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Decomposition for decarbonisation: evaluation of decarbonisation programmes

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ABSTRACT

The Kaya Identity has long been used as a simple yet rigorous way to assess options in energy and climate policy. Its shortcoming is that it fails to address the very wide range of non-energy factors. This paper presents a simple extension of the Kaya Identity – the Emissions Quantification Tool or EQT – that incorporates the missing factors while retaining the mathematical transparency of the original. The tool allows national policies to be analysed and compared with international standards for allowable quotas, from which shortfalls or ‘carbon debts’ can be calculated. It can be used to represent almost any conceivable decarbonisation programme, testing assumptions and revealing necessary rates of change. The paper demonstrates the use of the tool by analysing prevailing UK policy and variant scenarios. The results are often surprising.

1. A simple algebraic representation of national carbon emissions

One of the most useful heuristic tools for analysing sustainable policy choices has been the so-called IPAT identity[1,2]. Its apparent simplicity masks a surprising analytic power, and an exceptional utility in providing a framework for debate across different specialisations, not least between specialist and lay commentators.

The term ‘identity’ is used because the relation $I = P \times A \times T$ is true by definition, where mnemonically I is ‘environmental impact’ usually with unspecified units, P is the human population under consideration, A is ‘affluence’ or GDP per capita or GDP/P and T is ‘technology’ or environmental intensity or I/GDP using the same units as I. Cancelling leaves $I = I$. The procedure essentially ‘decomposes’ I into three components that can each be subject to policy initiatives.

Labelling conventions

Emission categories are each given a specific label. The four ‘Kaya’ terms are retained in the form used by Kaya and Yakobori[3], while others are grouped with mnemonic subscripts in terms of particular ‘frames’ or ‘accounts’ of emissions. Totals for each frame are given in the form Σ_X, where X indicates the frame in question for the specified year. Note that the frames are nested, each succeeding item embracing all previous items.

Σ_K	Energy account
Σ_T	Territorial account
Σ_P	Production account
Σ_C	Consumption account
Σ_N	Net account
Σ_E	Extended account

Kaya group

p	Population, dimensionless
g	Gdp/capita, £ p^{-1}
e	Energy intensity, kWh $£^{-1}$
f	Carbon intensity, kgCO_2e kWh^{-1}

Additional territorial group

T_{ag}	Food and agriculture
T_{res}	All other territorial emissions
T_{seq}	Natural territorial sequestration

Additional production group

P_{sh}	International shipping
P_{av}	International aviation

Additional consumption group

C_f	Embodied in imported food and feed
C_{gs}	Embodied in imported goods and services

Additional net emissions group

N_{non}	Non-GHG forcing effects
N_{seq}	Engineering sequestration
N_{cr}	International credits

Additional extended emissions group

E_i	Extra-territorial land-use emissions

Accumulated emissions will be designated in the form A_{Xt1-t2}, where X is the frame, t1 is the start date and t2 the target date, for example $A_{K2010-2050}$.

A weakness in quantifying the IPAT identity is finding robust metrics for *I* and its derivative, *T*, the environment intensity. In the context of climate change and greenhouse gas (GHG) emissions, an ingenious resolution was proposed by Kaya[3], decomposing *T* into two components, *viz*., energy intensity in energy units per currency unit (*e*) and carbon intensity in mass of CO_2 emissions per energy unit (*f*). This generates a measurable, approximately conserved quantity that is a good proxy for many other environmental impacts[4]. Kaya's decomposition allows us to model these two factors separately, and gives an additional 'policy lever' to explore and evaluate.

Since energy-related CO_2 accounts for around 70% of global GHG emissions, the Kaya formulation is widely regarded as a reasonable approximation for emissions in general. However, it turns out that decarbonising energy systems is relatively straightforward, at least in a technical sense, whereas reducing emissions from non-energy sectors tends to be more problematic. As a result, decarbonisation policies and proposals tend to leave the non-energy emissions on one side while the energy system is decarbonised. As decarbonisation proceeds, the non-energy sectors make up an increasingly large proportion, and eventually dominate the exercise[5]. Further, a large fraction of consumption emissions from wealthy importing nations is generated outside their territory and is beyond their control. In some cases, the domestic energy fraction is already less than 50%, and due to shrink further, hence the need for a more comprehensive formulation that embraces non-energy and extraterritorial factors.

In this paper, I will present a simple extension of the Kaya identity that maintains its essential robustness and transparency, but captures a wider range of GHG sources and offers a much wider range of policy levers for consideration. It is a transparent mathematical formalisation that permits examination of assumptions and modelling of a wide range of policy choices including actual national programmes, hypothetical variants, and rapid decarbonisation programmes. Mathematically it 'works' because it expresses each relevant term in CO_2e units, which are essentially conserved quantities, and can therefore be represented and manipulated algebraically. In this respect, it can also be a considered a mass-balance model where all emissions and sinks must be accounted for. In addition, it offers a transparent formalisation of the key 'pollution' term in the World3 model of Meadows *et al*.[6], recently updated by Turner[7].

The formalisation is best appreciated through user interaction with a spreadsheet version, and such a version is available online as supplementary data (http://www.ingentaconnect.com/content/stl/sciprg/supp-data). Here however the procedure will be described and key results shown in noninteractive form. Although there appear at first to be many terms, mathematically it is trivial. It will be referred to simply as the Emissions Quantification Tool (EQT) or simply 'the tool'.

In general, the EQT has the form [Kaya +], that is, it builds from the basic Kaya identity that captures the essential features of the territorial energy system, and adds other known factors with the intention of representing all climate-forcing processes for which a 'reporting nation' might be considered responsible. The units are all CO_2e year^{-1}, and can be simply summed to give total emissions per year. Yearly emissions themselves can be summed to generate cumulative emissions, now acknowledged as the key metric for any national emissions policy. Labelling conventions are shown in Box 1.

The key components of the Kaya Identity are as follows: *p* denotes population, a dimensionless number; *g* denotes GDP per capita, or average affluence, in currency units such as €, $ or £; *e* denotes energy intensity, energy/currency, *e.g.* MJ €$^{-1}$, kWh £$^{-1}$ *etc.*; and *f* denotes emissions intensity, emissions/energy, *e.g.* $kgCO_2$ kWh^{-1}. If the total of energy-related emissions shall be designated $\boldsymbol{\Sigma}_K$ (*i.e.* the Kaya total), measured in (say) $MtCO_2$, then

$$\Sigma_K = p \times g \times e \times f \qquad \text{Equation 1}$$

Note that if the identity is factorised (*i.e.* p × GDP / P × Energy / GDP × Emissions / Energy), cancelling leaves 'emissions', in other words $\boldsymbol{\Sigma}_K = \boldsymbol{\Sigma}_K$, true by definition, hence the label 'identity'.

Any of these factors are eligible as policy levers and are differentially favoured by different interests and parts of the policy-aware community. The symbols *p* and *f* together are commonly described as 'scale factors' that determine the overall size of the economy, and in most government and academic discourse are not considered to be available as realistic policy levers; debate focuses on the relative merits of energy intensity *versus* carbon intensity.

Many decarbonisation scenarios concentrate entirely on the energy sector, but there are many other sources and sinks that might be included. In this treatment, I have favoured classes for which data are readily available.

The 'Kaya factors' constitute a natural group, and are supplemented by a further five nested groups. Such groups are often used implicitly but failure to specify them precisely leads to misunderstandings. Accordingly, I felt it useful to make them explicit and offer an unambiguous terminology, as follows: energy emissions, Σ_K; territorial emissions, Σ_T; production emissions, Σ_P; consumption emissions, Σ_C; net emissions, Σ_N; and extended emissions, $\Sigma_{E.}$ These are dealt with in turn.

1.1 Territorial emissions

Under the Kyoto Protocol, and more generally, governments tend to collect data and report emissions in terms of territory, that is, all emissions arising within the national land-mass, including goods that are subsequently exported. In addition to energy, we can identify three other classes: T_{ag} denotes domestic agriculture, largely emissions of N_2O and CH_4, which can be converted to CO_2 equivalents or CO_2e by generally agreed conventions; T_{res} denotes non-energy 'residuals' such as emissions from cement, land-fills, fertiliser production, refrigerants (this class embraces a mixture of gases, again convertible to CO_2e); and T_{seq}

denotes effects of intra-territorial land-use change, often net sinks, so might have a negative value.

Altogether these add to another total, $\boldsymbol{\Sigma}_{\mathrm{T}}$, the territorial emissions, such that

$$\Sigma_{\mathrm{T}} = (p \times g \times e \times f) + (T_{ag} + T_{res} + T_{seq}) \qquad \text{Equation 2}$$

It is this total that most European governments publish annually to demonstrate that their emissions are declining in line with their Kyoto commitments and other long-term policy goals (*e.g.* ref.[8]).

Where 'the tool' is used for scenario-building or analysis, T_{ag} would be considered proportional to p, and T_{res} to both scale factors. It is entirely possible to decompose each term further and develop sub-models, but for present purposes I propose to maintain the simplicity of the formulation, and introduce likely influences of the scale factors, or other interactions, on a case-by-case basis. It might be thought that virtually all terms are functions of the scale factors, but this is not necessarily the case. Emissions from food for example are likely to reflect p, but not necessarily g.

1.2 Production emissions

Emissions from international aviation and shipping take place largely outside a nation's territory and are often disregarded as 'not our responsibility'. This is unreasonable, and most nations do acknowledge these emissions as part of a so-called 'production account' that includes: P_{sh} denoting international shipping and P_{av} denoting international aviation.

Emissions associated with these two categories can be estimated fairly accurately from 'bunker fuels' dispensed in ports and airports. Note that aviation is unusual in having potential forcing effects not attributable to GHGs. This poses an accounting problem since a different metric is involved. The effect is usually approximated by applying a 'multiplier' to the actual GHG emissions of aviation, thus converting the extra forcing to a CO_2e equivalent. It is not entirely clear whether these 'virtual emissions' can be considered cumulative in the same way as CO_2 itself, and in view of many uncertainties, they will be recorded separately, and designated N_{non} under the category of 'net emissions'. Both P_{sh} and P_{av} can be considered proportional to the scale factors, but again to keep things simple we will ignore this effect for the time being and adjust them according to other assumption made in any given scenario.

The factors listed so far are those usually acknowledged by governments as representing all emissions for which they can be considered responsible, and together are commonly referred to as 'environmental accounts', or more generally 'production accounts'. Indicating the groupings with brackets, the new production account total Σ_{P} is now

$$\Sigma_{\mathrm{P}} = (p \times g \times e \times f) + (T_{ag} + T_{res} + T_{seq}) + (P_{sh} + P_{av}) \qquad \text{Equation 3}$$

1.3 Consumption emissions

In principle, the total of all world emissions is simply the sum of all national production emissions, $\Sigma(\Sigma_{\mathrm{P}})_{\mathrm{i}}$. In recent years, it has become widely accepted that 'production accounts' do not really reflect the distribution of emissions in a fair way. 'Fairness' has emerged as a key aspect of GHG emissions policy since it is essential for international agreements. The veteran climate theorist Hans Joachim Schellnhuber resonantly summed up the twin requirements as 'fairness and physics'[9].

It is generally agreed to be fairer to allocate emissions in terms of consumption, *i.e.* all emissions generated to deliver what a nation consumes, rather than what it produces, irrespective of their territorial origin. This allocation generates 'consumption accounts' $(\Sigma_{\mathrm{C}})_i$, in contrast to 'production accounts'. Note that the sum of all national consumption accounts generates the same world total as the sum of all production accounts, so $\Sigma(\Sigma_{\mathrm{P}})_{\mathrm{i}} = \Sigma(\Sigma_{\mathrm{C}})_{\mathrm{i}}$.

In consumption accounts, some emissions are considered to be 'embodied' or 'embedded' in the imported goods, generating 'indirect' extraterritorial emissions. Measurement of these emissions is usually done in terms of multiregion input–output tables, and despite inevitable uncertainties, many nations acknowledge the value of such data. Some governments do occasionally publish 'consumption accounts' even though these have no legal significance (*e.g.* ref.[10]).

It is notable that for all wealthy countries, the level of emissions embodied in imports has risen rapidly in the last decade or so, to such an extent that the 'consumption accounts' show a rising trend even though the 'production accounts' are declining[11,12]. It can be argued that in fact the 'production accounts' are declining precisely because the 'consumption accounts' are increasing, and that ignoring emissions embodied in trade constitutes a fatal political and methodological flaw in 'production accounting'.

'The tool' uses a consumption total Σ_{C} that includes net imports. 'Net' indicates that exports are deducted, otherwise there would be inconsistent double counting. Note that this value can be negative if more is exported than imported. It is useful to separate food imports from other imports, for reasons that will be clear later. 'The tool' can of course be used to model developing countries as well. The two key terms here are: C_f denoting GHG embodied in net imports of food for direct consumption and feed for livestock and C_{gs} denoting GHG embodied in net imports of all other goods and services.

$$\Sigma_{\mathrm{C}}, \text{ then} = (p \times g \times e \times f) + (T_{ag} + T_{res} + T_{seq}) + (P_{sh} + P_{av}) + (C_f + C_{gs})$$

Equation 4

Once again, we ought to consider that C_f could be a function of p, and C_{gs} a function of both p and g, but again these effects will be ignored for reasons of simplicity, and factored in if necessary.

The terms discussed so far cover most sources of GHGs. There remain a few other items that we might wish to take into account when evaluating or 'designing' decarbonisation scenarios, or which might serve as 'extra' policy levers to explore. These are described in the following section.

1.4 Net emissions

N_{non} denotes non-GHG forcings of all kinds including non-fuel aviation effects, black carbon and other albedo effects such as the reflectivity of crops and roofs. In view of the uncertainties here, the only effect included in the EQT is the aviation multiplier, easily changed according to the balance of scientific opinion. The multiplier value adopted is that used in UK government protocols, $0.9 \times P_{av}$, so the total emissions from aviation are considered to be $1.9 \times P_{av}$[13]. This is significant in energy decarbonisation programmes because direct emissions from aviation fuels might well be reduced close to zero, but their indirect effects would remain.

N_{seq} denotes territorial sequestration processes other than those arising 'naturally' from land-use changes. They usually entail some form of engineering intervention and have been termed 'geoengineering', although there are clearly both benign and malign forms[14,15]. Here we have in mind deliberate incorporation of biomass into permanent structures or in engineered stores, a kind of reversal of the historic release of carbon fuels into the atmosphere[16].

N_{cr} denotes international credits. If, for reasons discussed in this paper, it is likely that many wealthy nations will fail to decarbonise their own territorial processes, they will need to 'invest' in decarbonisation processes overseas. This could entail helping other nations to decarbonise their energy systems, conserving forests, establishing carbon sinks and so on. It is particularly likely to entail what Read[17] termed Biosphere Carbon Stock Management on an international scale.

Adding these extra terms gives what we shall call a 'net account', Σ_N, that embraces all emissions and other emission-related processes for which a nation might be considered responsible. $\Sigma_N = \Sigma_P$ if N_{seq} and N_{cr} are zero.

1.5 Extended emissions

There is one final and rather problematic term. E_i denotes emissions arising from extraterritorial Land Use, Land Use Change and Forestry (LULUCF), sometimes referred to as indirect Land Use Change (iLUC). This is a difficult and uncertain category, but it is clear that substantial emissions do arise from various land-use practices, mostly in tropical countries, and often associated with food systems in Annex 1 countries[18]. The question arises as to how these emissions should be allocated. Allocation systems have been proposed, and do allocate some of these emissions to Annex 1 countries according to various formulae. Actual values can be allocated.

On account of the methodological difficulty of allocating iLUC emissions, it will be given its own total, Σ_E, the overall total including iLUC. So finally we have:

$$\Sigma_N = (p \times g \times e \times f) + (T_{ag} + T_{res} + T_{seq}) + (P_{sh} + P_{av}) + (C_f + C_{gs}) + (N_{non} + N_{seq} + N_{cr}) \qquad \text{Equation 5}$$

$$\Sigma_E = (p \times g \times e \times f) + (T_{ag} + T_{res} + T_{seq}) + (P_{sh} + P_{av}) + (C_f + C_{gs}) + (N_{non} + N_{seq} + N_{cr}) + E_i \qquad \text{Equation 6}$$

This formalisation is completely transparent and algorithmic. Although strictly most of the units are flows in MtCO$_2e$ per year, they accumulate as physical quantities and can be simply added, exploiting the fact that CO$_2e$ is, to a good approximation, a conserved and measurable quantity. It is obvious how values and formulae can be represented in a spreadsheet. It only requires the insertion of empirical data (usually derived from national statistics) to generate a variety of totals that act as baselines for examining the implications of future changes to the baseline. The effects of different values in any one term are easily assessed while all others are held constant. Scenarios are readily generated by varying various factors in systematic ways and noting the totals. Alternatively a target total can be set, and various ways explored to achieve that target. Rates of change from one date to another are also easily calculated, and act as a useful check on the viability of any given pathway.

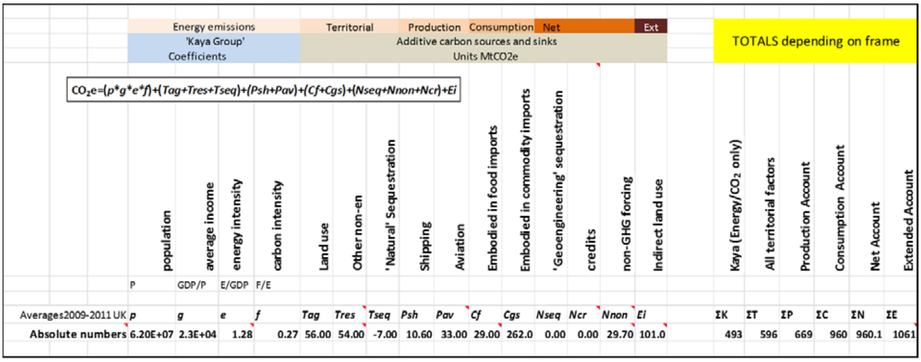
2. A real-world example

To give an example using real data, we can use government statistics from the UK, focusing on 2010 for which reliable data are readily available, although is usually preferable to take three-year averages, 2009–2011, to minimise the effects of annual anomalies. It should be noted that 'official' values can vary somewhat depending on the different statistical conventions and occasional retrospective revisions. It should be obvious that complete precision is not necessary for the purposes of the exercise, and neither is it usually achievable.

Part of the source spreadsheet is shown in Figure 1. The values are in millions of tonnes CO$_2e$ per year, apart from the first four terms, that multiply to generate MtCO$_2e$. Totals are derived by simply adding the relevant terms according to Equations 1–6. These totals are shown in Table 1.

It can immediately be seen that the total emissions (shown on the right in Figure 1) are dependent on the boundary conditions, or 'frame' chosen. These frame totals are shown more clearly in Table 1. The largest frame is more than twice as large as the smallest, which relates only to energy. It is far more than simply a question of national energy supply.

Of course the spreadsheet can easily generate charts illustrating the various elements of 'the tool', and sometimes these are easier to grasp. An example of the largest frame is given in Figure 2, a bar chart, from UK national statistics 2009–11.



Energy emissions | Territorial | Production | Consumption | Net | Ext

'Kaya Group' | Additive carbon sources and sinks

Coefficients | Units MtCO2e

TOTALS depending on frame

CO₂e=(p*g*e*f)+(Tag+Tres+Tseq)+(Psh+Pav)+(Cf+Cgs)+(Nseq+Nnon+Ncr)+Ei

	population	average income	energy intensity	carbon intensity	Land use	Other non-en	'Natural' Sequestration	Shipping	Aviation
	P	GDP/P	E/GDP	F/E					
Averages2009-2011 UK	*p*	*g*	*e*	*f*	*Tag*	*Tres*	*Tseq*	*Psh*	*Pav*
Absolute numbers	6.20E+07	2.3E+04	1.28	0.27	56.00	54.00	-7.00	10.60	33.00

	Embodied in food imports	Embodied in commodity imports	'Geoengineering' sequestration	credits	non-GHG forcing	Indirect land use	Kaya (Energy/CO₂ only)	All territorial factors	Production Account	Consumption Account	Net Account	Extended Account
Averages2009-2011 UK	*Cf*	*Cgs*	*Nseq*	*Ncr*	*Nnon*	*Ei*	ΣK	ΣT	ΣP	ΣC	ΣN	ΣE
Absolute numbers	29.00	262.0	0.00	0.00	29.70	101.0	493	596	669	960	960.1	1061

Figure 1 *Basic layout of 'the tool' spreadsheet with source data.*

Table 1 *Carbon emission totals from the UK economy, according to differing framing conventions*

Frame	Symbol	Total, MtCO$_2$*e*
Energy	Σ_K	493
Territorial	Σ_T	596
Production	Σ_P	669
Consumption	Σ_C	960
Net	Σ_N	960
Extended	Σ_E	1061

3. Using 'the tool' to represent and analyse an actual case

How can the EQT formalisation be used to model decarbonisation scenarios relative to a baseline such as that already described? It can be used in numerous ways. One is simply to take existing programmes, insert known quantities, and explore implications for the unknown quantities. 'The tool' shows the necessary rates of change, and can reveal unstated assumptions and unexpected difficulties.

Figure 3 shows an example based on the real UK data for 2010 shown in Figure 1, in row A, together with the energy (Kaya) total Σ_K and the territorial (Kyoto) total Σ_T, as defined in Equations 1 and 2.

The UK government plans to reduce territorial emissions by 80% relative to 1990, by 2050 *i.e.* to 152 MtCO$_2$ year^{-1}. This frame involves only the 'Kaya group' plus T_{ag}, T_{res}, and T_{cr} (Equation 2). All other factors are left out of account[19].

A worked example shows how 'the tool' is used for simple and accessible 'back-of-the-envelope' calculations to probe assumptions. Row B in Figure 3 shows a possible Business As Usual (BAU) 'comparator' to establish the most likely default assumptions in the absence of directed policy initiatives. Many changes and trends occur 'endogenously', that is they emerge as observed

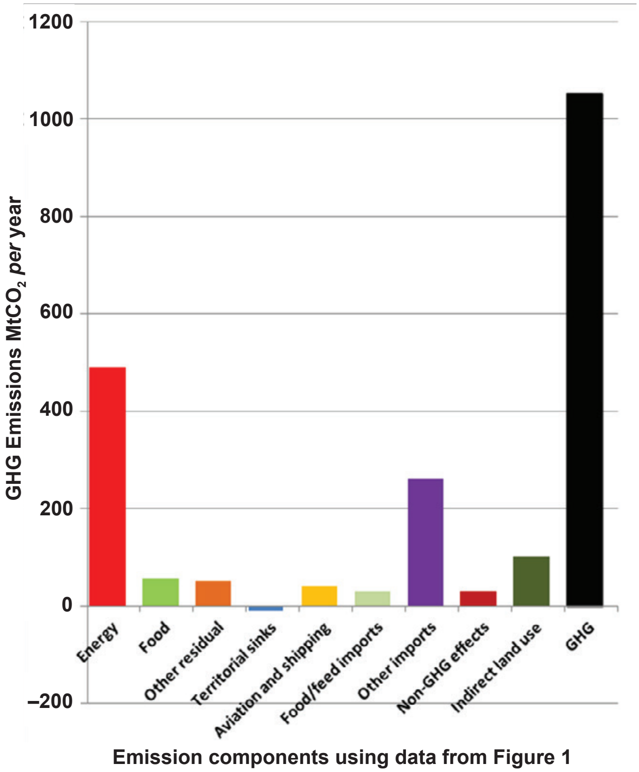
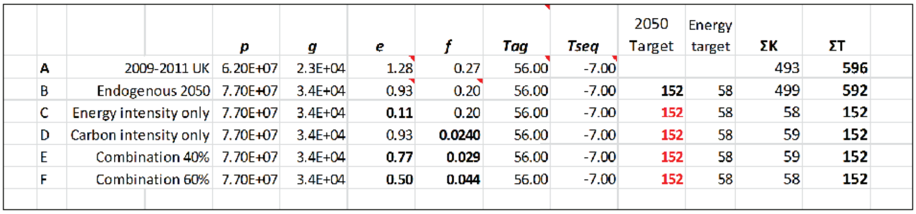


Figure 2 *Bar chart showing components of an extended emissions total,* Σ_E*, shown in black.*

tendencies over time in a wide range of modern societies irrespective of government policies. Examples include economic growth, reduced energy intensity and a wide range of technical developments[20]. Other trends can be anticipated from government projections. For example, the UK population in 2050 is expected to be 77 million[21]. Since there is no suggestion that the UK government intends to restrain economic growth, let us assume conservatively that growth continues at the historically low rate of 1% per year. This means the g factor, registered at £23,000 per head in 2010, would be $23 \times (1+0.01)^{40}$ in 2050, or £34,600, 49% larger, while the population would be 22% larger.



		p	*g*	*e*	*f*	*Tag*	*Tseq*	2050 Target	Energy target	ΣK	ΣT
A	2009-2011 UK	6.20E+07	2.3E+04	1.28	0.27	56.00	-7.00			493	**596**
B	Endogenous 2050	7.70E+07	3.4E+04	0.93	0.20	56.00	-7.00	**152**	58	499	**592**
C	Energy intensity only	7.70E+07	3.4E+04	**0.11**	0.20	56.00	-7.00	**152**	58	58	**152**
D	Carbon intensity only	7.70E+07	3.4E+04	0.93	**0.0240**	56.00	-7.00	**152**	58	59	**152**
E	Combination 40%	7.70E+07	3.4E+04	**0.77**	**0.029**	56.00	-7.00	**152**	58	59	**152**
F	Combination 60%	7.70E+07	3.4E+04	**0.50**	**0.044**	56.00	-7.00	**152**	58	58	**152**

Figure 3 *Table showing Row A: 2010 data, B: BAU to 2050 C-F values for various measures required to reach the UK Climate Change Act target of 152 MtCOe/y in 2050.*

The scale factors would therefore be 86% larger than today on a BAU model. Note that if growth occurred at the more aspirational rate of 2% per year the UK economy would be 2.75 times larger. It is a commonplace in the 'sustainable consumption' literature that most mainstream 'sustainable policies' struggle to overcome the scale factors, and that in the end, a planned cessation of physical growth appears to be unavoidable[22,23]. Such 'alarm bells' arise inevitably from application of the EQT tool.

What might 'endogenous changes' in the energy sector be? In anticipating the effects of a BAU model a few remarks are required. As it happens, the UK is unusual in having experienced a period of rapid decline in overall carbon intensity between 1990 and 2010. It would be tempting to simply extrapolate this trend to 2050. However, closer examination shows this rapid decline to have been due to two factors that cannot be continued indefinitely. One is the switch from coal to gas for electricity generation; the other is the 'offshoring' of high-intensity manufacturing and commodity supply, generating large emissions overseas that do not appear in the territorial accounts[24].

In view of these unusual factors, much of the UK's recent performance in reducing its emissions can be considered temporary. It remains true however, that modern economies do steadily reduce their intensities in a 'endogenous' manner, and the projections adopted are the recent historic average rate for the OECD group as whole. These are -0.8% a year for energy intensity (e) and -0.7% a year for carbon intensity (f)[53].

There is no suggestion in the UK climate change programme that food or land use is to be changed, presumably because the planning and lifestyle changes are too politically contentious. It is reasonable then to make the default assumption that expected increases due to population and improving efficiency cancel each other out, leaving emissions from agriculture at present levels. Note that the recent IPCC report of 2014 raised the GWP equivalence of methane to 33 relative to CO_2, rendering official agriculture emissions understated by about 10%. Note that all these assumption can easily be changed, and other possibilities quickly tested. As it happens, reported emissions from agriculture have been declining in recent years, but as with so many other aspects of the UK economy, this is most likely to be attributable to increased imports.

Factor T_{res} (industrial residuals) can be expected to increase with both scale factors, although it contains enough 'low-hanging fruit' that we might expect some practical reductions. Reductions have been fairly rapid since 1990, especially with respect to landfill gas, so a continuing reduction of -2% a year seems a plausible default assumption. The calculation is then $T_{res2050} = T_{res2010} \times 1.86 \times (100.02)^{40} = 44.5\ \mathrm{MtCO_2}e\ \mathrm{year}^{-1}$. Factor T_{seq} (territorial land-use sinks) might be greater or less. It has varied considerably over recent years, so the present value of $-7\ \mathrm{MtCO_2}e/\mathrm{yr}$ is maintained.

Based on these default assumptions, row B in Figure 3 shows a default expectation for 2050. Note that any of the calculations can be checked simply by applying Equation 2, bearing in mind that the data in Figure 3 are rounded. Row B shows that under these assumptions, the 2050 target is missed. In fact, the emissions are virtually the same as they were in 2010. Perhaps it is no surprise that simple BAU is unlikely to deliver. As has been repeatedly observed, the scale factors nearly always cancel out 'merely' endogenous improvements. This 'non-result' demonstrates the transparent logic embodied in the EQT tool.

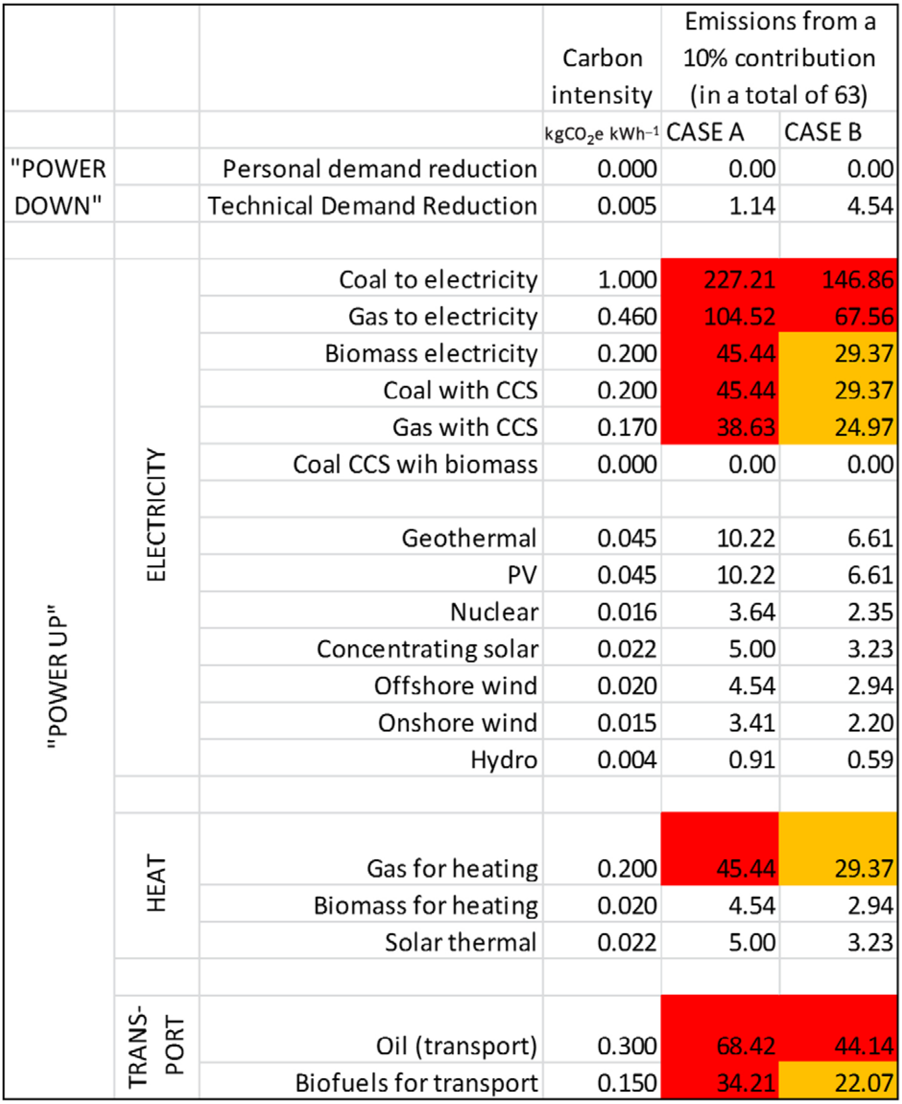
The most striking result, however, is that the territorial target of 152 $MtCO_2e$ $year^{-1}$ is almost certain to be dominated by non-energy factors. It appears to be widely assumed in policy circles that the task is to devise energy systems that emit no more than (approximately) 152 $MtCO_2e$ $year^{-1}$. But this is clearly mistaken. On the plausible assumptions made above, only around 58 $MtCO_2e$ are attributable to the energy sector in 2050. There is inevitably considerable uncertainty here, but there is probably no reason to vary the non-energy factors greatly. It must be asked, then, what patterns of energy production will together generate less than 58 $MtCO_2e$ $year^{-1}$?

Rows C−F in Figure 3 demonstrate coarse changes in the energy system that would deliver the target level of 58 $MtCO_2e$, indicated in the column Σ_K. Altered numbers in each row are shown in bold. Row C demonstrates the effect of reaching the target simply by changing the energy intensity (e) of the UK economy (sometimes called the 'power down' factor)[25]. Mathematically it requires a reduction of energy input to about 10% of the present level, relative to the size of the economy. Decarbonisation scenarios vary widely in their treatment of e (of this, more below), but very few have yet suggested such a drastic reduction. This then, tests an extreme case and can be rejected as unlikely (but see for example [26]).

Row D demonstrates the generally-favoured alternative, decarbonising the energy system (f) while maintaining energy intensity (e) at the 'endogenous' level. In this case, it entails a reduction of average intensity to around 24 g kWh^{-1} by 2050. This is approximately the current level reported for hydro, wind, biomass, some solar thermal applications, and nuclear energy, so it is plausible by 2050 (see Table 2). It is hard to see anything but a very small role for fossil fuels under these assumptions, because at carbon intensities in the hundreds of grams per kWh they would quickly exhaust the quota, even with carbon capture and storage (CCS), at present rates of capture.

Rows E and F show that these severe constraints can be relaxed somewhat if a combination of energy and carbon intensity reduction is followed. Row E shows a reduction of 40% in energy intensity relative to today (67% relative to the projected economy of 2050), but this gives only a slight increase in allowable carbon intensity. A 60% reduction of energy intensity from today's level (explicitly modelled in the 2013 Zero-Carbon Britain scenario[27]) however, permits average carbon intensity of 47 g kWh^{-1}. This would readily allow a mixture that included PV and geothermal at between 40 and 50 g kWh^{-1}, but still makes more than a small fraction of fossil energy impossible.

Table 2 *Energy technologies with 2010 carbon intensity values, and emissions from 10% contribution to the economy of 2050. Cells highlighted in red would be completely ruled out. Cells highlighted in yellow could make only a very small contribution.*



			Carbon intensity	Emissions from a 10% contribution (in a total of 63)	
			kgCO$_2$e kWh^{-1}	CASE A	CASE B
"POWER DOWN"		Personal demand reduction	0.000	0.00	0.00
		Technical Demand Reduction	0.005	1.14	4.54
"POWER UP"	ELECTRICITY	Coal to electricity	1.000	227.21	146.86
		Gas to electricity	0.460	104.52	67.56
		Biomass electricity	0.200	45.44	29.37
		Coal with CCS	0.200	45.44	29.37
		Gas with CCS	0.170	38.63	24.97
		Coal CCS wih biomass	0.000	0.00	0.00
		Geothermal	0.045	10.22	6.61
		PV	0.045	10.22	6.61
		Nuclear	0.016	3.64	2.35
		Concentrating solar	0.022	5.00	3.23
		Offshore wind	0.020	4.54	2.94
		Onshore wind	0.015	3.41	2.20
		Hydro	0.004	0.91	0.59
	HEAT	Gas for heating	0.200	45.44	29.37
		Biomass for heating	0.020	4.54	2.94
		Solar thermal	0.022	5.00	3.23
	TRANS-PORT	Oil (transport)	0.300	68.42	44.14
		Biofuels for transport	0.150	34.21	22.07

We should bear in mind that the intensities of 2010 will not necessarily be the intensities of 2050. As the economy decarbonises, the energy needed to produce and install intrinsically zero-carbon systems will itself be decarbonised, so many low-carbon sources will be increasingly eligible. However, this coarse initial exercise clearly shows how difficult would be the inclusion of more than a few percent of fossil fuels, even with carbon capture and storage (CCS), if the target is to be met. Table 2 gives total emissions from a range of energy technologies if they were to make a 10% contribution to the energy system, given their presently-reported carbon intensities[28].

Using standard carbon intensities for different energy systems[28] the total emissions from any given proportion of these systems can be calculated, given various assumptions regarding the size of the economy and its energy intensity. To give a rough test of which technologies might be used, the final two columns of Table 2 show emissions expected for a contribution of 10% for each technology. Case A assumes an intensity ***e*** of 0.93 kWh £$^{-1}$ of GDP, case B a more radical scenario with an intensity of 0.6 kWh £$^{-1}$ of GDP. These emissions compare with a benchmark of 58 MtCO$_2$*e* g kWh^{-1}. Severely-unviable options are highlighted in red, and probably-unviable options highlighted in yellow.

It is immediately obvious that none of the standard fossil fuel options is viable as a major contributor, whether for electricity, heating or transport. Even with CCS – widely assumed to be a key part of the standard baseload model of the low-carbon future *e.g.* only a 10% contribution uses up half the allowance relative to the benchmark[29].

Nuclear power and the renewables come out of the exercise relatively well. Biomass however, is an odd case. Simple biomass electricity is considered no better than 'clean coal'[28], but this is an artefact of the requirement for fossil fuel inputs for growing and harvesting, an effect that would decline in a decarbonised energy scenario. Further, once the CCS technologies have been established, which conventional thinking assumes will be the case, it is relatively straightforward to cofire biomass with coal to create a genuinely carbon-neutral 'firm' electricity supply, limited only by possible supplies of biomass[30,31]. In 2012, the UK burned about 42 Mt of coal to generate about 104 TWh of electricity. If this were cofired with 20% biomass, say 8 Mt, with fully-operational CCS it could in principle generate carbon-neutral electricity.

At this point in the discussion I simply wish to point out that, on the assumptions made, the UK target of 152 MtCO$_2$*e* in 2050 cannot be met if the energy systems uses more than a very small fraction of fossil fuels, with or without CCS. It is an easy matter to use an active version of Table 2 to test the approximate viability of various kinds of energy mixtures. As most scenario builders have found, these tend to generate energy systems with a very high proportion of low-carbon electricity, even for heating and transport, where heat pumps and electric vehicles almost invariably feature strongly. But contrary to the prevailing 'baseload' philosophy, fossil fuels can make only a token contribution. The EQT tool indicates unambiguously that the choices lie with demand reduction, nuclear power, and a wide range of renewables.

Before leaving Figure 3, we can also see how the rates of investment and installation can be easily calculated. They are not particularly challenging. Assuming a rapid start in 2015, to deliver 40% reduction of primary energy supply by 2040 would require an annual change of just over 1% of the starting value per year. To deliver a reduction of carbon intensity from 1.28 kg kWh^{-1} to (say) 40 g kWh^{-1} would require an annual change of around 2.5% of the starting value. Other energy transition scenarios have reported similar results[32,33].

Of course, on its own 'the tool' does not tell us whether any given combination is viable in land-use terms, or whether it will 'keep the lights on'. These matters have to be tested separately, as they have been in the *Zero-Carbon Britain* series and elsewhere. In general, they are physically easy but politically difficult, but I see it as the task of enlightened analysts to insist that political and economic structures must be built around the subset of physically viable scenarios, rather than the other way round. As Canute the Great once demonstrated, in the end 'physics trumps politics'[34].

4. The 'budget' approach

In its early years, the climate change policy debate was dominated by 'targets' and 'target dates' such as the one we have just been discussing. More recently we have come to understand that neither a target level, nor a date, nor both combined, unambiguously serve to evaluate a programme or a scenario. It is the shape of the trajectory that counts, or rather, the area underneath it, reflecting the cumulative emissions between two given dates. The reason why this is important is due to the unusual property of many GHGs, and especially CO_2, of persisting for a long time in the atmosphere after they have been emitted. As an aside, it is unfortunate that the idea of 'allowable accumulated emissions' has become known as a 'carbon budget', because the same term was established earlier to describe the net balance between global carbon sources and sinks[35,36]. But this new meaning has now become established and I shall use it.

The formalisation I have described, and its spreadsheet version, easily allows cumulative emissions to be approximately calculated, again in a simple and transparent 'back of the envelope' spirit. Where we have (emissions / year) × (years), we are left with emissions. A geometrical equivalent allows a default estimation to be made by imagining a straight line between the level of emissions E_0 at time t_0 and a 'target' level of emissions E_t at target date t_t. The area under this line is usually the sum of the areas of a triangle and a rectangle, both easily calculated. This elementary principle is illustrated in Figure 4.

Take the case I have just been discussing, the UK target of 152 tCO_2e in 2050. This was explicitly launched in 2008, and prospective cumulative budgets published for the first 20 years.

The total period then is 42 years, and the level is never intended to drop below 152. Therefore part of the total is $152 \times 42 = 6384$ $MtCO_2e$. On top of this notional 'rectangle' is a triangle described by $(627 - 152) \times 42/2 = 9975$. The implied total for cumulative emissions is therefore 16,359 $MtCO_2e$.

As it happens, the UK government has published its own budgets till 2027, the total at that point being 10,294 $MtCO_2e$. It is easy to fill in the remainder, giving a total of 16,256 $MtCO_2e$, lower than the default estimate, but

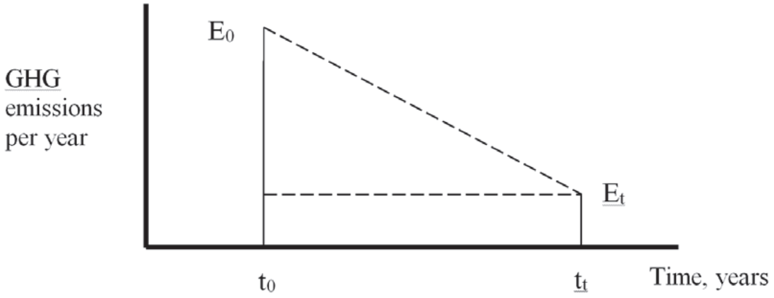


Figure 4 *Geometrical method of calculating default cumulative emissions in a given time period.*

reasonably close. The important question now is how to evaluate such cumulative emission values against some kind of global standard. Are they really sustainable?

The concept of global carbon budgets in the sense used here emerged largely in Germany, and it was German theorists who first developed the global estimates[37,38]. These are couched in terms of total emissions of CO_2/CO_2e allowable between certain dates. The largest time frame stretches back to the beginnings of the industrial revolution forward to 2200, but more commonly global budgets are given for 2000–2100 or 2000–2050, or from whatever date the estimate is made.

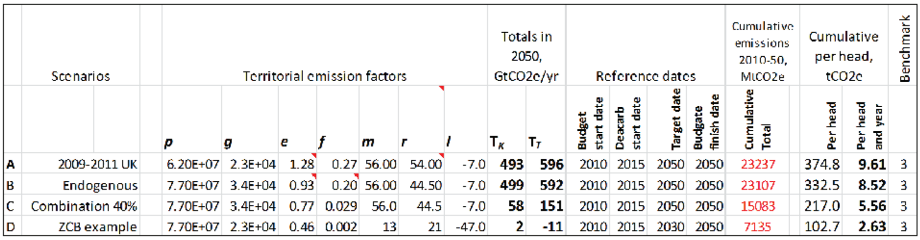
The budget emissions can be used to calculate consequent concentrations of GHG in the atmosphere, and climate models are used to calculate the expected effects on temperature. There is a widespread consensus that the global temperature should not exceed 2 °C, but because the link between concentrations and temperature rise is uncertain, various budgets are assigned probability values in terms of percentage chance of avoiding the 2 °C limit. What probability is 'reasonable' is of course a political or subjective matter. It is rather surprising that the most commonly cited budgets are those that give a 66% chance of avoiding 2 °C. One might have thought that taking a one-third risk on a lurch into the unknown with potentially catastrophic consequences, is hardly a reasonable choice. As a modest gesture to sanity perhaps we will move the probability to 80% and apply calculated budgets accordingly.

The global budget for all GHG associated with an 80% probability of avoiding 2 °C is approximately 1000 $GtCO_2e$ 2010–2050. There is little disagreement that elementary fairness requires this to be allocated on an equal per capita basis across the entire global population[39]. The global budget can therefore be translated into a simple benchmark on a per capita basis. The average world population between 2010 (6.84 billion) and 2050 (9.3 billion mid-range forecast) is hard to calculate but is close to 8 billion. 1000/8 gives a per capita allowance of 125 tCO_2e between 2010 and 2050, or 3.13 tCO_2e per person and year, although this value is eroded as time goes by because average per capita emissions are higher than the annual quota. By 2015 the average global share of the remaining budget will be less than 3 tCO_2e per person and year. I suggest 3 t per person and year as an approximate benchmark, with an allowance of ±0.25, for programmes intended to start in 2015.

‘The tool’ allows cumulative emissions to be evaluated against this benchmark, and some examples based on UK data are given in Figure 5, which can be seen to be an extension of Figure 3. Numbers in red show cumulative emissions 2010–2050 ($A_{T2010-2050}$) in $MtCO_2e$, and those in bold show values per capita and per capita year. The benchmark is shown in the final column. The same one-number benchmarking principle could be applied to virtually any proposed decarbonisation programme, such as those reviewed by Wiseman and Edwards[40].

Consider the rows in turn, from this ‘budget’ perspective. Row A shows what would happen if the UK continued with no changes to any of the decomposition terms. We know already that it would fail to meet the official 2050 target. Unsurprisingly its cumulative per capita emissions at 9.61 far exceed the benchmark of 3. Row B shows the BAU trajectory with ‘expected’ changes. The population of the UK in 2050 is expected to be 77 million. In 2010, it was 62 million. The exact trajectory between these two points is uncertain, but the average must be close to 69.5 million. The result is very similar to the ‘no change’ scenario. Row C shows approximately the case already discussed, of the UK government succeeding in reaching its 2050 target. In spite of this, it fails to meet its cumulative budget. Allowing for the extra two years (2008–2049 of the UK programme), accumulated emissions per head are 207 t $head^{-1}$, and 4.94 t per year, substantially higher than the global benchmark. It does not meet Schellnhuber’s standard of ‘fairness and physics’, and probably cannot do so if changes are restricted to the energy system.

To meet the standard, UK territorial emissions (*i.e.* Equation 2) would have to be no more than 8340 $MtCO_2e$ between 2010 and 2050. Could this be achieved by more rapid decarbonisation? A partial answer to this question is provided by CAT’s series of Zero-Carbon Britain (ZCB) studies (CAT, 2007, 2010, 2013) proposing a reduction of UK territorial emissions to zero by 2030. These studies made one or two improbable assumptions, such as a



	Scenarios	Territorial emission factors							Totals in 2050, GtCO2e/yr		Reference dates				Cumulative emissions 2010-50, MtCO2e	Cumulative per head, tCO2e		Benchmark
		p	***g***	***e***	***f***	***m***	***r***	***l***	**T_K**	**T_T**	**Budget start date**	**Deacarb start date**	**Target date**	**Budgate finish date**	**Cumulative Total**	**Per head**	**Per head and year**	
A	2009-2011 UK	6.20E+07	2.3E+04	1.28	0.27	56.00	54.00	-7.0	**493**	**596**	2010	2015	2050	2050	23237	374.8	**9.61**	3
B	Endogenous	7.70E+07	3.4E+04	0.93	0.20	56.00	44.50	-7.0	**499**	**592**	2010	2015	2050	2050	23107	332.5	**8.52**	3
C	Combination 40%	7.70E+07	3.4E+04	0.77	0.029	56.0	44.5	-7.0	**58**	**151**	2010	2015	2050	2050	15083	217.0	**5.56**	3
D	ZCB example	7.70E+07	2.3E+04	0.46	0.002	13	21	-47.0	**2**	**-11**	2010	2015	2030	2050	7135	102.7	**2.63**	3

Figure 5 *EQT representations of emission drivers and values, showing accumulated emissions over the period 2010–2050, and per capita values relative to a suggested benchmark. Based on UK data from 2010.*

constant value for g and a value for f assumed to be literally zero by the target date, but the key innovation was to address a number of non-energy factors as well as decarbonising the energy system. These included minimising industrial residuals, completely overhauling the agricultural system, greatly increasing the contribution of biomass energy, and generating a territorial sink worth −47 MtCO$_2$*e* a year through natural vegetation and soil management.

A simple calculation based on Figure 3 shows whether, if this rapid decarbonisation proved possible, the 'budget' could be met. Territorial emissions were 596 MtCO$_2$*e* in 2010. Assuming this level continues until 2015, followed by a rapid decarbonisation to zero in 2030, continuing at zero to 2050, would give $596 \times 5 + (590 - 11) \times 15/2 - (11 \times 20) = 7135$ MtCO$_2$*e*, or 2.63 t head^{-1} year^{-1}, comfortably within the budget.

In fact, the ZCB studies of 2010 and 2013 modelled a slightly larger frame: all production emissions including international aviation and shipping (Equation 3). The starting value was 664 MtCO$_2$*e* year^{-1}, so the cumulative total 2010−2050 would be 8673 MtCO$_2$*e* or 3.1 tCO$_2$*e* per person and year, within the benchmark margin of error. Does this mean that the requirements of 'fairness and physics' can in principle be met by decarbonisation programmes with sufficiently low and rapidly-achieved targets? The answer depends on the frames chosen, and once again the EQT can generate general indications of which pathways are more likely.

5. Considering larger emission frames

I have tried to show that in terms of the key metric of carbon budgeting, current UK policy, widely considered forward looking, fails to deliver even within its own terms. It can however be 'rescued' by more aggressive decarbonisation programmes, modelled in the ZCB studies, which demonstrate low cumulative emissions within a 'production' framework[25,27,41]. The same would probably be true of similar exercises carried out in other Annex I countries.

However, in any future international agreement regarding the allocation of climate change mitigation tasks, it is likely that nations will be measured on the basis of consumption rather than production[42,43]. It could be argued that consumption accounting is an elementary aspect of the 'fairness' principle[44]. It asks, in particular, how are we to deal with factors j and b in the formalisation, the extraterritorial emissions embodied in trade?

A few basic numbers will serve to illustrate the problem. In 2010, the UK is reported to have imported goods (net of exports) with embodied carbon of 29 MtCO$_2$*e* for food and 262 MtCO$_2$*e* of other goods, a total of 291 MtCO$_2$*e*. Since 2000 the trend has been steadily upwards. Other things being equal, we might expect this level of importing to increase proportionately to the scale factors of the UK economy, expected to be 81% larger in 2050, so 541 MtCO$_2$ in 2050. We can model these BAU cumulative emissions using the geometrical principle of Figure 5. From 2010−2050 the arithmetical interpretation is

$291 \times 40 + (541 - 291) \times 40/2 = 16640$ $\mathrm{MtCO_2}e$ or nearly 6 $\mathrm{tCO_2}e$ $\mathrm{year^{-1}}$ $\mathrm{head^{-1}}$, far above the benchmark level for just indirect emissions in imports.

Suppose we now model the opposite case, reducing the level of imports themselves to zero by 2030. Surprisingly perhaps, even this improbable state of affairs fails to reduce the cumulative emission 2010–2050 below the benchmark. The reason is that the initial level is so high that mathematically it is impossible to fit within the constraints. This is clear when using the live version of the EQT tool, but a brief calculation here will illustrate the assertion. The level of T_C for the UK was 960 $\mathrm{MtCO_2}e$ in 2010. Suppose this continues until 2015, when a rapid decarbonisation begins, reaching zero in 2030. Again using the geometrical approximation in Figure 5, we have $960 \times 5 + 960 \times 15/2 = 12000$ $\mathrm{MtCO_2}e$, or 4.3 t $\mathrm{h^{-1}}$ $\mathrm{year^{-1}}$. This also assumes either that imports are zero at 2030, or that trading partners also have zero-carbon economies. Neither of these is plausible, and 'consumption accounts' pose serious problems for the claims of Annex I countries to be pursuing sustainable policies.

The situation is even worse if we widen the frame even further to include an allowance for emissions from indirect land-use changes overseas. Audsley *et al.*[18] estimate this currently at 101 $\mathrm{MtCO_2}e$ a year. If this term is included in virtually any scenario, it renders the benchmark beyond reach.

It might be worth remarking that the iLUC term *i* is widely associated with grazing livestock, and strictly speaking 101 $\mathrm{MtCO_2}e$ a year should be allocated to the UK, given existing agricultural and dietary practices. Where else would the responsibility lie? The only theoretical way to reduce such emissions is something along the lines pursued in ZCB2030[25]: this scenario permits no imports of livestock products or feed materials, and reduces other food imports to less than 20% of the total food consumed, of products with low carbon intensities. With such measures it is reasonable to ignore the *i* term; without them, it is a serious omission and should be included in national budgets.

Leaving the *i* factor aside, 'the tool' demonstrates quite clearly that even extremely rapid and radical decarbonisation cannot meet the requirements of 'fairness and physics' if the analysis embraces wider (and fairer) frames.

6. Widening the frame in the time dimension

Hitherto we have considered cumulative emissions only within the period 2010–2050. In an international context, it is often pointed out that most of the accumulated GHGs in the atmosphere have been generated by the Annex I countries during the course of their economic development. In some ethical sense, it 'belongs' to them, and should be their responsibility to deal with. This is of course another aspect of Schellnhuber's 'fairness' principle, but is not merely an ethical matter: it has a diplomatic hard edge that is bound to figure in international negotiations[45,46].

The matter is often expressed in terms of 'historical responsibility'[47]. How far back should emissions be counted? Again 'the tool' can be used to model these factors, at least with respect to the usable 'back-of-the-envelope' spirit of the IPAT and Kaya identities. It is simply a matter of adding known national totals for a given range of historical years, and proceeding to calculate the cumulative emissions. In effect, it adds another 'dimension' to the analysis.

Suggested dates for 'back-counting' are as follows: 2010 because nearly all national statistics are collected and data are good and because some global budgets have been worked out from this date; 2000 because the original Meinshausen[37] calculations were based on this date; 1992 because most nations signed the FCCC in that year, committing themselves to 'avoiding dangerous climate change'; 1990 as a 'round' proxy for 1992; and various earlier dates back as far as the 18th century when the industrial revolution can be said to have begun.

From an ethical, radical decarbonisation perspective, these alternative time frames are problematic because they cover emissions that were made in the past that no current or future action can mitigate. Nevertheless they still exist in the atmosphere, contribute a major fraction of the 'problem', and have to be dealt with in some 'fair' way.

We are now in a position to create a table of both dimensions, frames for emissions and frames for time, and to insert the cumulative emissions under various assumptions. This allows us to explore the limits of potential rapid decarbonisation scenarios. As an example, I shall use an approximation of the ZCB scenario of 2013[27], which despite its apparent radicalism has been thoroughly checked for functionality except for assumptions about term b, net imports of goods and services other than food, so a further assumption is made for this factor. In addition, factor s (territorial sinks) is allocated an 'extra' value of -30 $\mathrm{MtCO_2}e$ year^{-1}, which is plausible given the scenario's overall changes in land use.

The assumptions for the scenario then, are as follows: the process begins in 2015 and is complete by 2030, continuing to 2050; zero economic growth between 2015 and 2050; near-zero emissions from the energy system and transport; residual emissions reduced to 40% of their level at 2010; territorial agricultural emissions reduced to 22% of the 2010 level; food imports reduced to 21%, and associated emissions reduced to 20%; 47 $\mathrm{MtCo_2}e$ year^{-1} of natural sinks; aviation reduced by two-thirds, with consequent reduction of non-GHG forcing to ~ 12 $\mathrm{MtCO_2}e$ year^{-1}; and reduction of import volume by 50%, assumption of 4% year^{-1} reduction in intensity of trading partners 2015–2050.

Some discussion is required regarding assumptions on emissions embodied in imports, because the analysis will be sensitive to the values adopted. It has to be acknowledged that most Annex I nations are high net importers and structurally dependent on imports of low-cost commodities and finished goods. They have moved steadily into the 'post-industrial' condition where up to 80% of the GDP (in the case of the UK for example) is generated from services. It would be very difficult for them to readjust suddenly, but we have to think seriously about what is likely, or indeed possible, in a rapidly-decarbonising world.

It is true that on average the GHG intensity of the world economy is declining, if slowly, and we probably have to assume that this must accelerate, or simply admit defeat. Probably the *b* term would need to be treated like any other, with strict targets and target years. Importing nations would have to reconsider their commodity bases, and their manufacturing sectors, but these would have implications for their territorial emissions.

For the discussion below, the assumption has been made that the world economy decarbonises by 4% a year, 2015–50, as it must for a reasonable chance of avoiding the 2 °C threshold. As Randers and Gilding [48] have observed, such rates of change are entirely feasible and have robust historical precedents. At the same time it is assumed that the UK's trend to import a greater fraction of its goods and services, is reversed, and that by 2050 the total volume of imports is 50% of its present level. Together these assumptions generate annual emissions of 31.4 $MtCO_2e$ in 2050. It would be relatively easy to model alternative assumptions, but they are unlikely to modify the eventual conclusions.

Decarbonisation programmes are of course vital, but they do not reduce the cumulative emissions to zero, because: (a) it takes time to bring down existing emissions; (b) some emissions are outside national control; and (c) historical emissions still in the atmosphere are not affected by subsequent emission reductions.

Table 3 shows some examples, again using UK data. Benchmark quotas naturally vary for each time period, and decline with later dates, simply reflecting the fact that the global carbon budget is being rapidly run down. To simplify what could be a large table, I include only the 'production total' T_P and the 'consumption total' $T_{C,}$ and three representative time frames each with its own 'budgetary' quota.

The very smallest frame, production emissions from 2010 ($C_{P2010-2050}$), meets the benchmark criterion, but consumption emissions ($C_{C2010-2050}$) within this time frame do not. All other frames are even worse. The excess of emissions

Table 3 *Cumulative emissions for UK production and consumption over various budget periods, assuming total territorial decarbonisation by 2030*

Budget periods	Cumulative production emissions, $MtCO_2e$	Cumulative consumption emissions, $MtCO_2e$	Quotas for each period	Excess consumption emissions over quota, $MtCO_2e$
2010–2050	8396	12897	8688	4209
2000–2050	15047	22498	11800	10698
1990–2050	21747	32100	16060	16040

over the benchmarks can be considered as ‘carbon debts’ and some are shown in red in the table. To put these debts in perspective, they can be expressed in values per year or per person. In the case of the longest time scale, the carbon debt would amount to a value of about 458 MtCO_2e a year between 2015 and 2050, or 6.6 tCO_2e per person and year, comparable with the annual energy emissions of the early 21st century.

The situation is represented graphically in Figure 6. Here all UK emissions are represented between 1990 and 2050, using official data and projections by Scott *et al.*[49]. The vertical axis is MtCO_2e year^{-1}, the horizontal axis time in years, so the areas represent cumulative MtCO_2e. The various emission frames can be clearly seen, relative to the allowable quota ‘benchmarks’ shown in purple at the bottom.

The Zero-Carbon Britain studies can be represented on the diagram as a triangle spanning the 15 year period 2015–2030. Within the narrower frames, we can see that this area is smaller than that of the quota between 2015 and 2050, and it is clearly better than official UK policy, outlined in black dashes, that it was designed to challenge. In larger frames however, the area is overwhelmed by the scale of other emissions, and it is obvious that no matter how fast the process, simple decarbonisation is not enough to ‘pay the debts’.

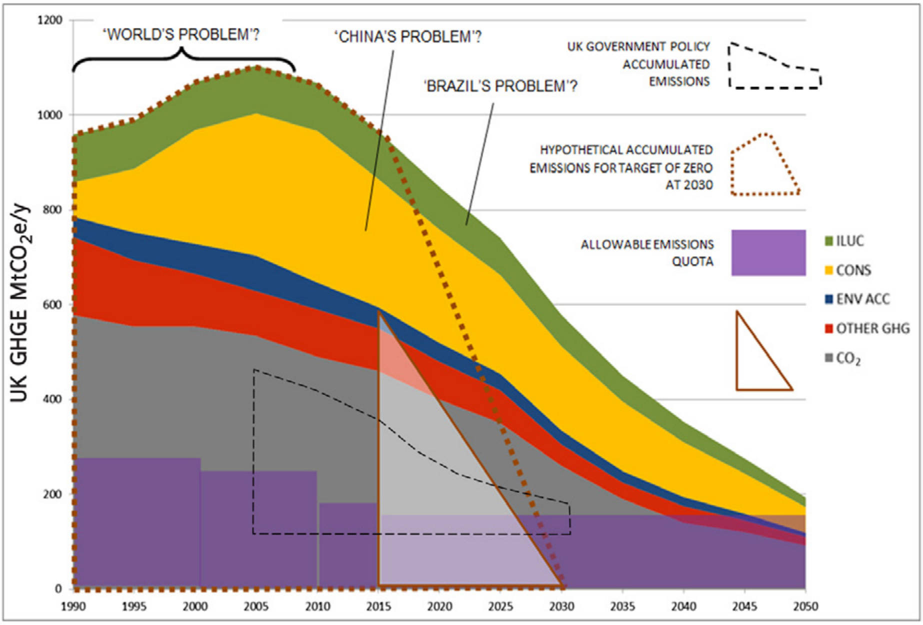


Figure 6 *Cumulative emissions for the UK, 1990–2050. Coloured areas represent emission frames as discussed in text. The translucent triangle represents a rapid and total decarbonisation between 2015 and 2030, as envisaged in the Zero-Carbon Britain reports. The area outlined in a brown dashed line represents hypothetical cumulative emissions for the widest frame, even given rapid total decarbonisation.*

If the focus remains on ‘production accounting’, responsibility for the larger frame emissions passes to other geopolitical entities. In terms of Figure 6, ignoring imports turns much of the yellow section, figuratively speaking, into ‘China’s problem’; ignoring iLUC turns the green section into ‘Brazil’s problem’; while ignoring historical emissions turns them into ‘the world’s problem’. Brutally, we appear to have a situation that defies both fairness and physics. How are we to get global emissions to fit inside the purple rectangle between 2015 and 2050?

7. Some implications

In terms of the arithmetic of the EQT tool and the geometry of Figure 7, there appear to be only two classes of further options. They are not mutually exclusive. One is greatly accelerated decarbonisation at a global scale. The other is the development of carbon-negative processes, again on a global scale.

If the UK is representative, Annex I countries are likely to have exhausted any possible territorial resources to comply with their quotas. ‘Carbon debts’ are inevitable and must become integrated into mitigation policy. This leads to an obvious conclusion: that most Annex I countries should pay for extraterritorial resources to restore the balance.

Such extraterritorial resources would include accelerated decarbonisation of national economies, and rapid development of benign carbon sinks. Of course rapid national decarbonisation policies remain essential, but they are never going to be enough to reconcile fairness and physics.

Figure 7 summarises the options in a simplified geometrical form. Areas above the line are positive emissions, areas below are negative, and can be subtracted. The net area must conform to the budget.

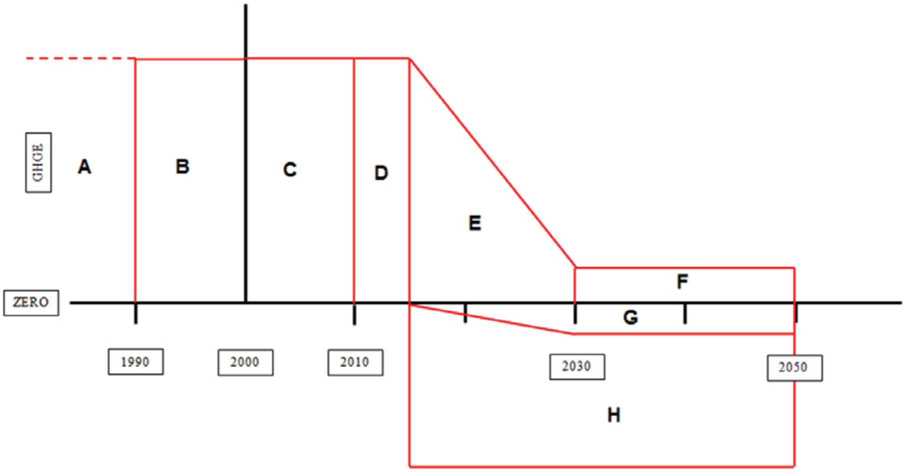


Figure 7 *A geometrical representation of a decarbonisation process, showing positive and negative emissions over time.*

What might this mean for Annex I countries? Let us return to the EQT tool for a quantitative test. Using the data and assumptions of ZCB, Table 3 showed a carbon debt of 10698 $MtCO_2e$ for the period 2000–2050, a likely minimum requirement for the recognition of 'historical responsibility'. There are two terms in the EQT not yet used as policy levers, s, engineered territorial sinks, represented by area G in Figure 7, and c, international credits for any purpose, represented by area H.

With respect to s, the possibility was crudely explored in ZCB2030[25], and a maximum level of engineered photosynthesis-based carbon storage estimated at around 30 $MtCOe_2$ $year^{-1}$ in addition to the semi-natural sinks. This could allow a 'negative carbon Britain' between 2030 and 2050, accumulating $20 \times 30 = 600$ million 'negatonnes' of CO_2e. Sadly, as Table 4 shows, this has little impact on the 'debt'.

Could other territorial sinks be envisaged for the UK and similar countries? The ZCB studies only permit themselves existing or near-commercial technologies, but other possibilities might be conjectured, notably pure Biomass with Carbon Capture and Storage (BECCS), which in principle combines biological carbon fixation with geological storage[16]. Considered as an energy technology, BECCS might deliver negative carbon intensities of around -1500 g kWh^{-1} [50] provided the proposed geological sinks operate as predicted.

The latest ZCB study, *Rethinking the Future*[27] prudently allocates its expanded biomass resources to synthetic liquid and gas fuels, leaving only enough to generate 14 TWh $year^{-1}$ of electricity for balancing and backup. The logic is of course that there is plenty of electricity from variable renewable sources, but only biomass can provide the crucial storable, transportable, high energy-density fuels. It is possible, however, to envisage an alternative scenario that generates four times as much electricity using dedicated BECCS stations, *i.e.* 56 TWhe $year^{-1}$, without exhausting the capacity of the land-use system. If these stations achieved the IEA (2009) level of sequestration, they would create 84 million 'negatonnes' per year. Giving s this value generates 1600 million 'negatonnes' between 2030 and 2050, but as Table 4 shows, still does not abolish even part of the historical carbon debt.

Consider now the final term, c. The exercise must be to find what level will bring the debt to zero. This is easy using the EQT tool, and the answer (all other

Table 4 *UK carbon debt 2000–2050 under Zero-Carbon Britain assumptions and two extra conditions*

	Carbon Debt 2000–2050, $MtCO_2e$
Standard ZCB run	10698
$N_{seq} = -30$ $MtCO_2e$ $year^{-1}$	8978
$N_{seq} = -84$ $MtCO_2e$ $year^{-1}$	7493
$N_{cr} = -357$ $MtCO_2e$ $year^{-1}$	0

factors remaining unchanged) is 357 $MtCO_2e$ $year^{-1}$ in international credits to balance the UK's emission books, payable between 2015 and 2050. This kind of value is likely to apply to most other Annex I countries. If substantial territorial decarbonisation measures are not applied, the requirement for credits would be much greater, but it will be hard to avoid the need to pay for extraterritorial resources.

The economic implications here can be roughly assessed. Carbon is internationally traded in the EUETS at less than €20 per tonne of CO_2, but much higher prices are anticipated in the future. For example, if the value were €125 t^{-1}, then purchase of 310 Mt of credits would cost about 2% of the UK GDP. This would be additional to the cost of territorial mitigation measures. Other prices can easily be modelled to see where the limits might lie. Limits are usually political rather than strictly economic. Compare for example ref.[51,52].

It is important to note that such credits might be 'spent' in a wide variety of ways including certified sinks for which host countries would receive credits. The development of carbon-negative processes in particular, is likely to be a crucial part of global mitigation strategy. However, the 'windows of opportunity' in avoiding the 2 °C temperature guardrail appear to be closing, and rapid, coordinated international action would be necessary for a successful outcome[48].

8. Conclusions

Using a transparent formalisation tool, I have explored various assumptions and options regarding the decarbonisation of the UK economy, and whether it meets the requirements of 'fairness and physics'. On the whole it does not, even with very rapid territorial decarbonisation measures. Large 'carbon debts' remain. It is essential therefore to explore further options, and 'the tool' allows us to calculate, for a wide range of assumptions, how much residual carbon debt would need to be redeemed by national contributions to international decarbonisation. No country can 'save itself'. The atmosphere is a shared resource and it is going to require determined collective effort to manage it sustainably. Substantial financial investments by wealthier nations in poorer nations are necessary.

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