KAYA PLUS AND MINUS.

A simple extension of the Kaya Identity to provide robust first-order checks of emission-reduction policies

Peter Harper

University of Bath

Stephen Peake

Open University

ABSTRACT

*Since climate change is the ‘problem of our time’, it demands the widest possible debate. Driven by political expediency, governments are inclined to deviate dramatically from the informed consensus in logic, physics and ethics, but these deficiencies can be hidden beneath a smokescreen of complex and arcane theory. To allow more generalised understanding, robust but accessible tools for quantification are required. This article proposes such a tool, paradoxically simple: an extension of the Kaya Identity that embraces the entire economy rather than, as hitherto, the energy sector only. To demonstrate its surprising scope and flexibility, the tool is applied to a particular case, the UK decarbonisation programme, with some surprising implications. The well-known tale of the Emperor’s New Clothes, a fable of simplicity versus government legerdemain, is used as a metaphorical parallel.*

In 1992, virtually all national governments signed the UN Framework Convention (UNFCCC), pledging to implement measures that would avoid ‘dangerous climate change’. The quantitative meaning of this aspiration remained uncertain, but in the period since, we have seen improved understanding of the dynamics and drivers of the climatic system. In 2015, the 21st Conference of the UNFCCC signatories proposed an operational definition of ‘dangerous’ in terms of a global temperature rise of 1.5°C, beyond which risks and uncertainties would multiply (United Nations, 2016).

At the same time, there has been an acknowledged failure to control the principal driver of climate change at the global level: greenhouse gas emissions (GHGE; LeQuéré *et al.,* 2018). The UN’s authoritative research body in this field, the Intergovernmental Panel on Climate Change (IPCC), announced in 2018 that at the prevailing rate of emissions, only 12 years remained before the 1.5°C threshold would be breached (IPCC, 2018).

Although this 12-year period is dependent on the underlying pattern of GHGE[[1]](#endnote-1), it emphasises a level of urgency that applies particularly strongly to high-emitting, high-importing nations with a legacy of historically high emissions. The physical measures implied by this urgency are often at odds with prevailing national policies, as this paper will attempt to demonstrate.

Although the scientific justification for urgency is perfectly clear, it is nevertheless widely ignored and even doubted (Giddens, 2008; Marshall, 2016). Part of the reason for this lies in the apparent complexity of the subject and the opacity of the expert community. Policymakers, the concerned public, even many academics, are compelled to rely on the assessments of experts, based on highly complex models. Sadly, a credibility gap has emerged that clouds discussion and delays necessary policy initiatives. There is perhaps room for simpler and more robust ‘models’ that can be applied by laypeople to check the basic underlying trends and patterns, which in essence are *not* complicated.

The underlying simplicity of the climate problem and GHGE *can* be represented in simple formulae that act as a first-order check. If a policy passes this check, it might still fail more sophisticated assessments, but if it fails at this stage it is definitely questionable, as we shall see. The approach owes a debt to an eminent advisor of the UK government, the late David Mackay, who favoured a simplified, quantitative approach to energy policy and was famously ‘pro-arithmetic’ (Mackay, 2009). It is surprising what simple arithmetic, and a dash of geometry, can achieve.[[2]](#endnote-2)

What is proposed is a simple formula that represents all GHGE, while capturing key dynamics and policy levers that will allow non-experts to probe the consistency and implications of proposed policies. We are particularly concerned to reveal serious mismatches between a government’s claims and the underlying physical reality, with special attention to the UK, which prides itself on advanced policies. To leaven the dough, we will make metaphorical use of the widely-known story of The Emperor’s New Clothes, an ancient tale made famous by Hans Christian Andersen (Andersen, 2005). The UK government makes great claims for its climate policies. Are they really credible? Is the Emperor as finely-attired as he would like us to believe?

EARLY CLARIFICATIONS

In the early years of modern environmentalism there was much argument about the principal physical drivers of environmental impacts. Vigorous schools of thought emerged, respectively highlighting population growth (Ehrlich, 1968; Parsons, 1971), economic growth (Mishan, 1967; Meadows et al., 1972) and changing technology (Carson, 1962; Commoner, 1967). The arguments were partially resolved by the insight, due to Ehrlich and Holdren, that certain drivers are essentially *multiplicative* (Ehrlich and Holdren 1971). These authors derived the equation ***I*** = ***P*** x ***A*** x ***T***, commonly referred to as IPAT, where I is environmental ***I***mpact, P is ***P***opulation, A is ***A***ffluence, and T is ***T***echnology. At first sight this appears somewhat arbitrary, but the various terms can be rigorously defined. If ***A*** is actually GDP/capita and ***T*** is environmental intensity I/GDP, then ***I*** = ***P***\*(GDP/***P***)\*(***I***/GDP), which after cancellation yields ***I*** = ***I***, known mathematically as an *identity*, true by definition. The process is also referred to as a *decomposition*, because it reveals components of ***I*** in the form of robustly multipliable factors (Harper, 2017)***.***

The algorithm is brutally simple and instantly checkable. IPAT thus offers a highly transparent ‘back of the envelope’ ability to understand, and in a crude sense to model, the core dynamics of environmental damage. This is not to say it is beyond criticism (see for example Alcott, 2010); nor that it should replace more complex modelling such as Integrated Assessment Models (Weyant, 2017). These incorporate many more factors, taking into account interactions and feedback loops, and remain the mainstay of scholarly debate on climate change policy. However, such sophisticated models cannot be instantly checked by laypeople, and they lack the deterministic links between the components that generate rigorous first-order results.

IPAT’s strange combination of simplicity and rigour led to many applications in which specific values could be attached to the terms and their rates of change (Dietz and Rosa, 1994; Harper, 2000; York et al., 2003, McGee and Devezas, 2018). With respect to the Climate Change problem, it requires only that ***I*** be quantified as GHGE and we have a fully-measurable system based on a wealth of empirical data, that might be relabelled ***C*** = ***PATC*** , where ***TC*** represents all the technologies associated with GHGE, positive and negative.

This approach, however, places too much burden on ***TC***, and attempts have been made to further decompose it. I propose to do this by means of a simple extension of IPAT known as the Kaya Identity, and then to extend the Kaya Identity itself.

THE KAYA IDENTITY

In a significant paper, Kaya and Yakobori (1997) applied the IPAT principle to energy systems. This had several advantages. ***I*** could be defined in terms of CO2 emissions from energy-using processes, which can be precisely quantified. Further, because there is coherent coupling between energy, GHGE and economic processes, they could quantifiably decompose ***T*** into two components to create yet another policy option. They also relabelled the components, so the new identity is

**c** *=* ***p*** *\** ***g*** *\** ***e*** *\** ***f***

 where

***c*** is emissions of CO2, usually in MtCO2/y

***p*** is population, a dimensionless number

***g*** is GDP per capita, usually international dollars per unit population

***e*** is energy per unit of GDP, usually kWh/$

***f*** is CO2 emissions per unit of energy, usually kgCO2/kWh

This formula, known as the *Kaya Identity*, is remarkably helpful in checking the assumptions of proposed scenarios. Note that p\*gdp/p\*e/gdp\*CO2/e, after cancelling leaves CO2, or c. As with P and A in IPAT, ***p*** and ***g*** are often referred to as ‘scale factors’ and again ***p\*g*** quantifies ‘the size of the economy’. Meanwhile ***e\*f*** are together a measure of *emissions intensity* within the energy sector, analogous to ***T*** in IPAT. The identity is starkly algorithmic: specification of any four factors exactly implies the fifth.

The Kaya Identity can be used to decompose many different kinds of energy-using entities, even households and institutions. For example, Table 1 shows actual data for a university in 2017[[3]](#endnote-3):

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| ***c*** | ***p*** | ***G*** | ***e*** | ***f*** |
| ktCO2/y | *#students* | *£/student* | *kWh/£* | *kgCO2/kWh* |
| **24.4** | **17308** | **15426** | **0.34** | **0.27** |

*Table 1*

On a completely different scale, the whole world can be represented, as in Table 2, although many assumptions are required and reliable data are more difficult to obtain. If we insert official values, using international dollars, in this case for 2015,[[4]](#endnote-4) it looks like this:

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| ***c*** | ***p*** | ***g*** | ***e*** | ***f*** |
| GtCO2/y | Billions | 103 $/head | kWh/$ | kgCO2/kWh |
| **35.8** | **7.32** | **15.77** | **1.39** | **0.223** |

*Table 2*

It is oddly fascinating to see how headline emission figures break up into what are sometimes surprising values.

Naturally, the greatest interest arises from representations of *national* statistics, since nations are the principal decision-making entities with respect to energy and climate policies. Table 3 shows data for UK territorial energy-related emissions in 2017, again on an international dollar basis.[[5]](#endnote-5)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| ***c*** | ***p*** | ***g*** | ***e*** | ***f*** |
| MtCO2/y |  | $103/cap | kWh/$ | kgCO2/kWh |
| **373** | **66** | **40** | **0. 92** | **0.16** |

 *Table 3*

These simple statistics, derived from UK data, are already rich in policy implications.

USING THE KAYA IDENTITY TO CHECK IMPLICATIONS AND CONSTRAINTS

Through the Climate Change Act of 2008, the UK government committed itself to an emissions target of 159 MtCO2e in 2050.[[6]](#endnote-6) This has now been superseded by a more demanding target, discussed later, but the power of the simple arithmetic can be demonstrated well enough on the 2008 policy, widely thought to be leading the international field.

It is important to note that not all the emissions represented in the target value would be CO2 from energy, so if we are to use the Kaya Identity to probe future energy policy, we must deduct the non-energy emissions expected in 2050.

This is not entirely straightforward, and there is no clear methodology. Non-energy emissions for 2050 are calculated at 60 MtCO2e per year (/y), leaving (159-60) 99 MtCO2e/y as strictly energy emissions.[[7]](#endnote-7)

The identity allows various projections and assumptions to be swiftly checked by elementary arithmetic.…and to spot potential ‘naked Emperors’. Ostensibly, the UK has to reduce energy emissions from 373 to 99 in 33 years. Is this plausible?

THE EFFECTS OF GROWTH

One important feature of the formula is that it forces us to acknowledge the effect of growing GDP at any projected future date. Other things being equal, the energy system has to match this increased demand. So, if the scale factors ***p\*g*** increase by (say) 50% and the intensity factors ***e\*f*** remain the same, the absolute level of emissions will also increase by 50%. Modelling often assumes a kind of automatic decoupling of emissions from economic growth, but this requires explicit assumptions and must be taken into account for future projections.

Economic growth projections for 2050 carry an inevitable burden of uncertainty, but all available sources predict substantial growth in the UK economy. Relative to a GDP of $2.62 trillion in 2017 in international dollars, extrapolation of the UK Government forecasts to 2035 give $5.2 trillion in 2050 (BEIS, 2019, Annex M). OECD projections give a value of $4.9 trillion, (OECD, 2018), while PWC (2017) give $5.41T, all on the basis of purchasing power parity. We must have a number for the calculations, and a mean of $5.2 trillion is adopted.

These future GDP values are the simple consequences of growth at an average compound rate of around 2% a year. While there are grounds for doubting this rate can be maintained (Gordon, 2016) and even stronger grounds for questioning the wider benefits (Jackson, 2009; Kallis, 2017) there is little doubt this trajectory is widely expected in business and government circles. The Kaya Identity allows us to probe its implications, which are not publicly discussed by the UK government.

If we take the central UK figure here, the UK economy will be 98 *%* larger in 2050 than in 2015. Yet the 2008 Climate Change Act still mandates total emissions of 20% those of 1990. This requires a much sharper reduction in carbon intensity than is commonly assumed. Recall that the overall carbon intensity of the energy system is decomposed into two components, ***e*** and ***f***. Suppose that ***e*** continues to decline at its historical rate of about 2.4% a year. That would bring it from 0.92 in 2017 to 0.37 in 2050. But this lower intensity has to serve a larger economy, so the total amount of primary energy is only 20% less (Table 4).

|  |  |  |  |
| --- | --- | --- | --- |
|  | ***e,*** kWh/$ | GDP, $ 1012 | Primary energy, PWh |
| 2017 | 0.92 | 2.62 | 2.41 |
| 2050 | 0.37 | 5.2 | 1.92 |

*Table 4*

If this primary energy input is not itself radically decarbonised, the UK will fail to meet its target. It puts much greater pressure on the development of low-carbon energy systems, represented by the term ***f***. Economic growth makes a big difference, and the Kaya Identity forces analysts to take it into account. In planning his wardrobe, the ‘Emperor’ might not have expected this.

WHAT IFs

The Kaya decomposition presents us with four ‘policy levers’: ***p***, ***g***, ***e*** and ***f***. Discussions regarding deliberate policies to limit population levels (Parsons, 1998; Hoff, 2012) or economic growth (Victor, 2008; Maxton and Randers, 2016) certainly exist, and can easily be modelled in a ‘what-if?’ spirit using the Identity. But they are firmly disregarded in official policy circles. That leaves us with ***e*** and ***f.*** The identity allows us to vary their values and consider the consequences.

The product ***e***\****f*** is the overall carbon intensity of the economy, presently 0.92\*0.155 = 0.143. What would this need to be to meet the assumed requirements of 2050? The answer is 99/(75\*67) = 0.019, about 14% of the 2017 value. This is worth pondering: the arithmetic tells us that, on the assumptions made and available data, in 2050 the UK energy system would have a carbon intensity about 14% of 2017 value, which of course it must if it is to reach even the limited 2008 target. These elementary calculations help to hold the Emperor’s feet to the fire.

Next, we can explore the components of ***e***\****f*** separately. If for example the 2050 target of 99 MtCO2 were to be met *only* by reducing the energy intensity ***e*** (leaving ***f*** at its 2017 value), the identity quickly tells us the required value is 0.10, 13% of the present value, and that the then-larger UK economy would be consuming only 653 TWh of primary energy, or around 28% of the current energy input (99/(75\*67\*0.155)\*5.1). This presupposes energy efficiency levels not found in any low-carbon scenario, and such extreme ‘low ***e***’ policies are widely doubted (e.g., Sorrel, 2015). The UK government’s projections are consistent with this. The official projection of energy consumption to 2035 shows little change from today’s (BEIS, 2019, Annex E). There is no suggestion of a sudden change between 2035 and 2050, so we are forced to conclude that, implicitly at least, UK policy is to reduce GHGE in 2050 on the basis of the existing level of primary energy input, and to presume a continued reduction in ***e*** that precisely matches the growth of the economy.

Although presented here as a *reductio ad absurdum*, radical reductions of ***e*** beyond the historical trends are, at least in certain sectors, likely to be cost-effective and well-worth pursuing, even if there are no further displacements of emissions to trading partners (Hardt et al., 2018). We do not really know where the limits are. Perhaps 0.1 is beyond the pale, but 0.25 is surely achievable (see for example, Grubler *et al*., 2018).

The same what-if exercise can be applied to ***f***. How low would it need to be if it were the only lever applied to achieve the UK 2008 target? The Identity quickly gives the answer (99/75\*67\*.92), about 0.021, or about 21 gCO2/kWh, lower even than most of the ‘low-carbon’ sources (see Table 5).

It should be remarked that most low-carbon energy scenarios presume a future energy system dominated by electricity, so that electricity generation becomes very significant (CAT, 2010; Nijs et al., 2018; National Grid, 2018). We must not forget however that some sectors of the economy are hard to electrify fully, and in many cases it is necessary, or perhaps just more efficient, to deliver a service using fuels or heat. Fuels for heating usually have lower intensities than fuels for electricity. Our Kaya system reflects this.

Using the Identity once again, we can now calculate the implications for ***f*** in 2050, with more moderate assumptions. If ***e***2050 is indeed 0.37, then ***f***2050= 99/75\*67\*0.37 = 0.053 kgCO2/kWh or 53 gCO2 for each kWh of primary demand, relative to the 2017 average value of 155 gCO2/kWh. Compare this value with those given in Table 5, using data from the IPCC’s AR5 report (IPCC, 2013).

|  |  |
| --- | --- |
| ENERGY SOURCE | CARBON EMISSIONS PER kWh, g |
|  | Electricity (Heating) |
| Coal | 820 (321) |
| Gas | 490 (184) |
| Oil | (280) |
| Coal with CCS | 200 |
| Gas with CCS | 170 |
| Biomass | 230 (90) |
| Nuclear | 12 |
| Photovoltaic | 48 |
| Concentrating Solar Power | 27 |
| Solar Water Heating | (20) |
| Wind | 12 |
| Geothermal | 38 (12) |
| Tidal | 17 |
| Hydro | 24 |

Table 5

53 g/kWh is an intensity well below any of the fossil fuels, even with Carbon Capture and Storage (CCS: Bui et al., 2018). It must be emphasised of course, that this is an average value, and some higher intensity technologies can coexist in a mix with those of lower intensity, just as they do today.

Nevertheless, this elementary result is slightly awkward for official UK policy, since both the government and the power supply industry have historically favoured a ‘baseload plus dispatchable supply’ system, using storable fossil fuels to match supply and demand, with a large component of Carbon Capture and Storage (CCS). This preference arises from a desire to avoid the intrinsic variability of most renewables, but this – apart from the use of nuclear power as a baseline source -- is not favoured by the calculations. Further, the transport and space-heating systems are harder to electrify and (so far) remain almost entirely dependent on fossil fuels. Overall, the calculations suggest that fossil fuels can be used only very sparingly, offering support to those analysts who urge that we ‘leave them in the ground’ (Leggett, 2014; Berners-Lee and Clarke, 2013). The Emperor, if not entirely naked, is scantily clad. So, it might reasonably be asked what other policy options are being considered.

BECCS

The requirement for a low value of ***f*** could be a problem for UK policy, but fortunately there is a plausible ‘get out of jail free’ card (at least for electricity) in the form of Bio-Energy with Carbon Capture and Storage (BECCS: Gough *et al*., 2018). Here (usually) biomass is converted to electricity in a plant fitted for CCS. Carbon is withdrawn from the atmosphere in growing the plants, then the energy is released, but the resulting emissions are captured and sequestered. All stages have been demonstrated as technically feasible, while the economics remain yet uncertain. This is an energy source that can be operated both as base-load and as a dispatchable load-follower, ideal for traditional energy supply systems.

The important point is that BECCS is in principle a *negative emissions* energy technology. It delivers energy while at the same time removing CO2 from the atmosphere. Although the technology is still immature and its effectiveness heavily dependent on specific circumstances (Fajardy and MacDowell, 2017) it is undoubtedly one of the more benign of negative emissions technologies, and widely invoked in low-carbon scenarios. Newton-Cross and Gammer (2016) calculate that if 10% of overall UK energy demand were met with BECCS, a ‘credit’ of -55 MtCO2/y could be generated. In passing, the land-use implications of BECCS are significant and cannot be ignored, but Newton-Cross and Gammer (2016) calculate that less than 2 Mha of land would be required to supply this quantity of biomass, and consider this to be possible without undue disturbance of prevailing agricultural practice (total UK land area is 24 Mha, while the strictly agricultural area is around 18 Mha).

Although this might be a rather-too-sanguine view of BECCS (Fajardy et al, 2019), it seems reasonable to consider that a suite of Negative Energy Technologies (Pires, 2019) will form part of the UK’s decarbonisation strategy. Even if the BECCS estimate above is too great, others will raise the total, and we shall assume that the effects of the whole suite are represented by the -55 MtCO2/y ‘BECCS credit’ (Committee on Climate Change, 2019).

The Kaya identity allows us to calculate the effect of such a measure on the UK energy supply in 2050. By lowering the overall intensity below 53 gCO2/kWh, it allows ‘space’ for higher-intensity technologies. How much? With a ‘credit’ of -55 MtCO2 a year, the calculation is 44/(75\*67\*0.37) = 0.024 kg/kWh, Table 6.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| ***C*** | ***P*** | ***g*** | ***e*** | ***f*** |
| MtCO2e | Millions | $1000/p | kWh/$ | kgCO2/kWh |
| **44** | **75** | **67** | **0.37** | **0.024** |

Table 6

With BECCS and other NETs contributing a negative intensity, the net effect is to reduce the overall energy intensity low enough to allow some of the lower-emitting fossil-technologies into the mix, perhaps gas with CCS used as backup plant. For example, one scenario calculated that an all-renewable UK would need 45 MW of backup capacity, generating 27 TWh a year. (CAT, 2013). If this were gas CCS at 170 kg/kWh, the total emissions would be 4.6 MtCO2e a year, a small proportion of the target allowance.

This is encouraging, and other possibilities are imaginable.

* The UK government could aggressively pursue reduction in ***e*** beyond its historic rate of decline;
* The efficiency of capture and storage will be increased, reducing the carbon intensity of gas-CSS and ‘co-fired’ coal-with-CCS;
* The IPCC’s 2013 estimates of carbon-intensities are likely fall as economies are progressively decarbonised, because the embodied energy of low-carbon sources will itself have lower carbon intensities.

These are plausible speculations, and would appear to provide a reasonable outfit for the Emperor.

RATE CALCULATIONS

Another simple application of the Kaya Identity is to calculate necessary *rates* of change. These can be important for policy planning. Once a beginning and end point have been established, it is possible to calculate the average rate of change across the interval, and that gives some guidance for specific technical and political policymaking. For example, the change required between **e**\****f***2017 and **e**\****f***2050 without BECCS is -86%. That represents a linear rate of change of about -2.6% of the 2017 level each year. Is this plausible? Actually, according to the published statistics, this is more or less the rate of decarbonisation achieved between 2009 and 2018, possibly reflecting the effects of the Climate Change Act of 2008 following a much slower decline 1990-2008 (BEIS, 2019, Annex A; see Figure 1).

Furthermore, if this rate were continued, removing an average of 15 MtCO2 from the UK economy each year, the 2008 target would be reached in 2030, and zero by 2037. On the basis of official data and simple arithmetic, the Emperor can take a bow.

But is this all it seems? We have yet to consider

* The advent of a more demanding target
* The possible exhaustion of ‘low-hanging fruit’
* Non-energy emissions
* Cumulative emissions 2017-2050
* Britain’s wider obligations to global decarbonisation

A RADICAL SHIFT IN UK POLICY

The 80% reduction target in place since 2008 was widely-regarded as path-breaking. But by 2018 it was increasingly obvious that this was not enough, especially in view of the IPCC’s new emphasis on the 1.5°C threshold (IPCC, 2018). Accordingly, the CCC pressed the government to adopt a stronger target, net-zero by 2050, and this duly occurred in June 2019 (UK Government, 2019). ‘Net-Zero’ is simply an acknowledgement that some emissions are simply impossible to abolish, and must be offset by negative emissions. The situation in 2050 then, assuming ***p***, ***g*** and ***e*** are as before, is shown in Table 7

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| ***c*** | ***P*** | ***g*** | ***E*** | ***f*** |
| MtCO2e | Millions | $1000/p | kWh/$ | kgCOe/kWh |
| **0** | **75** | **67** | **0.37** | **0** |

Table 7

The Identity tells us (of course) that zero cannot be attained without one of the component terms being zero, and in terms of the classic version of the Kaya Identity, this has got to be ***f.*** But of course, ***f*** = 0 can be attained through a mixture of positive and negative intensities, and requires some negative energy technology such as BECCS, or some other non-energy process that we will shortly discuss. According to the default assumptions we have made, BECCS (and other NETs) give us a ‘credit’ of -55 MtCO2 a year that we can ‘spend’ on energy production to meet the demand of 2.3 PWh a year, less the 0.23 PWh that BECCS itself would contribute according to the assumptions of Newton-Cross and Gammer (2018), and perhaps a slightly reduced energy input in 2050.

This is much to the Emperor’s credit, but doubts are simmering. According to his official press releases, both encouraging and puzzling features appear. Consider Figure 1

Figure : Reported territorial Greenhouse Gas Emissions for the UK. Data for 1990-2018 are measured, other data points (in blue dots) are projected by the source. The pattern falls into three clear phases, 1990-2008, 2009-2018, and 2019-2035. Data points for 2009-2018 are extrapolated in the dotted black line (author’s addition).

Here we see reported emissions up till 2018, and projected emissions to 2035 (blue dots). One sees a relatively leisurely reduction to 2008, then an acceleration to 2018, perhaps in response to the 2008 Act. Were this ten-year trend to be continued, zero-emissions would be achieved even sooner than the government’s target date, sometime in the late 2030s, as previously remarked.

Oddly, however, the official projections carried out by BEIS suggest very slow decarbonisation, as if the UK government has completely lost interest in meeting its newly-imposed targets. How can this be explained? Undoubtedly part of the explanation of the recent steep decline is the rapid displacement of coal-fired electricity by renewables (Ofgem, 2019); and it is widely thought that emissions are progressively ‘offshored’ as industrial production is displaced by imports (Helm, 2015). Possibly these effects are now weakening (Hardt et al, 2018), and the ‘low-hanging fruit’ has largely been plucked, but no official explanation is forthcoming.

 Now the real task begins, and yet Figure 1 suggests an abandonment of the project altogether, as if the Emperor is entirely indifferent to his wardrobe.

Given the acknowledged urgency, and the inevitable lead times surrounding research, development and roll-out, there is no sign that the UK is preparing itself for what will inevitably be a very rapid transformation. It is particularly odd that, given the huge reliance on BECCS in virtually all the official scenarios, there is so little funding and research activity in this area. Oblivious to the doubts surrounding his appearance, this Emperor is not even placing orders.

NON-ENERGY EXTENSIONS OF THE KAYA IDENTITY

Perhaps the foregoing gives some idea of the simple power of the Kaya identity to identify key constraints, and also to suggest areas of RD&D that need to be undertaken with the greatest dispatch. Yet the formulation is still incomplete. The Kaya Identity deals only with energy and CO2 emissions from the energy system, yet the UK government is committed to reductions from *all* greenhouses gases. What else is needed? In a previous paper (Harper, 2016) I attempted to include numerous additional factors, but these clutter the accessible simplicity of the Kaya Identity. Instead, I propose here only **two** additions, one positive, the other negative, that will nevertheless offer a further range of policy levers for consideration, and cover all emissions. The extended system is called simply ‘Kaya Plus and Minus’, abbreviated as Kaya±.

Ideally, we would wish to decompose emissions driversfurther by the addition of factors analogous to ***e*** and ***f*** that respond coherently to changes of ***p*** and ***g***. This, however, is not practical because energy is a special case: its elements are conserved, well-behaved and easily measured, so can be treated multiplicatively. and it was Kaya’s great insight to grasp this. Other factors behave differently, and must be *added or subtracted* to arrive at a simple but mathematically complete model of the total emissions. We are still able to use categories for which official statistics are readily available.

 The new equation requires a new total, embracing all emissions, not just those from energy, and therefore measured in CO2 equivalent units, CO2e, using a capital ***C***. Keeping the original Kaya symbols, the equation could look like this:

***C*** = ***p*** \* ***g*** \* ***e*** \* ***f*** + ***S*** - ***N***

Where

***S*** represents the sum of all non-energy emissions, in CO2e units, and

***N*** represents the sum of net-negative processes either natural or engineered, also in CO2e units.

These are given upper case symbols as representing quantities of emissions that need adding and subtracting rather than multiplying, and are measured in CO2e units. Of course, these can themselves be split into components, and detailed analysis will require this. Most signatories to the Kyoto Protocol collect good data on these components as part of their reporting obligations (FCCC, 2013).

With these extra data included, in 2017, UK non-energy emissions, ***S***, were as follows, in MtCO2e/y, ranked order:

Agriculture 44

Waste 16

HFCs 13

Non-energy industrial processes 11

TOTAL **84**[[8]](#endnote-8)

Each of these can be considered as a focus for decarbonisation policies in its own right. Net-negative processes, reported in the UK Kyoto submission for 2017 under the standard category Land Use, Land Use Change and Forestry (LULUCF) were -7.4 MtCO2e.[[9]](#endnote-9) The revised 2017 Kaya± data are shown in Table 8.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| ***C*** | ***p*** | ***g*** | ***e*** | ***f*** | ***S*** | ***N*** |
| MtCO2e | Millions | $/head | kWh/$ | kgCO2/kWh | MtCO*2*e | MtCO2e |
| **450** | **66** | **39.7** | **0.92** | **0.155** | **84** | **-7.4** |

*Table 8*

This is essentially what was reported to the UNFCCC under the Kyoto Protocol for the year 2017. It was also widely reported in the UK media as evidence of steady progress towards the 2050 target.

The CCC has its own net-zero scenarios (CCC, 2019) but tends to neglect economic growth and non-energy emissions. Instead, we can model likely possibilities using the Kaya± system and published government projections to 2035, extrapolated by default to 2050. ***S*** and ***N*** are given the values previously estimated. Table 9 shows a base case with the 2008 target:

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| ***C*** | ***p*** | ***g*** | ***e*** | ***f*** | ***S*** | ***N*** |
| MtCO2e | Millions | $/head | kWh/$ | kgCO2e/kWh | MtCO2e | MtCO2e |
| **159** | **75** | **67** | **0.37** | **0.053** | **60** | **0** |

Table 9

This simply tells us that if ***C*** is a required target, there are now six possible ‘policy levers’. In practice of course, discussion focuses on some more than others, particularly the term ***f***. However, we can see that, even with the much larger UK economy of 2050, the energy supply and non-energy emissions can comfortably be accommodated within an allowable total of 159 MtCO2e a year. The Emperor can afford a condescending smirk.

But with the new target of net-zero it is much harder to deliver either energy or emission targets, even with -55 MtCO2e/y of BECCS as previously envisaged. If the expected projections are maintained, and (as an alternative to adjusting ***f*** ) the BECCS credit is inserted into the ***N*** column, the result is far from the target. The BECCS credit merely offsets the non-energy emissions, as we can see in Table 10

*Table 5*

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| ***C*** | ***p*** | ***g*** | ***e*** | ***f*** | ***S*** | ***N*** |
| MtCO2e | Millions | $/head | kWh/$ | kgCO2e/kWh | MtCO2e | MtCO2e |
| **104** | **75** | **83** | **0.37** | **0.053** | **60** | **-55** |

Table 10

Something has got to give if the UK is to make progress towards its stated policy goal. Of the six potential levers, we have already rejected population and economic growth as the subject of deliberate policy. Meanwhile, ***e*** and ***f*** are set at historically ‘reasonable’ levels. Turning to ***S*** and ***N***, it is obvious that a large part of the new problem lies in emissions from the *non*-energy sector, and that we need to pay special attention to these ‘extras’ in the extended Kaya identity. The increasing proportion of non-energy emissions in a world of decarbonising energy systems, has long been predicted (Anderson and Bows, 2008; EPA, 2012).

What is the minimum level of non-energy emissions, ***S***? Or, to put it another way, what is the irreducible minimum of ‘residual’ emissions consistent with running a modern economy 98% larger than that of 2017? This exercise was carried out twice by research teams attached to the Centre for Alternative Technology in the UK, yielding two results. In 2010 the answer was 67 MtCO2e/year (CAT, 2010), while in 2013 it was estimated at 43 MtCO2e/year (CAT, 2013), but this was arrived at only after a very radical decarbonisation programme including substantial reduction of livestock, and for the year 2030. In terms acceptable to the British government, ***S***2050 could not be lower than this. In fact, 50 MtCO2e a year is probably the lowest conceivable level, especially in view of the much-expanded British economy in 2050.

There remains column ***N***, negative emissions. ‘Negative Emission Technologies’ are widely bruited (EASAC, 2018; Pires, 2019). At this point in the discussion, they seem our only hope. Assuming we can somehow wrestle down the non-energy emissions to 50 MtCO2e/y, and banking the -55 from BECCS, what further would be required of ***N***2050 to reach the target of zero? On the basis of the foregoing assumptions, the calculation is simple [(104-50)/75\*67\*0.37\*0.053] and yields an answer of ***N***2050 = -54.8 MtCO2/y.

We are already using a NET: BECCS. This, according to Newton-Cross and Gammer (2016) takes 2 Mha to sequester 55 MtCO2e; here we are implying a further 2Mha, or 4 Mha altogether. Is this possible? Physically it is (CAT 2010), but this would have a strong impact on the UK land-use system, and the UK government has given no hint that this is a possibility. Neither are there plans to explore other NETs.

Of course, the UK government is trying to achieve its goals with minimum disruption to customary practice. What the Kaya analysis seems to be telling us is that this is not going to be possible, and we must be prepared for more radical measures. There is no sign of this understanding in official policy. From this perspective at least, the Emperor is very scantily clad.

ACCUMULATED EMISSIONS

So far, we have used the Kaya± system to explore some of the implications of the UK target set for 2050 in 2008, and the even more demanding target set in 2019. The latter target is hypothetically achievable with planned departures from Business As Usual, and is clearly ‘sustainable’. But the goal is not achieved for 30 years, so it is reasonable to ask, what about the emissions on the way?

As it happens, most GHGs have a long residence time in the atmosphere, and so accumulate, giving the well-known concentration levels usually stated in parts per million (Scripps, 2019). In the last decade, cumulative emissions have emerged as the key metric for avoiding dangerous climate change (Meinshausen, 2009; Matthews et al., 2017). Estimates of the actual allowable global ‘budget’[[10]](#endnote-10) vary considerably, depending on the threshold adopted, the probability of exceeding it, and whether non-CO2 forcing is included (Myrna et al., 2013). Of course, the remaining ‘budget’ declines as more GHGs are added each year.

Moving from basic arithmetic to basic geometry, we can calculate accumulated emissions from the area under a reduction curve. In the case of the UK’s aspiration for net-zero, accumulated emissions can be approximated by assuming a straight-line trajectory by default, as shown in Figure 2.[[11]](#endnote-11) The reported reduction 2015-19 is actually faster than the required average pathway to the target, for reasons previously discussed (see Figure 1) but the shape is very close to a right-angled triangle, so the area under the curve (GHGE/yr)\*yr = GHGE ≈ 500/35/2 ≈ 7.14 GtCO2e. In terms of per-capita values, the UK average population between 2015 and 2050 is likely to be close to (65+75)/2 = 70, so the per-capita share is 7.14/70 = 102 tonnes. This is about 2.9 tCO2e per year for each person, relative to 2017 territorial emissions per capita of 6.9 tCO2e.

Figure : Default model for UK 2019 decarbonisation programme, assuming a linear path to the target. 2015-2018 are based on historical published data. Accumulated emissions are simply the area under the curve. Note that a convex path will generate higher total emissions, a concave path lower emissions.

How does this compare with the world as a whole? What yardsticks might we use to evaluate it? Does it satisfy requirements for the global equity that will facilitate global agreements, or in Schellnhuber’s memorable phrase, ‘fairness and physics’ (Schellnhuber, 2004)? One commonly-used principle is ‘equal per capita entitlement’, which strikes most people as fair. The 1.5°C budget for 2015 has not been published, but can be estimated from the IPCC’s 2018 value of 420 GtCO2e, at around 570 GtCO2e. At an average global population of 8.5 billion, this is a per-capita value of 67 tCO2e, or 1.9 tCO2e per year. Although the UK ends the process at net-zero, its overall emissions in getting there have occupied one-third more than the UK’s fair share of ‘carbon space’.

Another way to put this is in terms of the actual accumulated value, 7.14 GtCO2e, relative to the budget-compliant value of 4.69. Paradoxically, steady progress towards what is claimed to be a world-leading national goal, generates what might be called a ‘carbon debt’ (Gignac and Matthews, 2015; Matthews, 2016) which reaches 2.45 GtCO2e in 2050, five times the annual emissions of 2017. This is not a good look for the Emperor.

Clearly accumulating debt has an *ethical* significance but might well translate into a political and diplomatic significance in terms of international climate treaties. Given that the whole world needs to reach net-zero in the second half of the century (Rogelj, Schaeffer and Hare, 2015), at least the UK is complying with the ‘contraction and convergence’ principle (Meyer, 2004) which accepts that some nations are bound to emit more than others on a per capita basis at the start, but should converge on an equal, sustainable level. The Committee on Climate Change can reasonably claim that UK policy aims at globally sustainable and equitable levels of emissions -- eventually. Very well, a linen shirt for the emperor.[[12]](#endnote-12)

This simple method of summing cumulative emissions can be used to evaluate any national policy from its expressed targets (Table 11). It can also be used to calculate the excess of emissions over the budgetary equal share, and hence the requirement for extra-territorial ‘carbon credits’.

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Scenario | ***C***Target | ***C***Result | ***P*** | ***g*** | ***e*** | ***f*** | Kaya energy emissions | ***S*** | ***N*** | AccumulatedGHGE2017-2050 | Credits required > 4.69 |
| Units |  | MtCO2e | 106 | $104 | kWh/$ | kgCO2e/kWh | MtCO2 | MtCO2e | MtCO2e | GtCO2e | GtCO2e |
| BaselineBEIS 2017 |  | 448 | 66 | 39.7 | 0.92 | 0.16 | 386 | 81 | -7.4 |  |  |
| Linear transition | 0 | 99 | 75 | 67 | 0.37 | 0.053 | 99 | 60 | -60 | 8.02 | 3.33 |

*Table 11*

Table 11 shows the effects of today’s pattern and the 2050 target on the UK’s contribution to GHGs in the atmosphere. On the ‘Steady as she goes’ assumptions so far deployed, the UK does not, and cannot, reach its declared target. The ‘Kaya group’ are shown, with their product ‘Kaya energy emissions’ highlighted. Thus, the annual total ***C*** (result) = **Kaya emissions** + ***S*** + ***N***. The default linear transition generates a value for accumulated emissions, 8023 MtCO2e. From this can be deducted the sustainable global average to arrive at a level of ‘carbon debt’ or requirement for credits over the period 2015-2050, which is 3330 MtCO2e. This can also be expressed as an annual debt, 3330/33 = 100 MtCO2e/y. On this showing, the debt would continue indefinitely beyond 2050.

Such accumulating debts are little discussed. They could possibly be dealt with via some kind of international trading system, but remind us of the probable need for technical and financial transfers from developed economies to developing ones in order to ensure low emissions and accelerated completion of the modernisation cycle (Michaelowa *et al*., 2019). At the proposed Carbon Price Floor of £70/tCO2e in 2030 (Hirst, 2018) this would amount to about £7 billion a year, which might be considered something of a bargain.

OTHER POSSIBLE FUTURES

Discussion of all the possibilities is not feasible here, but it is notable that many proposals have been made to reduce emissions to net-zero at various scales and time-frames, ranging from the entire world to nations and even individual cities (Randers and Gilding, 2010; Allen, 2016). In particular, a desk study of the UK was carried out in 2012 with the precise aim of modelling zero-emissions for the UK within 25 years (CAT, 2013). This can be examined in two parts, firstly with relatively ‘non-contentious’ measures including:

* Slow economic growth in line with recent performance ***p***2050 = 72, ***g***2050 = 55
* Rapid implementation of energy-intensity measures, so ***e***2050 = 0.3
* Virtually complete decarbonisation of the energy system, ***f***2050 = 0.007
* Technical reductions of non-energy emissions, waste, agriculture etc ***S***2050 = 50

To these measures can be added the CCC proposal for BECCS (assumed here to deliver -55 MtCO2e/y by 2050), perhaps relatively non-contentious, plus the expected -5 MtCO2e from LULUCF. The results are shown as scenario 1 in Table 12, assuming 2017 data as a start point, with the standard scenario above for comparison, and an even more determined scenario, labelled Scenario B, with more NETs.

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Scenario | C2050Tar-get | C2050Re-sult | ***p*** | ***g*** | ***e*** | ***f*** | KayaC2050 | ***S*** | ***N*** | AccumulatedGHGE2015-2050 | Credits required |
| Units |  | MtCO2e | 106 | $104 | kWh/$ | kgCO2e/kWh | MtCO2 | MtCO2e | MtCO2e | GtCO2e | GtCO2e |
| Linear reduction | 0 | 99 | 75 | 67 | 0.37 | 0.053 | 99 | 60 | -60 | 8.02 | 3.33 |
| Stronger measures | 0 | -1.68 | 72 | 55 | 0.3 | 0.007 | 8.32 | 50 | -60 | 7.43 | 2.74 |
| Scenario B | 0 | -38 | 72 | 55 | 0.3 | 0.007 | 8.32 | 45 | -90 | 6.67 | 1.98 |

*Table 12*

These extra measures have indeed achieved the goal of zero and reduced carbon ‘debt’, although not to negligible levels. The 2013 ‘scenario B’ report (CAT 3013) also considered the effects of more contentious measures, in particular a massive reduction of grazing livestock, and a more modest reduction of other livestock. These reduced agricultural emissions to 17 MtCO2e a year and released very large areas of grassland, which then became available for biomass production, both for energy and further sequestration. This is modelled in the table as Scenario B, where ***C*** is actually negative in 2050. This brings the carbon debt down to an entirely manageable $60 M/y, although perhaps at substantial social cost.

Scenario B attempted to show that a ‘zero-Carbon Britain’ could be achieved entirely on the basis of renewable energies, but Table 5 suggests that similar results could be obtained with a vigorous development of nuclear energy. This is another What-If?, and the CCC has quietly stirred it into the mix (Committee on Climate Change, 2019).

The arithmetic does suggest a further way out, not yet considered: to reach zero *earlier* than 2050. As Figure 1 shows us, the present trajectory if continued could reach zero by 2037 or thereabouts, a 20-year rather than 30-year transition. Applied to Scenario B, this wipes out the debt entirely. It is curious to note that a number of UK local authorities have pledged to achieve ‘net-zero-carbon’ even earlier, by 2030[[13]](#endnote-13), so rapid-transformations of this kind are not the exclusive preserve of environmental extremists.

Meanwhile, the UK as a whole remains focused on 2050. The conclusion we have reached is that even with vigorous policy measures, carbon debts are likely to accumulate. The Emperor, although decently clothed, remains in hock to his tailors.

CONSIDERATIONS OF LARGER FRAMES OR SCOPES

The Kaya± formulation helps us to understand necessary requirements for equitable decarbonisation, even by the strict standard of accumulated emissions. However, critics have asked, is this *really* equitable? There are two lines of criticism.

Firstly, they point out that the data are based on *territorial* accounting – emissions generated within the UK itself. Oddly, they do not include international aviation and shipping, because these emissions occur outside the territory of the UK. Surely this is absurd? But such is the logic of the statistical systems and the Kyoto Protocol. If we add these emissions, we find an additional:

International aviation serving British consumers 37.5

International shipping serving British consumers 12.5

…and in addition, the aviation values are considered to be subject to a multiplier than accounts for non-GHG effects in the upper atmosphere that amount to a factor of around 1.9 times the actual fuel emissions (Lee et al., 2009). If this is correct, the total is 12.5 + 37.5\*1.9 = 83.8 MtCO2e a year, a substantial addition.

These figures are somehow ‘missing’ in the headline figures, although the UK government does publish them separately, in obscure places. But the headline figures do include exports – even though the benefits of these goods (and services) are enjoyed elsewhere. Is this fair? Perhaps it is simply a matter of convention, but if exports are counted, why not imports too? We can then arrive at a figure of *net* import or export. We are then measuring emissions associated with what is *consumed* rather than what is *produced*, generating a ‘consumption account’ rather than a ‘production account’ (Davies and Caldeira, 2010; Moran *et al*., 2018). Consumption accounting is often considered ‘fairer’, although it is more difficult to quantify because we are obliged to rely on statistical data from other nations.

What is the effect of adopting this perspective on the analysis of UK emissions? As it happens, the UK imports a great deal more than it exports, so the overall effect is to greatly increase the emissions for which the UK might be considered responsible. It therefore increases the accumulated emissions and potentially the carbon debt. Unfortunately, the data available for calculating emissions embodied in net imports are inexact, resulting in a wide range of estimates (CCC 2013; Afionis *et al*., 2017), and they are often hard to extract from the official UK statistics. An example is presented in Figure 7, from 2011 (Scott, Owen and Barrett, 2013). Only the two bottom sections of the stacked bar are reported to the UNFCC (or the general public) as ‘the UK emissions’.

Let us simply apply these same proportions to our reference 2017 emissions of 448 MtCO2e and display an arguably more realistic value for ***S***2017. This makes it obvious that no conceivable amount of attention to ***f*** or ***N*** will bring this to zero.[[14]](#endnote-14)

Figure 3: Bar chart for components of the UK's Carbon Footprint in 2011, from Scott, Own and Barrett (2013). IA&S refers to international aviation and shipping, without the aviation multiplier. ILUC stands for Indirect Land Use Change and refers to emissions occurring overseas as a result of UK food and agriculture policies.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| ***C*** | ***P*** | ***G*** | ***E*** | ***f*** | ***S*** | ***N*** |
| MtCO2e | Millions | $/head | kWh/$ | kgCO2e/kWh | MtCO2e | MtCO2e |
| 1006 | 65 | 40 | 0.92 | 0.16 | 643 | -7.4 |

Table 13

Scott and Barrett (2015) have modelled various scenarios for the carbon intensity of international trade, but it should be clear that *on the basis of consumption accounting, the UK cannot deliver its budgetary quota*. That linen shirt? Sorry, your imperial majesty.

HISTORICAL RESPONSIBILITY

A second line of criticism regarding the UK’s emission figures concerns ‘historical responsibility’. It is perfectly clear that most of the GHGs presently in the atmosphere have been emitted by the wealthier nations, leaving a much-diminished quota for all to share from now on (Höhne and Blok, 2005). Indeed, at each new international agreement, the quota has diminished further. Does a country like the UK have any responsibility for past behaviour?

Assumptions about past responsibility can be simply modelled by calculating, and then including, past emissions. Instead of starting in (say) 2017, one can ‘backdate’ to any previous year and accumulate to some target level which might or might not be zero. The question must arise, what is a reasonable starting year? The UK’s CCC has established the UK budgets at 2008, which is when the Climate Change Act came into force. The implication is that our previous calculation of 7.41 GtCO2e is too low, and we need to include emissions from 2008-2014. This adds 4.96 GtCO2e (BEIS, 2019), making a total of 12.27 GtCO2e.

Other starting years have been suggested, as far back as the eighteenth century (Alcaraz *et al*., 2018). But most commonly, 1992 is cited as the year when most countries signed up to the UNFCCC and undertook to ‘prevent dangerous climate change’. A nation that has signed the UNFCCC cannot then say it was unaware of the problem. The appropriate temporal ‘scope’ would therefore be 1992-2050. Data from BEIS (2019) reveal that between 1992-2017 the UK emitted 16.89 GtCO2e, giving a total between 1992 and 2050 of 24.28 GtCO2e and a debt of 19.59 GtCO2e. This demonstrates immediately that the past can present a heavy burden for accumulated carbon quotas. No matter how rapidly a country plans to decarbonise, the unreconstructed past can negate its efforts. The Emperor is not only naked but has pawned his entire wardrobe.

Of course, some would argue that both consumption-accounting and historical responsibility should be applied together. Once again, we can use historical data to calculate this case (Scott, Owen and Barrett, 2013). 1992-2017 yields 26.83 GtCO2e, giving a total at 2050 of 42.18 GtCO2e, and a debt of 37.49 GtCO2e. It should be clear that from this perspective, no decarbonisation strategy can cope with this level of debt, and only the purchase of credits or other international transfers can clear the account. To give some idea of cost. Imagine the price of carbon is the 2030 floor price of £70/tCO2e, and it is paid between 2020 and 2050. This is about £179 billion a year, about 8% of the 2017 UK GDP. Perhaps this represents the level of assistance due to developing countries to ensure they do not rack up carbon debts, but are able to complete their modernisation cycles in a more benign, seemly and sustainable manner that benefits us all.

Re-clothed by the poor, the Emperor might be able to redeem himself after all, chastened but decently attired.

 CONCLUSION

Since Climate Change is arguably the greatest challenge of our time, it is important that engagement with its mechanisms and solutions is not confined to an elite of specialists. While complex modelling has an important role to play, I have proposed some very simple calculation methods that allow non-experts to explore options with due rigour, and even to challenge the authorities. Government and academic experts are often subject to pressures that obscure significant truths, and it is important they are held to account. The Kaya± approach offers a simple system to reveal ‘naked Emperors’ often found strutting shamelessly in the public domain.

REFERENCES

Afionis, Stavros, *et al*. (2017). Consumption-based carbon accounting: Does it have a future? Wiley interdisciplinary reviews: *Climate Change* **8** (1):1-19.

Alcaraz, O. *et al*. (2018). Distributing the Global Carbon Budget with climate justice criteria. [*Climatic Change*](https://link.springer.com/journal/10584)*,* **149** (2)131–145 2018.

Alcott, B. (2010). Impact caps: Why population, affluence and technology strategies should be abandoned. [*Journal of Cleaner Production*](https://en.wikipedia.org/wiki/Journal_of_Cleaner_Production). **18** (6): 552–560. [doi](https://en.wikipedia.org/wiki/Digital_object_identifier):[10.1016/j.jclepro.2009.08.001](https://doi.org/10.1016/j.jclepro.2009.08.001)

Allen, M. R. *et al.* (2018). ‘A solution to the misrepresentations of CO2-equivalent emissions of short-lived climate pollutants under ambitious mitigation’, *Climate and Atmospheric Science*, 1(1), 16.

Allen, Paul. (2015). *Who’s Getting Ready for Zero?* Machynlleth: CAT Publications.

Andersen, H.C. (2005)Frank, Diane Crone (Ed. and transl.). *The Stories of Hans Christian Andersen: A New Translation from the Danish.* Durham and London: Duke University Press*.*

Anderson, K. and A. Bows (2008). "Reframing the climate change challenge in light of post-2000 emission trends." *Philosophical Transactions of the Royal Society A*, **366,** 3863-3882.

BEIS (UK Government Department of Business, Energy and Industrial Strategy, 2019.). *Updated Energy and Emissions Projections: 2018*.

Berners-Lee, M., and Duncan Clarke. (2013). *The Burning Question*. London: Profile Books.

Bui, M. *et al.* (2018). Carbon Capture and Storage: The Way Forward. *Energy and Environmental Science*, No. 5.

Carson, Rachel. (1962). *Silent Spring*. Boston: Houghton Mifflin.

CAT (Centre for Alternative Technology, 2010). *Zero-Carbon Britain 2030*. Machynlleth: CAT Publications.

CAT (Centre for Alternative Technology, 2013). *Zero-Carbon Britain: Rethinking the Future*. Machynlleth: CAT Publications. www.zerocarbonbritain.com

CCC (UK Committee on Climate Change, 2016) *UK Climate Action Following the Paris Agreement (zero by 2040)*.

Committee on Climate Change (2013). *Reducing the UK’s carbon footprint and managing competitiveness risks.* April 2013.

Committee on Climate Change.(2019) *Net Zero – The UK’s contribution to stopping global warming*. <https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/>

Commoner, Barry. (1967). *The Closing Circle*. New York: Schopf.

Davis, S.J.; Caldeira, K. (2010). ["Consumption-based accounting of CO2emissions"](http://www.pnas.org/content/early/2010/02/23/0906974107.abstract). *Proceedings of the National Academy of Sciences*. **107** (12): 5687–5692.

Dietz, Thomas and Eugene A. Rosa. (1994). Rethinking the Environmental Impacts of Population, Affluence, and Technology. *Human Ecology Review*, **1**:277-300.

EASAC. (2018). *Negative emission technologies: What role in meeting Paris Agreement targets?* Policy report 35, February 2018.

Ehrlich, P.R. and Holdren, J. P. (1971). Impact of population growth. *Science* 171: 1212-1217.

Ehrlich, Paul. (1968) *The Population Bomb*. San Francisco: Sierra Club.

Environmental Protection Agency. (2012) *Non-CO2 gases*. *Summary Report: Global Anthropogenic Non-CO2 Greenhouse Gas Emissions: 1990 – 2030*.

Fajardy, M. and Niall Mac Dowell. (2013).  Can BECCS deliver sustainable and resource efficient negative emissions? [*Energy Environ. Sci.*](https://doi.org/10.1039/1754-5706/2008), 2017, **10**, 1389-1426.

Fajardy, M. et al. (2019). *BECCS deployment: a reality check*. Grantham Institute Briefing paper No 28 January 2019

FCCC. (2013). *Decision 24/CP.19. Revision of the UNFCCC reporting guidelines on annual inventories for Parties included in Annex I to the Convention.*

Giddens, A. (2008). *The Politics of Climate Change*. London: Polity Press.

Gignac, R. and H. D. Matthews. (2015).Allocating a 2 °C cumulative carbon budget to countries**.** *Environmental Research Letters***, 10** (7)**.**

Gordon, R. (2016). *The Rise and Fall of American Growth*. Princeton U.P.

Gough, C., *et al*. (2017). *Biomass energy and carbon capture and storage (BECCS): unlocking negative emissions*. New York: Wiley.

Grubler, A. A. (2018). low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. *Nature Energy,* **3**, 515.

Hardt, L. *et al*. (2018). Untangling the drivers of energy reduction in the UK productive sectors: Efficiency or offshoring? *Applied Energy* **223**, 124.

Harper, P. (2000). The End in Sight? *Futures*, **32**, 361.

Harper, P. (2016). Decomposition for Decarbonisation: Evaluating Decarbonisation Programmes Using an Extension of the Kaya Identity. *Science Progress*, **99**(3), 1 – 27.

Helm, Dieter. (2015) *The Carbon Crunch*. New Haven: Yale UP.

Hirst, David. (2018). House of Commons BRIEFING PAPER Number 05927, 8 January 2018 *Carbon Price Floor (CPF) and the price support mechanism*.

Hoff, Derek. (2012). *The State and the Stork: The Population Debate and Policy Making in US History.* Chicago: University of Chicago Press.

Höhne, N., and K. Blok. (2005). Calculating historical contributions to climate change: Discussion of the Brazilian Proposal’. *Climatic Change*, **71**(1), 141.

IPCC. (2018). *Special Report: Global Warming of 1.5°C*. Available on-line at <https://www.ipcc.ch/sr15/>. Retrieved 10 August 2019.

IPCC. (2013). *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.

Kallis, G. (2017). *Degrowth.*  Newcastle-on-Tyne: Agenda.

Kaya, Yoichi and Keiichi Yokobori. (1997). Environment, Energy, and Economy: Strategies for Sustainability. Tokyo & New York: United Nations University Press.

Lee, D. S. *et al*. (2009). Aviation and global climate change in the 21st century. *Atmospheric Environment* **43**, 3520–3537.

Leggett, Jeremy.(2014) *The Energy of Nations*. London: Routledge.

Le Quéré, C. *et al*. (2018). Global Carbon Budget 2018. *Earth System Science Data*, **10**, 1-54.

Mackay, David. (2009). *Sustainable Energy Without the Hot Air*. Cambridge: Green Books.

Magee, L. and T. C. Devezas (2018) Specifying technology and rebound in the IPAT identity. *Procedia Manufacturing* **21**, 476–485.

Marshall, George. (2014). *Don’t even think about it*. London: Bloomsbury.

Matthews, H.D. (2016). Quantifying historical carbon and climate debts among nations. *Nature Climate Change* **6**,  60–64.

Matthews, H.D. (2017). Estimating Carbon Budgets for Ambitious Climate Targets. [*Current Climate Change Reports*](https://link.springer.com/journal/40641), **3** (1) 69.

Maxton, Graeme and J. Randers. (2016). *Reinventing Prosperity*. Vancouver/Berkeley: Greystone.

Meadows, D. *et al*. 1972). *The Limits to Growth*. Washington: Potomac Associates..

Meinshausen, M. *et al*. (2009). Greenhouse-gas emission targets for limiting global warming to 2 C. *Nature* **458** (7242), 1158.

Meyer, Aubrey. (2004). Contraction and Convergence. *Engineering Sustainability* **157** (4): 189.

Michaelowa, C. *et al*. (2019). *Overview and Comparison of Existing Carbon Crediting Schemes.* NICA: Nordic Environment Finance Corporation.

Mishan, E.J. (1967). *The Costs of Economic Growth*. London: Staples Press.

Moran, D. *et al*. (2018). *The Carbon Loophole in Climate Policy: Quantifying the embodied carbon in traded products.* KGM and Associates Pty Ltd.

Myrna, G *et al*. (2013). Anthropogenic and natural radiative forcing. IPCC Working Group I, AR5. Cambridge: Cambridge University Press.

National Grid (2018) *Future Energy Scenarios*.

Newton-Cross, Geraldine and Dennis Gammer. (2016). *The Evidence for Deploying Bioenergy with CCS (BECCS) in the UK*. Energy Technologies Institute, UK.

Nijs, W. *et al*. (2018). *Deployment Scenarios for Low Carbon Energy Technologies*, Publications Office of the European Union, Luxembourg. doi:10.2760/249336, JRC112915.

OECD (2016), OECD Factbook 2015-2016: Economic, Environmental and Social Statistics, Paris: OECD Publishing.

OECD (2018): *Economic Outlook No. 103: Long-term baseline projections*. Paris: OECD Publications.

OFGEM (UK Office of Gas and Elecricity Markets. 2019).*Electricity generation mix by quarter and fuel source (GB).*

Parsons, J. (1971). *Population vs. Liberty*. London: Pemberton Books.

Parsons, J. (1998) *Human Population Competition*. Lewiston, NY: Edwin Mellen Press.

Piketty, Thomas. (2014). *Capital in the Twenty-First Century*. Boston: Belknap/Harvard University Press.

Pires, C.M. (2019). Negative emissions technologies: A complementary solution for climate change mitigation. [*Science of The Total Environment*](https://www.sciencedirect.com/science/journal/00489697) **672**, 502**.**

PWC. (2017). *The Long View: How will the global economic order change by 2050?* PriceWaterhouseCoopers.

Randers, J. and P. Gilding. (2010). The One-degree War Plan. *Journal of Global Responsibility*, **1**(1). 170-188.

Rogelj, J., M.Schaeffer, and B.Hare. (2015). *Timetables for Zero emissions and 2050 emissions reductions: State of the Science for the ADP Agreement*. Briefing Note, Climate Analytics.

Schellnhuber, H-J., Paul J. Crutzen, William C. Clark, Martin Claussen, Hermann Held (Eds). (2004). *Earth System Analysis for Sustainability*. Boston: MIT Press.

Scott, Kate and John Barrett. (2015). An integration of net imported emissions into climate change targets. *Environmental Science & Policy* **52**, 150-157.

Scott. K., A. Owen and J. Barrett (2013). *Estimating emissions assocated with future UK consumption patterns*. DECC: Committee on Climate Change.

Scripps Institution (2019). Keeling curve data <https://scripps.ucsd.edu/programs/keelingcurve/>

Smith, Adam. (2014). *The Wealth of Nations*. CreateSpace Independent Publishing Platform.

Sorrell, S. (2015). Reducing energy demand: A review of issues, challenges and approaches**.**

[*Renewable and Sustainable Energy Reviews*](https://www.sciencedirect.com/science/journal/13640321)*,* 47, 74-82.

United Nations (2016). *The Paris Agreement*. UN Treaty Collection, 8 July, 2016.

UK Government. (2019). UK becomes first major economy to pass net zero emissions law**.** UK Govt.

Victor, Peter. (2008). *Managing without Growth*. Cheltenham: Edward Elgar.

Walsh, Brian, *et al.* (2017). Pathways for balancing CO2 emissions and sinks. *Nature Communications* **8**, Article number: 14856.

Weyant, John. (2017). Some Contributions of Integrated Assessment Models of Global Climate Change. *Review of Environmental Economics and Policy*, 11 (1), 115–137.

World Bank (2017). National Accounts Data. <https://data.worldbank.org/indicator/NY.GDP.MKTP.KD.ZG?locations=XD> accessed 21/03/2018.

York, Richard, Eugene A. Rosa, and Thomas Dietz. (2003). STIRPAT, IPAT and ImPACT: analytic tools for unpacking the driving forces of environmental impacts. *Ecological Economics*, **46** (3):351–365.

END-NOTES

1. The IPCC projection is based on *accumulated* emissions and assumes continued annual emissions at present rates, but of course they might be higher or lower, or highly variable over the next decades. Reduced emissions would give us longer; for example, if emissions were reduced linearly to zero, that would allow 24 years to the 1.5°C threshold. [↑](#endnote-ref-1)
2. In the same vein, a further influence should be acknowledged: Thomas Piketty forged compelling conclusions from simple statistics, identity-formulae and order-of-magnitude arguments in his magisterial *Capital in the Twenty First Century* (Piketty, 2014). [↑](#endnote-ref-2)
3. These data are taken from statistics provided by Peter Phelps, Energy and Environment Manager in the Estates Department of the University of Bath, UK. [↑](#endnote-ref-3)
4. Assumes world GDP as 1012$115 on PPP basis. World Bank data, 2016. Total world energy consumption estimates range from 157005 TWh to 168575 (EIA). A rounded mean value of 160 PWh is used. 2015 is chosen because data are readily available. [↑](#endnote-ref-4)
5. 2017 is adopted as the ‘workhorse year’ for UK statistics, since at the time of writing they are the most recent readily available. [↑](#endnote-ref-5)
6. Officially, the Act committed the UK to total emissions of ‘20% of the 1990 level’ which was 795 MtCO2e, but it is more useful to use the actual target, 159 MtCO2e. [↑](#endnote-ref-6)
7. Published UK data show the projected level of non-energy emissions at 63 MtCO2 in 2035, with no change in the previous 5 years. Part of the explanation for this lack of mobility is that a considerable proportion arises from agriculture, where non-CO2 emissions are particularly hard to abate. Output from agriculture might be expected to rise with population (+15%), and the same might be true of waste treatment, but technical innovations might well balance this out. It is hard to judge. In default of any clearer policy proposals, the published figures are simply extrapolated from 2035 to 2050, giving a value of 60 MtCO2e a year (BEIS, 2019, Annex A), most of which is attributable to agriculture. This value can be deducted from the official target, leaving a residual energy target (159-60) of 99 MtCO2/year for 2050. [↑](#endnote-ref-7)
8. These figures use the IPCC AR4 value of 21 for the GWP100 of methane. The AR5 report revised this to 28, or if feedback effects are included, 34. The effect of applying the AR5 value would be to increase the non-energy total for 2017 to 98.5 MtCO2e/y, giving a strictly-energy component of about 50 MtCO2e/y. We adhere to the UK government’s own preferred conventions. [↑](#endnote-ref-8)
9. It might be remarked that BECCS is already a negative-emission technology (NET, EASAC, 2018) and might be incorporated into ***N***. That is indeed possible, but because it is part of the energy system and the carbon intensity is essentially a ‘negative intensity’ within the Kaya identity it can be included in the multiplying section. The other convention is shown in Table 10. [↑](#endnote-ref-9)
10. The term ‘budget’ has unfortunately acquired two different meanings in the climate change literature. The original meaning was simply the balance between emissions and removals (e.g., LeQuéré *et al*., 2018). More recently the term has been used in the sense of ‘allowable emissions’ (e.g., Matthews *et al*., 2017) and this is its usual colloquial meaning. [↑](#endnote-ref-10)
11. Simplified budget calculations like this are bedevilled by the existence of methane in the mix. Methane is a short-lived gas and does not accumulate in the same manner as CO2. It has been argued that its contribution is limited (Allen *et al*., 2018). The justification for leaving it in is that the decarbonisation time-scale itself is fairly short, so methane does make a contribution. Further, the use of the conventional GWP100 value is questionable in a time-frame of 33 years, when the probable value is around 50 rather than the 21 assumed in the data-set. If anything, the effect of methane is probably undercounted. [↑](#endnote-ref-11)
12. The reference is to Adam Smith, who considered a linen shirt the first step out of poverty (Smith, 2014). [↑](#endnote-ref-12)
13. For example, Wiltshire County Council, Bath and Northeast Somerset Council, Bristol City Council, all in 2019. [↑](#endnote-ref-13)
14. In view of the evidence that the import/offshoring effect is diminishing (Hardt et al., 2018), using data from 2011 might exaggerate the effect claimed. Almost certainly however, the principle is sound: that overseas emissions benefiting the UK are of similar size to the territorial emissions. The Emperor’s clothes are very largely imported, and not just metaphorically. [↑](#endnote-ref-14)