Advice on Climate and Energy

The UK climate change programme must be nationally driven, as the nation is committed to national (Climate Change Act 2008) and international (Paris 2015) targets. Planning for meeting the targets must be integrated, and not divided into separate factions or ministries, each with their own agenda. The approach must be focussed, as in wartime, as this problem has been ignored for far too long. The advice should reach the Prime Minister and the Chancellor, since they are ultimately responsible for allocating scarce resources between competing claims. While policy may be lead by the Treasury, it should not be determined without analysis, like a Spending Review. [1]

The UK needs entities to understand the challenges of climate change, to conduct analysis of the options and to give advice. Several UK universities are already addressing the challenges of climate change. These include Anglia Ruskin University, via the Global Sustainability Institute [2] , Imperial College London, via the Grantham Institute (Climate Change and the Environment) [3] , Leeds University, via the Sustainability Research Institute [4] , and University College London, via the Bartlett Development Planning Unit (Environment and Sustainable Development). [5] Cambridge University is also addressing the challenges of climate change, including via the Cambridge Institute for Sustainability Leadership. [6] However this document proposes a quantitative climate and energy and policy analysis capability, drawing on multiple departments of the university.

The Global Situation

The Limits to Growth study of 1972 showed that – even starting in 1975 - effecting a transition to a sustainable future would not be easy. The 'Standard Run' and many others end in overshoot and collapse. [7] It also showed that delaying the start to 2000 would make it even more difficult. [8] However, humankind chose to ignore these warnings.

In the note 'Avoiding Climate Change Disaster', [9] the two graphs (curves B and A), are based on those of Mulder, 1995. [10] These show that any remaining carbon budget must be largely devoted to buying a future powered by renewable energy.

In the paper 'A Comparison of the Limits to Growth with 30 years of Reality ', [11] the Abstract includes: 'This paper focuses on a comparison of recently collated historical data for 1970–2000 with scenarios presented in the Limits to Growth. The analysis shows that 30 years of historical data compares favorably with key features of a business-as-usual scenario called the "standard run" scenario, which results in collapse of the global system midway through the 21st Century'. I.e. they are closely matched.

Criteria – Tipping Points

Studies by Johan Rockstroem et al considered the current situation of nine global criteria that they termed 'tipping points'. [12] [13] They also produced a video of 18:41. [14]

There is a later paper by Steffen, Rockstrom, and Constanza: [15]
This includes: 'Our planet′s ability to provide an accommodating environment for humanity is being challenged by our own activities. The environment—our life-support system—is changing rapidly from the stable Holocene state of the last 12,000 years, during which we developed agriculture, villages, cities, and contemporary civilizations, to an unknown future state of significantly different conditions. One way to address this challenge is to determine "safe boundaries" based on fundamental characteristics of our planet and to operate within them. By "boundary," we mean a specific point related to a global-scale environmental process beyond which humanity should not go. Identifying our planet′s intrinsic, nonnegotiable limits is not easy, but here we specify nine areas that are most in need of well-defined planetary boundaries, and we explain the steps needed to begin defining and living within them'. 'Here, we present the underlying concepts and suggest ways to limit continued growth of the material economy on a finite planet'. [16]

Of the several 'safe boundaries', climate change could easily reach a tipping point beyond which it would be out of human control. [17] [18] The last time this happened was before the evolution of life, so if it happened again, this would be disastrous for all life forms, including humankind. Yet humankind has already started another mass extinction event. [19] So the global warming target of 1.5 to 2.0 C adopted in the Paris accord is a political and scientific judgement. [20]

The global warming mechanisms have been persistently understated, including in the latest, 2013 IPCC report. [21] So the global carbon budget may already be overspent, which would require a 'rollback' - e.g. by removing CO_2 from the atmosphere. [22] See also the articles by David Wallace-Wells, including James Hansen's contribution: [23] [24] [25]

Christiana Figueres et al authored a 2017 paper 'Three years to safeguard our climate'. [26] This includes a graph showing how world GHG emissions must fall from 2020, but not what measures to adopt.

Criteria – Social Thresholds
Kate Raworth developed a diagram that extends the diagram of Rockstroem et al (see above) to include 11 'Social Thresholds'. Here is a brief introduction: [27]

Here is an early discussion paper by her: 'A Safe and Just Space for Humanity: Can we live within the doughnut?'. [28]

Here is a video of 16:52 of a presentation by Kate Raworth 'Why it's time for 'Doughnut Economics'. [29]

Here is a later discussion paper from Oxfam: [30]

In 2017, Kate Raworth produced the book: 'Doughnut Economics'. [31]

Criteria – Zero Growth
In 2010, Daniel O'Neill and others organized a conference on the Steady State Economy at the University of Leeds.
Based on the proceedings, Rob Dietz and Dan O'Neill wrote the 2013 book: 'Enough is Enough'. [32] This also links the biophysical 'Planetary Boundaries' with the 'Social Thresholds' and includes the diagram developed by Kate Raworth (above).

From this book, a film of 18:34 was made: 'Enough Is Enough: Full Film' [33]

The latest paper by Dan O'Neill et al is: 'A good life for all within planetary boundaries'. [34]
Unfortunately, this paper cannot be accessed for free. However, it was reported in these articles:
'Britain is using far more than its share of world's resources' [35] and 'Developing world cannot sustainably achieve same living standards as West, says study' [36] This includes at the end:
'"Radical changes are needed if all people are to live well within the limits of the planet," said Dr Julia Steinberger, another of the study's co-authors. "These include moving beyond the pursuit of economic growth in wealthy nations, shifting rapidly from fossil fuels to renewable energy, and significantly reducing inequality."

The interactive web site associated with the paper can be accessed for free: 'A Good Life For All Within Planetary Boundaries' [37] This shows Social Thresholds Achieved and Biophysical Boundaries Transgressed, e.g. the UK at 8 and 5, Germany at 11 and 5, and the USA at 9 and 7.

See also: 'Explore Scenarios' [38] This could be used to see how high a 'social' score each country could achieve while keeping within the 'biophysical' boundaries.

Sustainability requires greater equality between and within nations. The latter has been shown to improve social metrics for both rich and poor. [39] By cutting 'conspicuous consumption', greater equality should also reduce the national and global energy demands for food, heating and cooling and transport.

Criteria – Timing and the Commons
The importance of timing is emphasized in: 'COP 21 Paris Climate Summit Danger, A Weak Agreement Could Delay Strong Action Until It's Too Late' [40] and ''Fixing the Paris Climate-Negotiation Failure'. [41] This starts with:
'Climate change is a problem of the commons. Nearly all agree. But the insidious nature of this problem is being largely ignored in Paris, and this has led to a self-contradictory approach'.
Near the end, it includes:
'4. This is how you solve a problem of the commons — Elinor Ostrom'.

This is linked to: 'Elinor Ostrom'. [42] It includes:
- 'It was long unanimously held among economists that natural resources that were collectively used by their users would be over-exploited and destroyed in the long-term. Elinor Ostrom disproved this idea by conducting field studies on how people in small, local communities manage shared natural resources, such as pastures, fishing waters, and forests. She showed that when natural resources are jointly used by their users, in time, rules are established for how these are to be cared for and used in a way that is both economically and ecologically sustainable'.
(So Elinor Ostrom's findings are based on extensive evidence from the real world).
and:
- 'Caring for the commons had to be a multiple task, organised from the ground up and shaped to cultural norms. It had to be discussed face to face, and based on trust. Mrs Ostrom, besides pouring over satellite data and quizzing lobstermen herself, enjoyed employing game theory to try to predict the behaviour of people faced with limited resources'.
See the book 'Trust and reciprocity: interdisciplinary lessons from experimental research. [43]
(So Elinor Ostrom's findings are also supported by experiments).

See also: 'Fixing Paris Climate Negotiation Failure' [44] and 'Price Carbon - I Will if You Will' [45]
These pages also have links to a free e-book of 151 pages, 'Global Carbon Pricing, We Will If You Will', with papers by David MacKay and others. [46]

Monitoring of GHG emissions
Worldwide agreement on global and national GHG releases (carbon budgets) also requires an agreed monitoring regime. 'Among the key provisions of the Paris climate deal, signed by 195 countries in December 2015, is the requirement that every country, rich or poor, has to submit an inventory of its greenhouse-gas emissions every two years. Under UN rules, most countries produce "bottom-up" records, based on how many car journeys are made or how much energy is used for heating homes and offices. But air-sampling programmes that record actual levels of gases, such as those run by the UK and Switzerland, sometimes reveal errors and omissions'.
'China's approach to reporting its overall output of warming gases to the UN is also subject to constant and significant revisions. Its last submission ran to about 30 pages - the UK's, by contrast, runs to several hundred. Back in 2007, China simply refused to accept, in official documents, that it had become the largest emitter of CO2. [47]

Some western European GHG emissions have also been under-reported.
'"Clean" Italy: virtually HFC-23-free since 1996 – according to the records
So far, so good. If it were not for the official figures from Italy, which did not report any appreciable HFC-23 emissions – and that since 1996. An isolated case? Reimann and his team wanted to dig deeper. With financial support from the [Swiss] Federal Office for the Environment (FOEN), they evaluated HFC-23 figures for 2008 to 2010 throughout Western Europe and pinpointed the source regions. The emission figures approximately doubled those that had been reported – whereby countries significantly differed in their 'reporting accuracy'. Alongside the 'front runner' Italy, also the Netherlands and Great Britain underestimated their HFC-23 emissions; France and Germany's figures, in contrast, lay within the reported values. And, to Reimann's delight, the computer model was able to identify all six HCFC-22 factories with great accuracy.
Overall the unreported amounts of 'Italian' HFC-23 could be calculated as 270,000 to 630,000 tonnes of CO2 equivalent – roughly corresponding to the annual CO2 emissions of a city of 75,000 inhabitants'. [48] [49]

Monitoring of local and national GHG emissions is also possible from satellites. This paper is by Chinese researchers, so they are well aware of what is possible. [50] This is what is happening now. [51] This is an EU project planned for the future. [52] China has launched a satellite to monitor global CO2 and published the first results. [53]

Modelling of Climate and Energy Options
In, 'The sower's way: quantifying the narrowing net-energy pathways to a global energy transition', by Sgouridis et al, the Abstract includes: 'Planning the appropriate renewable energy (RE) installation rate should balance two partially contradictory objectives: substituting fossil fuels fast enough to stave-off the worst consequences of climate change while maintaining a sufficient net energy flow to support the world's economy. The upfront energy invested in constructing a RE infrastructure subtracts from the net energy available for societal energy needs, a fact typically neglected in energy projections. Modeling feasible energy transition pathways to provide different net energy levels we find that they are critically dependent on the fossil fuel emissions cap and phase-out profile and on the characteristic Energy Return On (Energy) Invested (EROI) of the RE technologies. The easiest pathway requires installation of RE plants to accelerate from 0.12 TW p yr –1 in 2013 to peak between 7.3 and 11.6 TW p yr –1 in the late 2030s, for an early or a late fossil-fuel phase-out respectively, in order for emissions to stay within the recommended CO 2 budget'. [54]

So the early fossil-fuel phase-out requires the installation of RE plants to accelerate by 7.3/0.12 = 61-fold and the late phase-out by 11.6/0.12 = 97-fold. Further delay would mean that there is no solution that meets the target.

The Sustainable Energy Transitions (SET) Model 2 of Sgouridis et al takes account of the energy costs and EROIs of the proposed measures. [55] These are absolutely crucial when modelling energy and GHG transitions. This model could also be used to estimate the energy and GHG emission impacts of any possible policy measures. The source code of SET Model 2 may be downloaded. [56]

Energy and GHG footprints can be obtained from a Life Cycle Analysis database, such as EcoInvent. [57] An example of their work is: 2013-10 Life Cycle Assessment of Agricultural Systems: Introduction, Thomas Nemecek. [58]

The UK Climate Change Situation
In the Report of the Committee on Climate Change (CCC) to Parliament, June 2017, the Executive Summary includes:
'The UK urgently needs new policies to cut greenhouse gas emissions. Parliament has made commitments and the Government has a legal duty to propose policies to meet them. Despite this, no significant new policy plans have been published in the 11 months since the fifth carbon budget was set. Climate change will not wait while other priorities are addressed: plans must be published without delay, setting out how the Government intends to deliver the budget, which requires a 57% reduction in greenhouse gas emissions from 1990 to 2030.

Recent reductions in emissions should not detract from the urgent need for new policies to bring confidence to investors and to enable future targets to be met. Although UK emissions fell 6% in 2016 and are down 19% since 2012, progress has been dominated by the power sector. Carbon dioxide emissions from transport and buildings rose in 2015 and 2016, while progress in driving emissions reductions in industry and for non-CO 2 greenhouse gases has been minimal.

Despite promising advances in low-carbon technologies like electric cars and renewable power generation, emissions will not continue to fall without new and strengthened policies, and the fourth and fifth carbon budgets will be missed'. [59] Table 1 shows 'Possible package of measures to deliver the changes required, 36% reduction in UK emissions required from 2016 to 2030'. The package of measures appears to depend on: Sectoral scenarios for the Fifth Carbon Budget, Technical report, November 2015. [60] Yet the measures include nuclear power and CCS, neither of which are certain to be delivered. Also the scenarios modelling does not take account of the energy costs, EROIs and GHG footprints of the measures.

The 'Emissions Reduction Plan' was over a year late [61] and the name was changed to the 'Clean Growth Plan'. Yet meeting the climate targets requires keeping to the carbon budget. This means no material growth that is not offset fully by energy and GHG emissions savings elsewhere in the carbon budget. (See below, Delivering a UK Climate Change Solution).

The Clean Growth Plan was assessed by the CCC. The Foreword includes: 'However, whilst some new policies are announced in the Strategy, the detailed policies and measures to meet the targets are not, in general, set out.
Furthermore, even taking account of the Strategy's aspirations, a gap in meeting the fourth and fifth carbon budgets remains. Urgent policy development is therefore required'. [62]

The UK Carbon Budget

Adjustment of the UK Carbon Budget - for Equity
Contraction and Convergence is essential to achieve international agreement – including by less-developed countries. [63]
'Global emissions contraction must be fast enough to achieve the objective of the UN Framework Convention on Climate Change [UNFCCC] on a precautionary basis [for example 100% contraction by 2050]'. [64] So to avoid severe climate change before 2100 requires not Convergence (of all countries' GHG emissions) by 2050 and Contraction (to zero) by 2100, as IPCC AR5, but Convergence by 2020-2030 and Contraction by 2050, as UNFCCC.

Adjustment of the UK Carbon Budget - for Imports and Exports
'The UK reports Greenhouse Gas Emissions from a territorial basis, including all the emissions that occur within the territory of the UK. However, the UK is one of the largest net importers of emissions embodied in trade in the world.
While emissions continue to decline (albeit at a relatively slow rate) within the UK, the emissions associated with the imports of products consumed by the UK are not reducing with an increase in the emissions in 2012. These emissions are not included in the UK 2050 carbon target to reduce 1990 level emissions by 80%. The UK's boasts of cutting carbon emissions are illusory because the carbon embedded in imports outweighs the savings at home. UK territorial emissions have reduced by 194 Mt in 2012 compared to 1990. Net emissions embodied in trade added an additional 280 Mt in 2012 (see attached brief 'Climate Change targets must reflect the impacts of our consumption').
The emissions included under the UK's current 2050 target have reduced while aviation, shipping and emissions embodied in net trade, which are excluded from the target, have increased. With increasing global trade, emissions accounting and setting targets from a territorial perspective doesn't counteract the adverse impacts globally driven by a nation's consumption.
Research undertaken by the CCC and the University of Leeds demonstrated that even with deep cuts in global emissions, the UK would remain a net importer of global emissions in line with trends in imports up to 2050. If the UK was to take responsibility for these additional emissions, then the target would have to change.
At present, the UK has a legally binding commitment to reduce territorial emissions by 80% by 2050 based on 1990 levels. With the additional emissions included, the UK would need to achieve an 80% cut ten years earlier (80% reduction by 2040). Instead of emission reductions of 2% a year, the UK would need to reduce emissions at a rate of 3.5%. Without the tightening of the target and an increase in the rate of annual reductions, the UK will not achieve the intended climate outcome associated with the existing target'. [65] [66]

Imports and exports embody energy and GHG emissions, so the UK carbon budget should be adjusted accordingly.

Adjustment of the UK Carbon Budget - for Food Security
Pfeiffer, 2004 includes: 'Presently, only two nations on the planet are major exporters of grain: the United States and Canada. By 2025, it is expected that the U.S. will cease to be a food exporter due to domestic demand. The impact on the U.S. economy could be devastating, as food exports earn $40 billion for the U.S. annually. More importantly, millions of people around the world could starve to death without U.S. food exports'. [67]

FAO, 2009 includes: 'Global demand for food is on the rise, driven by unprecedented growth in the world's population, which is expected to surpass 9 billion by 2050, and widespread shifts in consumption patterns as countries develop. To meet the increased demand for food driven by these factors, the FAO projects that we must more than double global agricultural production by 2050'. [68] [69]

'A combination of just three catastrophic weather events could undermine food production across the globe'. This could 'lead to food riots breaking out in urban areas across the Middle East, North Africa and Latin America, leading to wider political instability and having knock-on effects for a wide range of businesses'. [70]

In de Ruiter, 2015, the Abstract includes: 'The UK is currently importing over 50% of its food and feed, whereas 70% and 64% of the associated cropland and GHGE impacts, respectively, are located abroad. These results imply that the UK is increasingly reliant on external resources and that the environmental impact of its food supply is increasingly displaced overseas'. [71]

The impacts of climate changes including surface warming, droughts and heat waves on food production is discussed in [72] and [73]. The latter focusses on the USA, as it is a major exporter of food – to the UK and other countries.

To reduce the risk of starvation, the UK should more than double the proportion of food produced domestically before 2025. So the resulting increase in GHG emissions must be allowed for in the carbon budget.

The UK Carbon Budget – after adjustments
The UK has a carbon budget that declines with time, due to the continuing GHG emissions. For fairness and prudence, the UK 'territorial' GHG emissions targets should be adjusted for equity, all imports and exports, and for food security. Carbon Brief reported that: 'UK emissions should be 'net-zero' by 2070 at the latest, study says'. [74] This refers to Pye et al, 2017. [75] The scenario for 'equity' (equal per capita basis) with a 66% chance of 2 C requires the UK to be 'net-zero' by 2060.

Energy Services
Energy services can be delivered by combinations of energy supply and energy demand reduction measures.
In the UK, like many developed countries, electricity accounts for about 20% of delivered energy, transport for about 30%, and heat at < 100 C for about 50%.

Energy Services - Electricity

EROIs for Renewable Electricity Supply
Energy Return on (Energy) Investment (EROI) is a crucial metric of energy supply and energy demand reduction measures.

According to the Fraunhofer Institute for Solar Energy Systems, ISE: 'The Energy Payback Time of PV systems is dependent on the geographical location: PV systems in Northern Europe need around 2.5 years to balance the input energy, while PV systems in the South equal their energy input after 1.5 years and less, depending on the technology installed.
A PV system located in Sicily with multi-Si modules has an Energy Payback Time of around one year. Assuming 20 years lifespan, this kind of system can produce twenty times the energy needed to produce it'. [76]
For a lifetime of 20 years and an Energy Payback Time of 1 year, the EROI is 20.

The EROI of a Vestas wind turbine in medium wind conditions is about 38 and in high wind conditions 44. [77]
The EROI of an Enercon wind turbine for inland sites is about 35, near-coastal sites about 41 and coastal sites 51. [78]
So the EROI of 20 assumed by Sgouridis et al, 2016 can be equalled in certain cases by solar PV, and exceeded considerably by MW-scale wind turbines.

Electricity Storage
The Faraday Challenge advice assumes that batteries will have a major role in balancing the grid. [79] However, this is not the case. The majority (by energy) will be Power-to-Gas (methane) storage, as shown by Specht et al in 2009. [80]

In Germany, the state of Baden-Wuttenburg has funded the ZSW (Centre for Solar Energy and Hydrogen Research) for more than 20 years. Over this time Dr Michael Specht and colleagues developed the technology of Power-to-Gas (methane), including a pre-pilot plant. The potential of this technology for storage in renewable power systems was described (in English) in the Ph.D. thesis of Michael Sterner of 2009. [81] A pilot plant of 25 kW was commissioned from ZSW by a newly-founded company Solarfuel (now Hitachi Zosen Inova Etogas GmbH) in 2009. The latter designed and built an industrial plant of 6 MW for the Audi division of the VW Group in 2013. These plants were included in a paper that reviewed 46 Power to Gas projects. [82]

Power-to-Gas and extensions thereof , known as Power-to-X, are regarded by the German Energy Agency (DENA) as key technologies of the 'Energiewende' (energy transition). [83]

Energy Services - Transport
One estimate suggests that it would take 20 years for BEVs to reach 100% of sales. [84] A modelling study suggests that the transition of the passenger car fleet from ICEVs to 90% BEVs will take several decades. [85] The French and UK governments have recently declared that they will end the sale of petrol and diesel cars (and vans) by 2040. [86] [87] 'Other countries including Norway, the Netherlands and India have set or are considering similar goals along with a number of big cities around the world, including Paris, Mexico City and Athens'. [88]

However, the Faraday Challenge advice may put too much emphasis on mitigating the GHG emissions from car and vans. To meet the GHG emissions targets, the volume of car transport may have to be reduced drastically. [89] This would be similar to wartime.

The Faraday Challenge advice also omits any mention of the transition for heavy duty vehicles, including trucks, long distance buses, non-electric trains, ships and aircraft. These duties are very unlikely to be met with batteries, so would require renewable synthetic fuels, produced by Power-to-Gas and Power-to-Liquids processes. (See Electricity above and [90]).

Energy Services - Heat and Cool
For most urban existing housing, heat below 100 C should be supplied via District Heating (DH). This gives the best exergy match and can be cascaded from CHP plants fuelled with renewable gas, municipal waste and biomass. The real merit of CHP for DH is discussed in [91] . Heat at below 100 C can also be supplied by large-scale solar arrays and geothermal boreholes.

Heat networks are widespread on the European continent, as shown in 'The Case for District Heating: 1000 Cities Cannot be Wrong'. [92] They enable all fossil-fuelled heat to be replaced with renewable heat. The heat network serving Copenhagen should be carbon-neutral by 2025. [93] In the UK, heat networks supply only about 2% of the building heat energy. Yet wind power and PtG methane synthesis, storage and GtP conversion could supply all the electricity and provide much of the heat via DH. [94]

New buildings should be of Passive House (PH) design, reducing the net energy consumption by some 80%. [95]

The UK and national (devolved) governments should require every town to develop a Heat Plan, as did Denmark in 1979. [96] This should show how urban heat supply would evolve from about 80% gas and 7% electric heat, to 100% DH from reject heat cascaded from power plants and industry and renewable energy. Such measures have been well-established on the Continent, particularly in Denmark, and towns are very similar, differing mainly in scale and extent. [97] However, there will be differences due to the number and size of power plants and industry for heat, and the availability of river water and seawater for cool. [98] [99]
District Cooling (DC) offers far higher energy efficiency and relief from the urban 'heat island' effect. This effect is expected to add a further two degrees to global warming estimates for the most populated cities by 2050. [100]
Deployment of DHC can be via local authorities or ESCOs and should proceed in parallel across all towns and cities in the UK, as it would take several decades. [101] This would provide many jobs – especially for local people – for long periods.

All new buildings should either be provided with DH, or built to PH standards. However in the UK, new buildings have heat losses above the design levels, known as the 'Performance Gap'. For a sample of 15 new houses, this was 10 to 125%. [102] For commercial buildings, it is often greater. So 100% should be tested for heat loss and air tightness by independent agencies, such as consultants.

Global Limits of Renewable Energies
Of the renewable energy resources, wind and solar electricity are large and hydro and biomass much smaller.

In 2011-06-29 'Global wind power potential: Physical and technological limits', de Castro et al. [103] the Abstract includes:
'We propose a top–down approach, such as that in Miller et al. (2010), to evaluate the physical–geographical potential and, for the first time, to evaluate the global technological wind power potential, while acknowledging energy conservation. The results give roughly 1 TW for the top limit of the future electrical potential of wind energy'.

In 2013-08-11 'Global solar electric potential: A review of their technical and sustainable limits', de Castro et al. [104] the Abstract includes: 'Although it is very difficult to give a global limit to the expansion of solar power, an overview of the land and materials needed for large scale implementation show that many of the estimations found in the literature are hardly compatible with the rest of human activities. Overall, solar could be more limited than supposed from a technological and sustainable point of view: around 60–120 EJ/yr'. (i.e. 1.9 to 3.8 TW average).

In 2016, 'Sustainable Energy Resources: Prospects and Policy', Moriarty and Honnery [105] , Table 1.2 'Range of global RE technical potential estimates (EJ)' includes solar electricity as 63.0-15,500 and wind electricity as 31.5-3000 (per year). (These correspond to annual averages of 2-490 and 1-95 TW). Page 15 includes: 'Only for hydroelectricity are estimates fairly tightly constrained at around 30-60 EJ'. (Assuming that the Capacity Factor is 1, this implies an annual average of 1-2 TW).

The solution-space of Sgouridis et al, 2016 would be reduced by the global wind and solar power limits of de Castro et al.
Fig. S19 mentions a turbine power density of 5MW/km2 while de Castro et al, 2011 P 6681 mentions 1W/m2 (= 1 MW/km2).
Fig. S20 shows a Total (Solar) Energy Resource of 362,500 Twh/y (41.4 TWaverage), while de Castro et al, 2013 mentions 60–120 EJ/yr'. (i.e. 1.9 to 3.8 TWaverage).

Sgouridis et al, 2016 say that the requirement is ~ 110 TWpeak by 2050. Yet de Castro et al, 2011 give (onshore) wind as about 3.3 TWpeak, and de Castro et al, 2013 give solar as about 9.5 TWpeak. However, Moriarty and Honnery, 2016 cite ranges of onshore wind as 1-95 and solar as 2-490 with hydro of 1-2 TWaverage, so the total could be from 4 to 587 TWaverage.

So climate change solutions may also require increased energy efficiency and savings and reduced energy services. [106] [107] [108]

Energy Demand Reduction

'One of the most significant opportunities to reduce emissions, particularly in the short term is to reduce demand for energy. Energy demand is driven by multiple factors beyond the remit of DECC and requires a government wide response to ensure that all government policy will lead to a reduction in energy use. For example, the National Infrastructure Plan, transport policy and taxation can all have a significant effect on energy demand.

Evidence shows that the energy demand of the UK economy has barely reduced for the past 20 years, despite widespread energy efficiency policies. From a consumption perspective, in 1990, the primary energy demand of the UK economy was 11.5 EJ and in 2011 it was 11.0 EJ 1 . If less is achieved through reducing demand for energy; energy supply will have to decarbonise further and faster significantly increasing the cost of abatement. Furthermore, demand reduction is an important transition mechanism while effective supply-side technologies are developed 2 .

Demand reduction can provide many parallel benefits, including fuel poverty alleviation, energy security, lower public health spending and job creation 3 .

Furthermore, it could reduce the need to invest in new supply capacity and grid reinforcement and requires no technological breakthrough. Despite this importance, support for demand reduction is marginalised in comparison to supply technologies 4 .

It's important to note that the majority of current policies are based on energy efficiency (using fewer units of energy for each unit of output) not a reduction in energy consumption (reducing absolute demand for energy). Energy efficiency does not necessarily lead to a reduction in energy use. Considerable evidence of rebounds effects demonstrate that efficiency gains drive further economic growth that, in turn, drive growth in energy consumption 5,6 .

As technological solutions become more expensive as budgets get tighter, DECC would benefit from broadening its remit to consider the role of resource efficiency to reduce energy demand. Considerable evidence exists that demonstrates significant emission reductions and cost savings for companies and households 7,8' . [109]

Scope for Energy Saving

In 2010-12-14, 'Reducing Energy Demand: What Are the Practical Limits?', Jonathan M. Cullen, Julian M. Allwood, and Edward H. Borgstein, the Abstract includes: 'The result demonstrates that 73% of global energy use could be saved by practically achievable design changes to passive systems'. [110]

In 2012, 'Energy Costs of Energy Savings in Buildings: A Review', Page 1725 includes: 'Dahlstrøm [84] studied the energy budget of advance windows in the Norwegian context. They noted that the energy payback time of improving the insulation of a window from U = 1.2 to U = 0.8 by an additional glazing and low-e coating to a double window, with argon filling and one low-e coating was roughly a year. Over a 35 years lifetime, this would translate in an EROI ≈ 35, which is broadly consistent with previous values [77–80]'.

'For a U.S. residential home build in Michigan, Keolian et al. [86] obtained an EROI of 60 from a specific so-called "Energy-Efficient Home" over a period of 50 years. This high EROI can be credited to the numerous strategies for lowering life-cycle energy consumption used. These strategies mainly focused on methods to reduce utility-supplied energy, but the reduction of the embodied energy and increased product durability were also addressed. Uzsilaityte and Martinaitis [87] studied the impact of various rebuilding strategies on a school building in Vilnius, Estonia. The derived EROI values were between 11.9 to 55.5 as a function of the measures that were implemented'. [111]

Scope for Increased Energy Efficiency

In 2010-03-05, 'Theoretical efficiency limits for energy conversion devices', Jonathan M. Cullen, Julian M. Allwood, the Abstract includes: 'The result estimates the overall efficiency of global energy conversion to be only 11 per cent; global demand for energy could be reduced by almost 90 per cent if all energy conversion devices were operated at their theoretical maximum efficiency'. [112]

Experience shows that, given the chance, engineers can design and manufacture affordable and durable devices that achieve within factor two of the thermodynamic minimum energy consumption. For example, working between the same top and bottom temperatures, the thermal efficiency of real internal combustion engines is about half that of the ideal Carnot engine. Taken with the above, this suggests that global energy demand could be reduced by about 45% if all energy conversion devices operated at half their theoretical maximum efficiency.

The lifetime primary energy use of GLS (incandescent) lamps is 3300 kWh, while that of an LED lamp is 700 kWh.
The production energy for an LED lamp = 10 kWh. [113]
So replacing GLS with LED, the lifetime primary energy saving = 3300 – 700 = 2600 kWh and the EROI = 2600/10 = 260.

The above two studies by Cullen et al are complementary as many energy-using devices involve both energy losses from passive systems (First Law of Thermodynamics) and active energy conversion (Second Law of Thermodynamics). For example, a refrigerator consists of a (passive) insulated box and an (active) electric heat pump.

Taken together, the above two studies imply that global energy use could be reduced by about 80%. Moreover, some energy demand measures have EROIs far greater than 20, the average value assumed for energy supply measures by Sgouridis et al, 2016. By including such demand measures, the accelerations could be reduced from 60-fold (early) or 97-fold (late), to more like 60/5 = 12-fold or 100/5 = 20-fold. Together these supply and demand measures could be far less challenging to implement, and keep the renewable energy supply capacities below the global limits of de Castro et al 2011 and 2013.

Negative Emission Technologies

One group of NETs for Carbon Dioxide Removal (CDR), described as artificial, includes Biomass Energy and Carbon Capture and Sequestration (BECCS) for power generation and cement and steel manufacture, and Direct Air Capture and Sequestration (DACCS) of CO2 from atmospheric air or flue gas. Alternatively, the CO2 from Direct Air Capture may be used as a feedstock for long-lived chemical products.

Boysen et al found that large-scale terrestrial CDR by BECCS is not a viable alternative to aggressive emissions reduction: 'Our results show that those tCDR measures are unable to counteract "business-as-usual" emissions without eliminating virtually all natural ecosystems. Even if considerable (Representative Concentration Pathway 4.5 [RCP4.5]) emissions reductions are assumed, tCDR with 50% storage efficiency requires >1.1 Gha of the most productive agricultural areas or the elimination of >50% of natural forests. In addition, >100 MtN/yr fertilizers would be needed to remove the roughly 320 GtC foreseen in these scenarios.

Such interventions would severely compromise food production and/or biosphere functioning. Second, we reanalyze the requirements for achieving the 160–190 GtC tCDR that would complement strong mitigation action (RCP2.6) in order to avoid 2 ∘ C overshoot anytime. We find that a combination of high irrigation water input and/or more efficient conversion to stored carbon is necessary. In the face of severe trade-offs with society and the biosphere, we conclude that large-scale tCDR is not a viable alternative to aggressive emissions reduction. However, we argue that tCDR might serve as a valuable "supporting actor" for strong mitigation if sustainable schemes are established immediately'. [114]

Likewise, Heck et al found that biomass-based negative emissions would be difficult to reconcile with planetary boundaries: 'However, large-scale deployment of BECCS would imply significant impacts on many Earth system components besides atmospheric CO2 concentrations. Here we explore the feasibility of NE via BECCS from dedicated plantations and potential trade-offs with planetary boundaries (PBs) for multiple socio-economic pathways. We show that while large-scale BECCS is intended to lower the pressure on the PB for climate change, it would most likely steer the Earth system closer to the PB for freshwater use and lead to further transgression of the PBs for land-system change, biosphere integrity and biogeochemical flows."' [115]

Naomi Vaughan et al investigated the feasibility of BECCS and found: 'CCS deployment rates in the scenarios are very challenging compared to historical rates of fossil, renewable or nuclear technologies and are entirely dependent on stringent policy action to incentivise CCS. In the scenarios, half of the biomass resource is derived from agricultural and forestry residues and half from dedicated bioenergy crops grown on abandoned agricultural land and expansion into grasslands (i.e. land for forests and food production is protected). Poor governance of the sustainability of bioenergy crop production can significantly limit the amount of CO 2 removed by BECCS, through soil carbon loss from direct and indirect land use change. Only one-third of the bioenergy crops are grown in regions associated with more developed governance frameworks'. [116]

A second group of NETs, described as Natural Climate Solutions (NCS), includes both terrestrial, such as Reforestation (tree planting) and Biochar (carbon sequestration in soils), and marine, such as Ocean Fertilisation (OF) (by iron addition).

Regarding terrestrial CDR, Griscom et al noted: 'We find that the maximum potential of NCS—when constrained by food security, fiber security, and biodiversity conservation—is 23.8 petagrams of CO 2 equivalent (PgCO 2 e) y −1 (95% CI 20.3–37.4). This is ≥30% higher than prior estimates, which did not include the full range of options and safeguards considered here. About half of this maximum (11.3 PgCO 2 e y −1) represents cost-effective climate mitigation, assuming the social cost of CO 2 pollution is ≥100 USD MgCO 2 e −1 by 2030.

Natural climate solutions can provide 37% of cost-effective CO 2 mitigation needed through 2030 for a >66% chance of holding warming to below 2 °C. One-third of this cost-effective NCS mitigation can be delivered at or below 10 USD MgCO2 −1 '. [117]

Regarding a study by Cecile Rousseaux et al: 'Carbon dioxide (CO2) from the atmosphere dissolves in cold ocean water. During a phytoplankton bloom, which can span hundreds of miles and be seen from space, the tiny organisms take up the dissolved CO2 and convert it to organic carbon – a form that animals can use as food to grow, the essential base of the marine food web. Then when the phytoplankton cell dies, it sinks to the ocean floor, taking with it the carbon in its body.

Because they are larger than other types of phytoplankton, diatoms can sink more quickly than smaller types when they die. A portion will circulate back to the surface because of ocean currents, and, like fertilizer, fuel another phytoplankton bloom. But the rest will settle on the sea floor miles below, where they will accumulate in sediment and be stored for thousands or millions of years. The process is one of the long-term storage options for carbon removed from the atmosphere'. [118]

Russ George asked whether Ocean Restoration (or Fertilisation) could remove a trillion tons of carbon from the atmosphere:
Nick Breeze (NB): In the context of climate change and carbon sinks, can we talk a little bit about the role the oceans play in photosynthesis?
'Russ George (RG): This blue planet is 28 percent land, of which half is rock and ice. So 14 percent of this planet has soil that might sustain green plants, but 72 percent of this planet is the ocean, all of which can sustain green photosynthesis.
So the green photosynthetic productivity in the ocean is down by 40-50 percent. That is the conservative data backed numbers for the collapse of phytoplankton in the worlds ocean. We are terrestrial beings so we think about forests. So everybody on the planet knows about the plight of the Amazon rainforest, and it is a global cause celeb. Tens of millions of dollars are being focussed on trying to save the remaining rainforests because 20 percent of the rainforest has been cut down.
But in every five year period of time since 1950, there has been a loss of green plant life equal to an entire Amazon in the worlds oceans. So here we are. A dozen Amazons have gone missing from the world.

NB: That is absolutely enormous in terms of scale. What state are they in, I mean how much of this impact can they absorb?
RG: Well, we know that since 1950 if we have lost 12 entire Amazon's worth of biomass in the oceans, if we merely restore it to that state, we'll capture that much sustainable living biomass in the oceans.
That is more forestry potential than exists than in all the lands on the planet. So we can grow plants in the ocean that will harvest many times the amount of CO2 than if we were to reforest all available land on the planet.

NB: The oceans have recently been described as a vast desert. Are you talking about turning them into a rich biodiverse environment?
RG: I describe the oceans as being a vast oceanscape, like a landscape. Scattered around on that oceanscape are pastures that come and go, like pastures on land. So the ocean pastures of the world come into being when the necessary nutrients arrive. The most critical nutrient for photosynthesis is iron. It is the rarest substance in the ocean.
The background level of iron in the open ocean, far from land, is only 3 parts per trillion. So when iron arrives, say in a dust fall from the Gobi Desert, or from the Sahara, the concentration of iron in the surface water rises from 3 parts per trillion to, say, 100 parts per trillion, or 1 part per billion.
When it does that, the ocean turns from blue to green immediately because iron empowers photosynthesis. So the potential is there to restore the ocean pastures of the planet. The ocean is not one single pasture; it is a collection of pastures'. [119]

In a very recent review of Negative Emission Technologies, Sabine Fuss et al found: 'Based on a systematic review of the literature, our best estimates for sustainable global NET potentials in 2050 are 0.5–3.6 GtCO 2 yr −1 for afforestation and reforestation, 0.5–5 GtCO 2 yr −1 for BECCS, 0.5–2 GtCO 2 yr −1 for biochar, 2–4 GtCO 2 yr −1 for enhanced weathering, 0.5–5 GtCO 2 yr −1 for DACCS, and up to 5 GtCO 2 yr −1 for soil carbon sequestration.
Costs vary widely across the technologies, as do their permanency and cumulative potentials beyond 2050. It is unlikely that a single NET will be able to sustainably meet the rates of carbon uptake described in integrated assessment pathways consistent with 1.5 ◦ C of global warming'. [120]
This study also considered Ocean Fertilization. Although global NET potentials of up to 45 GtCO 2 yr – 1 have been estimated, the present authors' assessment: '... suggests that OF is not a viable negative emissions strategy when performed with sustainability issues under consideration...'.

Climate and Energy Solutions
Climate and energy solutions can combine energy supply, energy demand reduction and negative emissions measures. However, the GHG reductions for each sector and measure would depend upon the starting point and scenario. Due to interactions and non-linearities, they could only be estimated with a mathematical model, such as SET. (see above Modelling.).

Delivering a UK Climate Change Solution
All policy options have energy and climate implications
All UK national and local government policies should support meeting the national (Climate Change Act) and international (Paris) climate targets. All policy options must be judged by their contributions to meeting the climate change targets. The UK climate change research and deployment programme should be guided by modelling of the climate and energy system. This requires clear definitions and quantification to minimise ambiguity and wriggle-room and keep everyone honest.

Brand-Correra et al, 2017 estimated the National-Level Energy Return on Investment ($EROI_{nat}$) of the UK. [121] This excludes both energy imports and exports and embodied energy imports and exports. (See Fig. 2). Despite being a net importer of both, the $EROI_{nat}$ for the UK so defined declined from 9.6 in 2000 to 6.2 in 2012. The latter is far below the value of 20 in 2014 taken as the starting point for energy transitions by Sgouridis et al, 2016. It reflects policy choices that are capital energy-intensive and increase operating energy consumption, so reducing the solution space for sustainable energy transitions. These choices include armaments such as nuclear submarines, aircraft carriers, and military aircraft. These are hugely costly in money and energy to build and to operate. Yet they are ill-suited to countering present and future military threats, such as terrorism and cyber-attacks.

Additional infrastructure such as roads, high-speed railways, and airport runways would also be unhelpful, as it would encourage more traffic. Yet to meet the demands for food and shelter within the climate targets may well require reduced transport volumes. (See above, Energy Services - Transport). So both armaments and additional infrastructure would be counter-productive to the greatest threat - climate change.

All operating UK nuclear sites are coastal, and could be swamped by sea level rise of up to 2.5 meters by 2100. [122] Several sites are also vulnerable to storm surges. So to ensure that their radioactivity is not released into the sea, all such sites must be fully decommissioned e.g. by 2050. There have already been releases from Windscale and the coastal nuclear power plants, but the potential magnitudes are far greater. This would be climate-change related, but there are also radioactive releases from operation and disasters. [123] The radioactivity spreads worldwide, is concentrated in food chains, and causes genetic damage to all life-forms, including humans. Among other reasons not to choose nuclear power, the EROI is only about 5 [124] and it is not 'low-carbon'. [125] Moreover, the EROI would fall, and the GHG footprint rise, as uranium ore is depleted and the grade declines. [126]

The latest roadmap for the ITER fusion power project suggests demonstration only by 2050. [127] So even if it worked and was affordable, the deployment of fusion power would be too late to mitigate climate change. Also, such projects incur huge opportunity costs. As well as the money and energy outlays, the many able scientists and engineers involved would be far better employed meeting the climate targets by other – proven – measures. So all fusion projects should cease and the people and money used for deployment of proven GHG reduction measures (See above Energy Services and more).

Like France, the UK should not approve any more carbon and hydrocarbon extraction on it's own territory – as an example to other countries. [128] Indeed, existing permits may have to be revoked. However, they could be replaced by permits to invest in indigenous renewable energy, such as wind and solar and synthetic fuels and chemicals made therefrom via PtG/PtL/PtX. For example, the UK has a vast wind power resource that may be harnessed by turbines onshore and offshore, including floating.

The UK must forego all policy options that are counter-productive or even unhelpful for meeting the climate targets. The main priorities must be food and shelter. This requires doubling, from under 50%, of the food produced within the UK. (See above Adjustment of the UK Carbon Budget - for Food Security).

The Role of Research

Much advice to government – especially from academe – is for more research. This includes 'The Faraday Challenge: advice from Sir Mark Walport, 2017-03-03'. [129] This is often taken as an excuse for further delay. Also the UK has persistently failed to bridge the gap between science and industry. This is unlike Germany, with the Fraunhofer Institutes (some 69), the USA, with the 'national labs', and Denmark, with the Danish Technical University. (See below From Science to Industry).

Action on climate change is needed now, and can go ahead by deploying measures that are well-proven abroad, such as DH-CHP and PH. These are 'no-regrets' measures since physics and thermodynamics show that nothing energetically superior is possible. So the UK requirement is largely the manufacture and deployment of proven technology, often from abroad. This could be by Foreign Direct Investment or by UK companies licensing the IPR and technology. The latter assumes that they can raise capital for such investments for manufacture. (See below Investment Capital). Experience on the Continent suggests that national and local governments should have no difficulty raising capital for the deployment of such measures.

From Science to Industry

The Faraday Challenge advice talks of a 'new way of working'. Yet Germany has the Fraunhofer Gesellschaft (now of some 69 institutes) dating from 1949. [130] This complements the Kaiser Wilhelm Institutes (later the Max Planck Institutes), dating from 1911. [131] [132] These inspired the the founding of the UK Department of Scientific and Industrial Research in 1923 [133] and numerous Research Associations of the 1920s-1940s. [134] However, public funding was gradually withdrawn and they were privatised and/or withered away in the 1980s.

The above link includes: '11. Bodies both inside and outside of Parliament have been concerned about innovation and the transfer of science for the benefit of the UK economy and society for a number of years—for example, our predecessor Committee published a report in 1994, The routes through which the science base is translated into innovative and competitive technology.[10] The UK began to explore an equivalent to the German Fraunhofer model with Faraday Partnerships in the 1990s. This initiative suffered from poor support from industry,[11] a "piecemeal approach" and a "variety of governance models".[12] '. 'Bodies both inside and outside of Parliament … for a number of years' is jaw-dropping understatement. It would be more honest to refer to the Lyon Playfair report of 1852 - the year after the Great Exhibition. [135] There were about a dozen in all, but very little effective action [136] - as shown by the above and the Faraday Challenge proposal. [137]

Investment Capital
Another persistent weakness in the UK is the lack of investment capital at competitive rates.
'In the real world most credit today is spent to buy assets already in place, not to create new productive capacity. Some 80 percent of bank loans in the English-speaking world are real estate mortgages, and much of the balance is lent against stocks and bonds already issued. Banks lend to buyers of real estate, corporate raiders, ambitious financial empire-builders, and to management for debt-leveraged buyouts. A first approximation of this trend is to chart the share of bank lending that goes to the 'Fire, Insurance and Real Estate' sector, aka the nonbank financial sector. Graph 1 shows that its ratio to GDP has quadrupled since the 1950s. The contrast is with lending to the real sector, which has remained about constant relative to GDP'. [138]
Yet Germany has many major and minor banks that lend for good quality industrial investments. The USA has many venture capitalists and billionaires, such as those that funded Tesla in its early years. Danish pension funds make diligent investments, notably in wind power. But the UK relies on Private Finance Initiatives, with very high interest rates, or Foreign Direct Investments. Examples of the latter are those of Siemens Gamesa and DONG of Denmark (now Oersted) in wind turbines and the Faraday Challenge proposal involving a Tier 1 battery company. [139] [140] [141]

Divestment from Fossil Fuels - Cambridge
Divestment from fossil fuels by Cambridge University was proposed by the Cambridge Zero Carbon Society (comprised of many students and some 100 academics) in 2016 [142] [143], but rejected by the University. [144] It was proposed again in 2018 [145], but again rejected by the University, which receives significant funding from fossil fuel interests including BP. [146] But the University is under increasing pressure on the issue. [147] This includes: '...350 academics including Professor Sir David King, who was Britain's Special Representative for Climate Change after his stint as the government's Chief Scientific Advisor, and Professor Sir Thomas Blundell, the former president of the UK Science Council, wrote an open letter to Cambridge'.

Cambridge Departments that could contribute to the advice
University research collaborations whose work is directly impacted by climate change include:
a) The Cambridge Centre for Climate, Energy (C-EENERG),
b) The Cambridge Centre for Climate Change Mitigation and Research (4MCR),
c) Cambridge Institute for Sustainable Leadership (CISL),
d) The Energy Policy Research Group (at the Judge Business School) (EPRG),
e) The Cambridge Conservation Initiative (CCI).
(See 'Fossil Fuel Divestment at the University of Cambridge' [148] page 33).

In the Department of Engineering, Professor Julian Allwood works on sustainable materials and the scope for saving energy. Cambridge also hosts the Winton Programme for the Physics of Sustainability. This is endowed with £ 20 million.

The 2017 book 'Global Carbon Pricing: The Path to Climate Cooperation', was co-authored by Sir David MacKay (deceased), formerly at the Cavendish Laboratory. [149] This describes a policy approach for 'public goods' that has been shown to work – by Elinor Ostrom and others.

Sir David King, former Chief Scientist, is Emeritus Professor in Physical Chemistry at Cambridge. He now advocates 'climate restoration', including the 'rollback' of CO2 to 350 ppm. [150]

Conclusions
Compared with other UK universities offering climate and energy advice to government, Cambridge University has departments – including Ocean Physics (including polar ice), Agriculture, Engineering and Ecology – covering most known GHG reduction measures. Cambridge has much to offer on reducing energy use and increasing energy conversion efficiency, including in buildings, transport and industry. As the CCC has noted, these have made little or no progress in the UK. Cambridge also hosts the Cambridge Institute for Sustainability Leadership and the Winton Programme for the Physics of Sustainability. It also has long experience of collaboration with other institutions. Cambridge is therefore able to offer advice based on a very wide range of evidence. It should also be able to attract more funding. Such an initiative could be built around modelling based on the SET model of Sgouridis et al.

Gordon Taylor B.Sc., M.Sc., M.I.Mech.E.
G T Systems
19 The Vale, Stock, Ingatestone, Essex, CM4 9PW, U.K.
Tel: +44(0)1277 840569
Mob: 07434163526
Email: gordon@energypolicy.co.uk
Web: http://cms.energypolicy.co.uk/

Glossary

BEV – Battery Electric Vehicle
BECCS - Biomass Energy and Carbon Capture and Sequestration
CCC – (UK) Committee on Climate Change
CCS – Carbon Capture and Sequestration
CDR – Carbon Dioxide Removal
CHP – Combined Heat and Power
DC – District Cooling
DH – District Heating
DHC – District Heating and Cooling
EJ – Exajoule = 10^{18} Joules = 1 billion billion Joules
EROI – Energy Return on (Energy) Invested
$EROI_{nat}$ – Energy Return on (Energy) Invested, national basis
ESCO – Energy Service Company (selling both energy supply and energy-saving measures as services)
FAO – Food and Agriculture Organization (of the UN)
GHG – Greenhouse Gas
GLS – General Lighting Service (here incandescent)
Gt – Gigatonne = 10^{9} tonnes – 1 billion tonnes
GtP – Gas-to-Power (usually Gas Turbine Combined Cycle plants, here CHP)
ICEV – Internal Combustion Engine Vehicle
IPCC – International Panel on Climate Change
IPCC AR5 – IPCC Assessment Report 5
IPR – Intellectual Property Rights (patents etc)
ITER - International Thermonuclear Experimental Reactor
LED – Light Emitting Diode
Primary Energy – Original fuel energy, as opposed to e.g. electricity from a thermal power station
PH – Passive House
PtG – Power to Gas (here methane)
PtL – Power to Liquids (synthetic hydrocarbon fuels)
PtX – PtG, PtL, Power to Heat, and Power to Chemicals (feedstocks)
RE – Renewable Energy
TW – Terawatt = 10^{12} Watts = 1 million million Watts
UNFCCC - UN Framework Convention on Climate Change

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