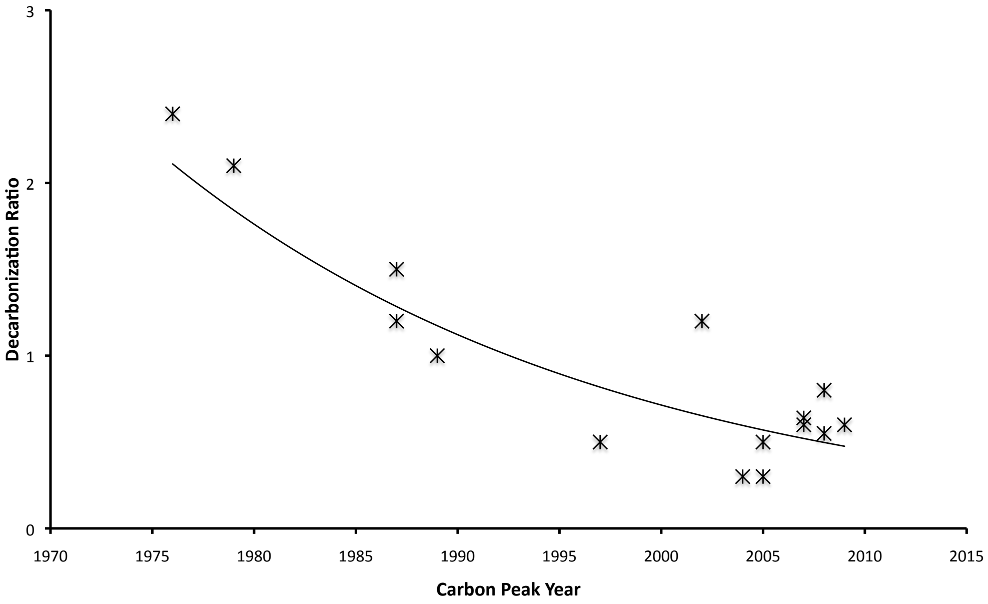


Figure 8. Estimates of the potential (green) and current (black) embodied carbon of aluminium (103-105), copper (96, 102), steel (106-109) and zinc (110-112), with CSIRO estimates (77) in red.

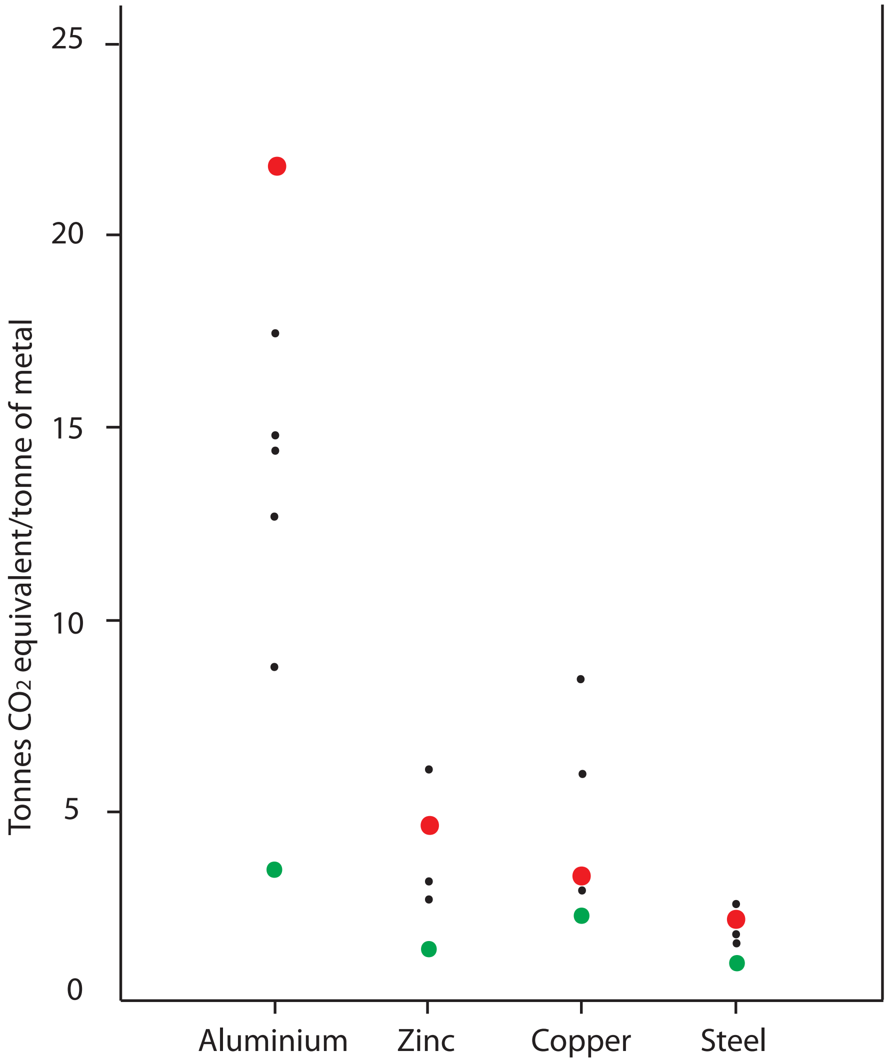


Figure 9. The carbon neutrality gap (Mt CO_2 eq a^{-1}) between greenhouse gas emissions outside the land use sector and net terrestrial sequestration in industrialized countries (in 2018) and in other countries (various dates) (126).

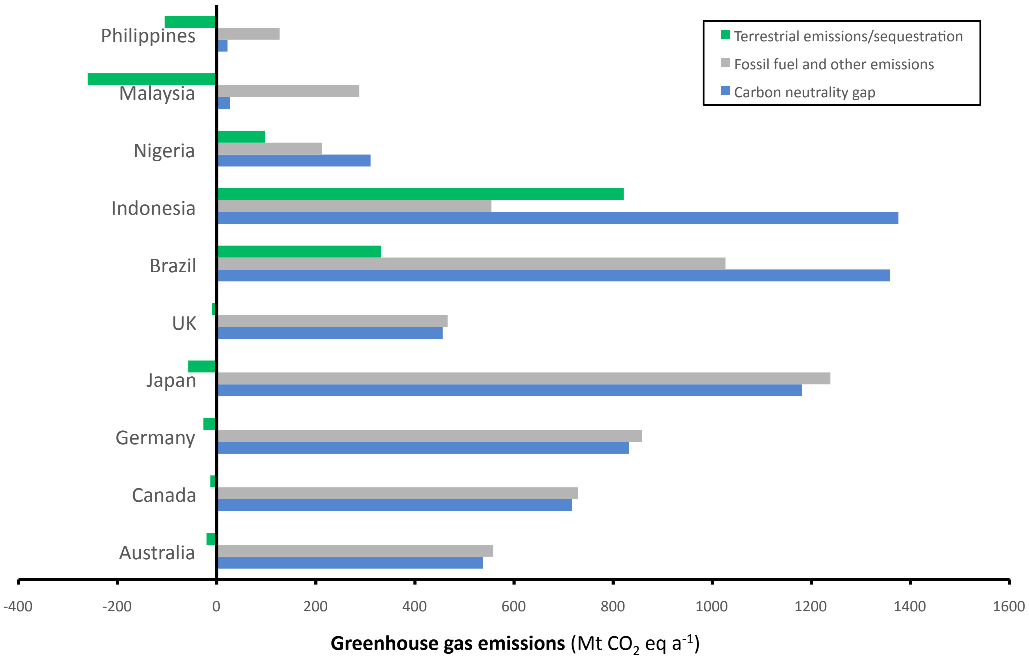


Figure 10. Carbon storage in forest and wood products pools with substitution for other products (here the use of concrete in house construction), showing two rotations of 80 years with two thinnings in each rotation of forests in the Pacific Northwest region of the USA (based on 128).

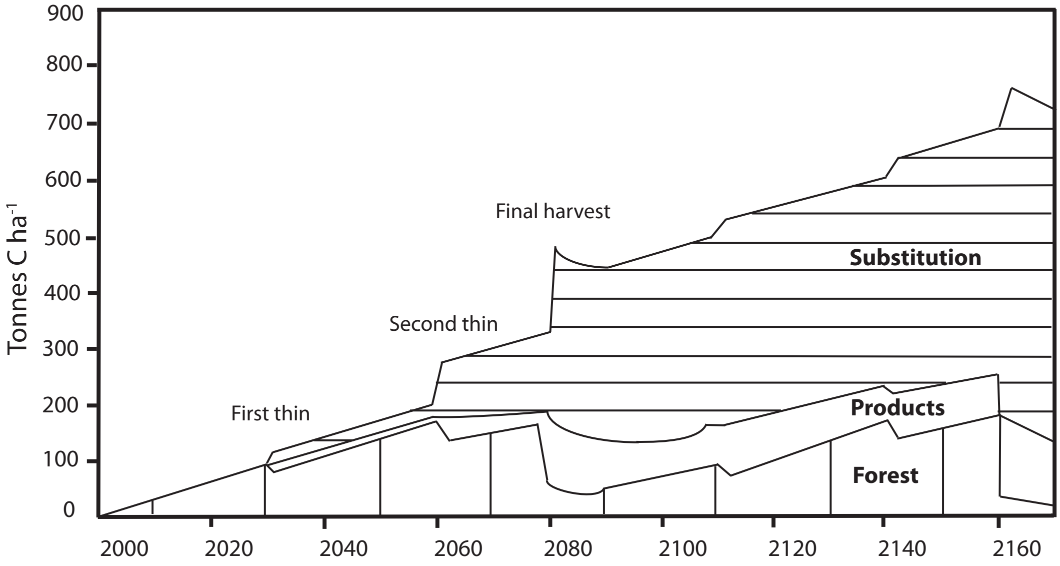


Figure 11. A carbon economy framework, combining the ecosystem and circular economy frameworks and a new institutionalism framework, and showing the transfer of materials between the biosphere and the Productive Capital (P) and Consumer Goods Capital (C) in the human economy as it expands towards ultimate carrying capacity. The institutional matrix (inset) shows variation in the density of institutions at different scales, according to the scales at which institutions originate in different economic or policy sectors. Critical Natural Capital (174) is that remaining above ultimate carrying capacity.

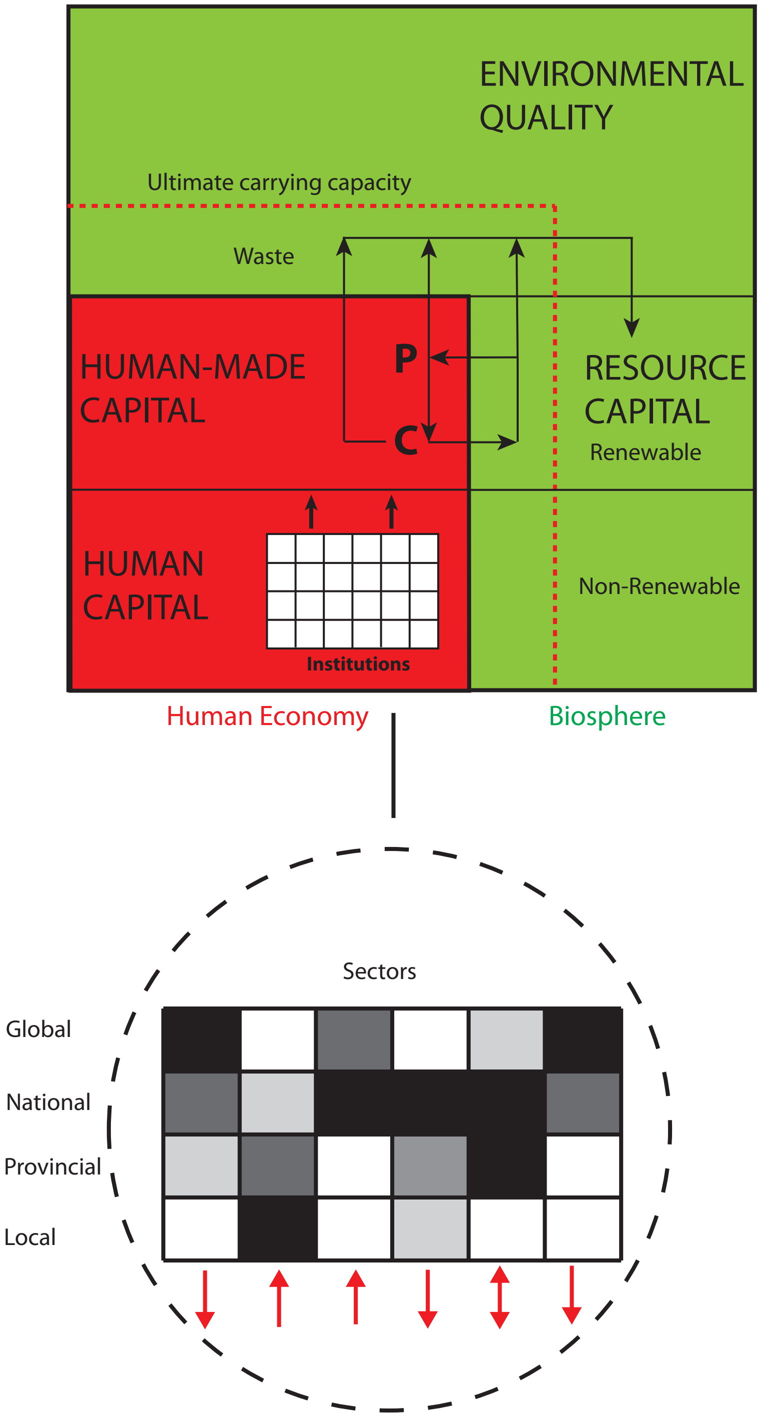
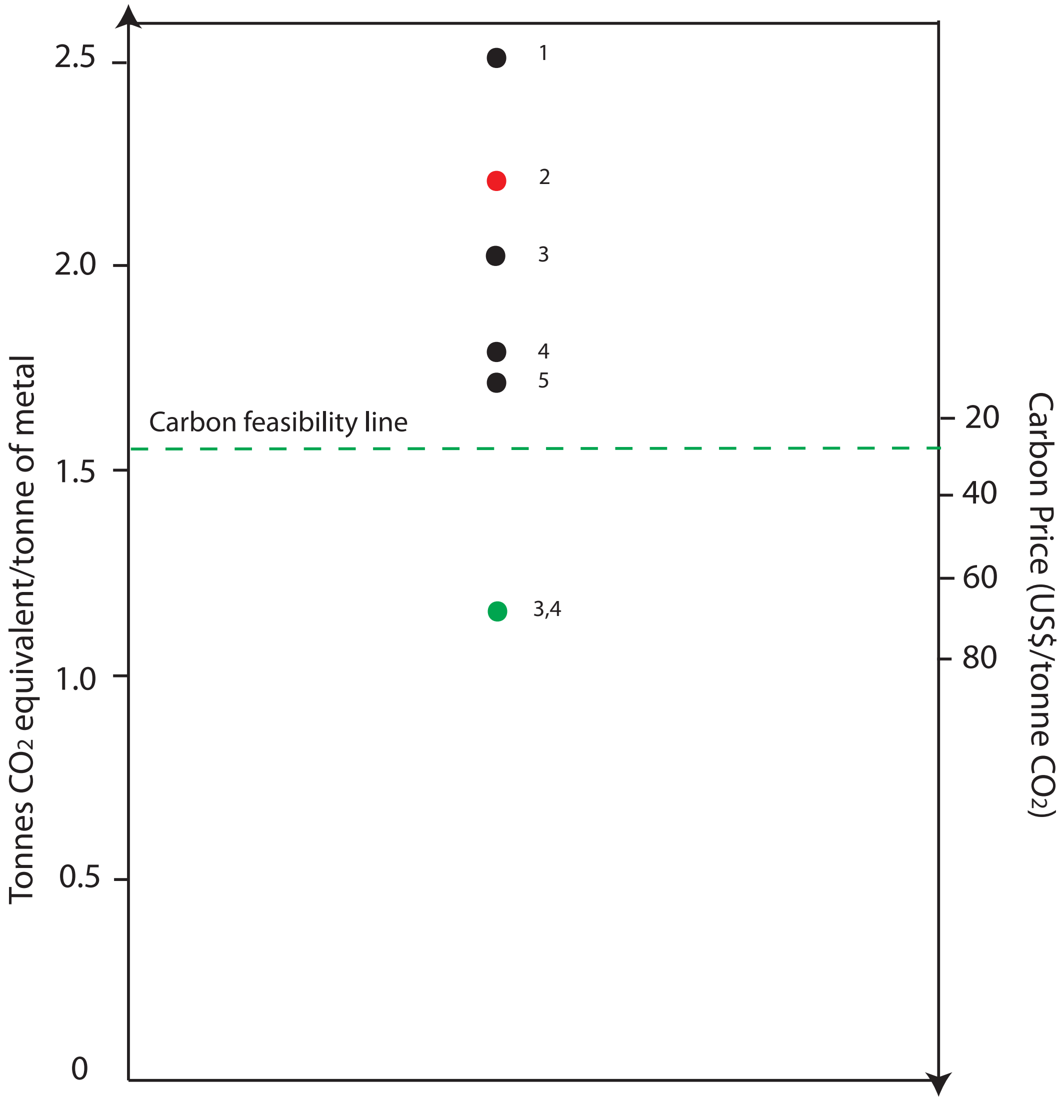


Figure 12. A carbon economy box showing the rise in the carbon price (117) needed to shift the carbon feasibility line downward from current (red and black) values of the embodied carbon of steel, to make potential steel technologies (green) economic. Locations of estimates: (1) Poland, (2) Australia, (3) China, (4) Europe, and (5) Italy (77, 106-109).



Supplementary Table S1. The subjects of 144 papers on “Materials” and 16 papers on “Forests” in the 2,265 papers in seven carbon literatures in Table 1.

Materials	
Aluminium	4
Copper	2
Iron and steel	17
Zinc	0
Other metals	6
Cement	39
Plastics	9
Chemicals	7
Energy intensive industries	10
Other general studies	24
Forest products	26
Sawnwood/pallets	*7*
Wood panels	*2*
Paper	*5*
Cork	*3*
Synthetic chemicals	*9*
Forests	
Carbon sequestration	10
Fuelwood	6

Supplementary Table S2. The scope of 65 individual life cycle analyses for four leading metals.

	Aluminium	Copper	Steel	Zinc	Percentage
Primary production	4	4	4	6	28
Metal products	1	4	1	2	12
Comparisons	1	2	11	0	22
Recycling	4	7	7	0	28
Other	1	2	4	0	11
Total	11	19	27	8	100