Energy efficiency in the energy transition

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Abstract
The energy transition to a zero carbon energy system will require both a shift to renewable energy and a major increase in energy efficiency. These are usually treated separately, but are not independent. Where renewable electricity replaces other fuels in heat and transport, there is a fundamental shift in energy supply from sources of heat to sources of work. This allows technologies such as heat pumps and electric vehicles to deliver large improvements in energy efficiency. Where new energy vectors such as hydrogen are required, there are more complex implications for energy efficiency, depending on the details of the energy conversion processes. The paper sets out a scenario for the UK where energy is provided solely by solar and wind energy. It makes plausible assumptions about which end uses of energy can be supplied directly by electricity, and assumes others will be supplied by electrolytic hydrogen. It shows that reductions of final energy demand by 50 % and primary energy demand by 60 % from current levels. The main driver is the improvement in conversion efficiencies at the point of energy use. This has major implications for the levels of renewable energy needed, which could be supplied entirely by UK indigenous resources. These types of changes to energy demand not fully captured by many global energy models and scenarios used to inform climate policy. They may therefore be unreliable and significantly over-estimating likely energy demand. The findings have important implications for policymakers in terms of lower and more realistic expectations of future energy demand.

Introduction
Most analysis of the potential for energy efficiency focusses on relatively short term change, with incremental improvements. This is understandable. At the level of the individual household and business, interest in energy efficiency, whether for cost or environmental reasons, lies principally with what can achieved in the short term. Globally, improvements in energy efficiency have been the key driver of reductions in energy intensity, which have averaged ~1 % annually in recent decades. In Europe, progress has been somewhat faster with reduction averaging 3 % in many countries.

Much analysis of the potential for energy efficiency produces numbers such as 20–30 %. This is generally because the focus is restricted to cost effective potential and medium term options. The ultimate potential is much larger, in the region of 85 % (Cullen and Allwood, 2010; Cullen et al 2011). This insight coupled with technological improvement is why the medium term cost effective potential remains significant, even when efficiency is improved (NAS, 2010; Lucon et al, 2014)

Thinking about the role of energy efficiency in the low carbon transition is often conditioned by this focus on incremental change. When radical change is considered, most attention focusses on decarbonising supply. In the global models assessed by the IPCC (IPCC, 2014), efficiency improvement tends to be seen as an important, but secondary contributor, see Figure 1.

In essence, it is suggested that energy efficiency improvement will continue to improve in line with historic trends, or with a medium term boost, whilst energy supply goes through a major, longer-term transition. Energy efficiency improvement is implicitly treated as distinct from supply side change. This paper argues that such an approach is fundamentally flawed and that energy efficiency is very likely to change significantly more than has been suggested in the context of such fundamental supply side change.

In the context of the energy transition, the usual question that is asked about energy efficiency is "what will be the contribution of energy efficiency to the transition?" This paper reverses that logic. It asks "what will be the impact of the transition on energy efficiency?"

The next section sets out some of the fundamental structural issues of energy systems that influence system efficiency and argues that the low carbon transition has major implications for overall system thermodynamics. The third section of the paper sets out a relatively simple case study: a stylised scenario for the UK, considering the implications a 100 % renewable energy system for energy demand and efficiency. This is followed by a discussion of the global models that underpin much climate analysis and why they seem not to capture the dynamics fund in the case study. The final sections discuss the implications and draw conclusions.

Energy, heat and work in the low carbon transition

Energy flows through any system are frequently represented by a Sankey diagram (Sankey, 1898). For a whole energy system (e.g. a country or the entire world). Conventionally energy sources are represented on the left, with energy uses on the intermediating conversion processes in between.

Sankey diagrams are usually quantitative, with the scale of flows proportional to arrow width. Figure 2 is a simpler qualitative representation of an energy system, useful for thinking about its more fundamental aspects.

Most representations of the low carbon transition differentiate between high carbon (fossil fuel) and other energy sources. Figure 2 instead distinguishes between heat and work, as this difference is critical to understanding the thermodynamics of energy transitions.

The ultimate end uses of energy, energy services, tend to fall naturally into these categories: some being essentially delivered by heating (raising the temperature of something), others by another form of energy (e.g. mechanical or electrical). Of course, there are some complexities, for example artificial light was historically produced through heating an emitter, with efficiency improved by increasing the temperature, but is increasingly delivered by direct conversion of electricity in an LED. But generally, there is distinction between services that use work and those that use heat.

Energy sources can be similarly divided. Fossil fuels and nuclear fission produce heat, as do some renewables such as biomass and geothermal. Other renewables produce other forms of energy (work). Again there is some complexity, for example solar energy may be used to produce either heat or electricity, but the overall broad distinction is useful. In general, it is thermodynamically preferred to minimise energy conversion processes, and therefore to use heating fuels for heating and work producing renewables for work.

In pre-industrial societies, heat and work systems were largely separate. Heat for was cooking, hot water, thermal comfort and metal production. And it was produced largely from burning wood. Work was either done by humans themselves or domesticated animals (essentially using food), supplemented by direct use of hydropower and windpower for services like grinding corn.

In post-industrial revolution economies, energy use has multiplied many-fold and fossil fuels have become the main source of energy. As a result, the flows shown by the red arrows in Figure 2 have become dominant. Fuels are refined and then burnt to produce heating. But, as the importance of energy services requiring transportation, stationary power and electrical appliances, have grown, fossil fuels have increasingly also been used to do work. Initially this was through the great breakthrough of the early industrial revolution that allowed heat to be converted to work, the steam engine. Over the last century heat to work conversion has become dominated by two sets of technology. The first is the internal combustion engine, providing motive power from a heat engine

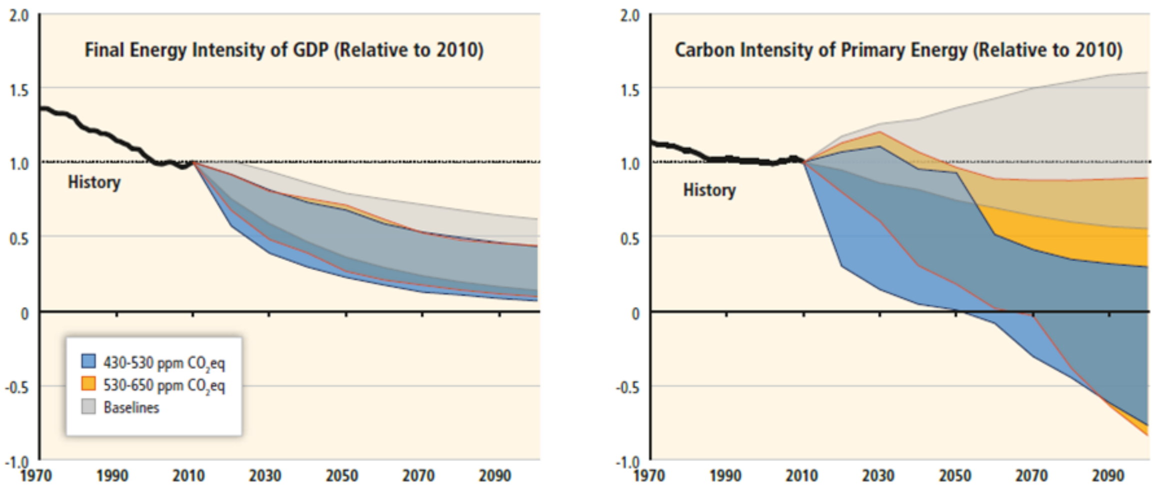


Figure 1. Contributions to global decarbonisation from energy and carbon intensity change for various carbon dioxide scenarios (IPCC, 2014).

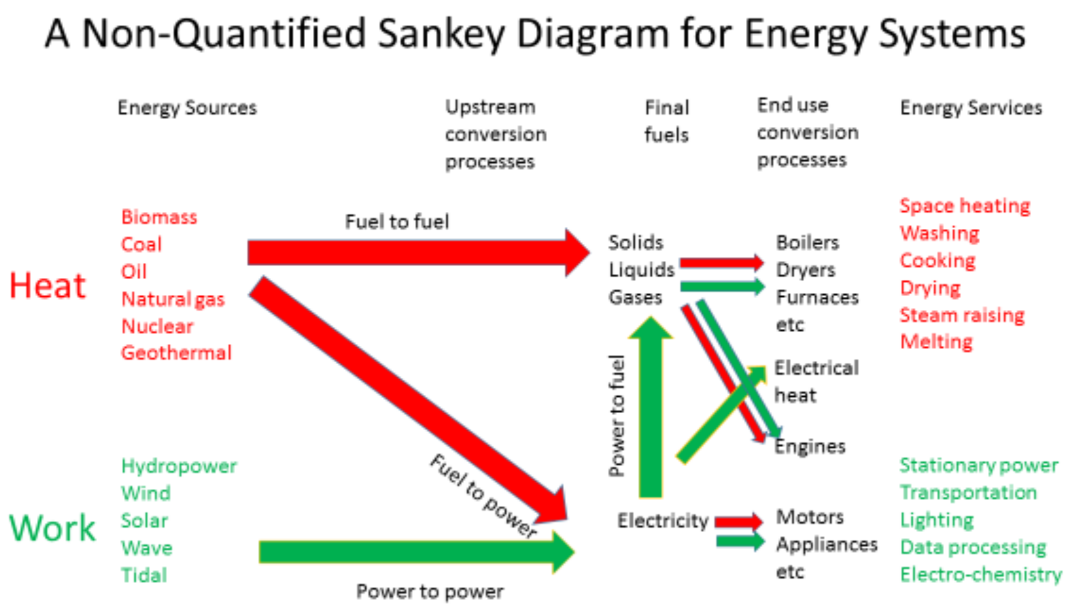


Figure 2. A qualitative and simplified Sankey diagram of an economy wide energy system.

from fuels (usually liquid) at the point of end use. The second also involves heat engines, in the form of steam and gas turbines, and then involves the conversion of mechanical energy into electricity for transmission to the final point of use where it is converted back to mechanical energy and other energy services.

The change to a low carbon energy system disrupts the trajectory of energy systems development more fundamentally than any change since the industrial revolution. It is now clear that the cheapest forms of low carbon electricity will be renewable rather than nuclear and/or fossil fuels with carbon capture and storage (CCS) (IRENA, 2016). The initial effects are already being seen with the displacement of fossil fuels from electricity generation by renewables. Followed through, and with adequate storage to address renewable variability, this can transition electricity to zero carbon.

But this is only the first step to a zero carbon energy system. It needs to be followed by the substitution of fossil derived fuels elsewhere in the energy system, i.e. for heating, transport and industrial processes. The details will depend on the renewables used for this substitution, in particular the availability of the heat producing renewables – biomass and geothermal. In much of the densely populated industrial areas of the world it seems likely that bioenergy will be constrained. Flows of energy will then be dominated by the green arrows in Figure 2, with electricity the dominant vector.

The growth of the role of electricity is widely seen in low carbon energy scenarios (IPCC, 2014). And the enhanced role of electricity produced without combustion has been widely commented upon (e.g. Lovins, 2013; Patterson, 2014). What is less commented on is the shift implied between heat and work. In this new system, the conversion processes required upstream are the opposite of those that have dominated industrial energy systems: the challenge will no longer be to convert heat into work, but to use the energy sources that produce work to supply most of our energy, including heat.

The exact routes and timing of the change are uncertain and likely to be geographically variable. What is clear is that end uses of energy currently supplied by fuels (as opposed to electricity) will need to be converted to electricity, to new zero carbon fuels, or at least to similar fuels produced in a different (zero carbon) manner.

This has multiple implications for energy efficiency.

- First, already underway, is that the inefficiency of fossil fuelled power generation (where done without cogeneration) will be largely eliminated.
- Second is that end uses of energy requiring work are more likely to be supplied by electric motors, with a typical efficiency of 85–90 %, than by heat engines, with a typical efficiency of 20–40 %. The most obvious example, already beginning to happen in stages, is the electric vehicle replacing the internal combustion engine vehicle.
- Third is the substitution of heat from fossil fuels by electricity. This almost always is accompanied by an efficiency gain, although the extent of this is case specific. The potential is highest for 'low temperature' applications such as space heating and domestic hot water. Fossil fuel boilers have typical efficiencies of 80–90 %, but electric heat pumps can achieve efficiencies of 300 %. (The meaning and interpretation of these anti-intuitive efficiencies exceeding 100 % is explored in the discussion section below). Higher temperature applications, such as many industrial processes, are not amenable to this scale of gain.
- Fourth is the substitution of fossil fuels by other fuels than electricity. With current technology, electrification is not a practicable option in some end uses, notably for aviation, shipping and some industrial processes. Nor is it likely to be economic for the whole of space heating in many places. In these cases, alternative fuels may be need to be manufactured using electricity. The most obvious option is hydro-

gen. This has potential efficiency benefits at the point of use, but any additional conversion process has energy losses, and the efficiency of electrolysis is ~80 % (Doods et al, 2015). Further conversion is possible to other options than may be more convenient to store than hydrogen, but inevitably incurs further losses.

The first three effects have an unambiguously positive impact on energy efficiency, some of it far exceeding that envisaged in 'business as usual' scenarios for energy demand. The fourth effect is more complex. The scale of the combined effect is investigated for a specific case study in the next section.

A 100 % Renewable UK Case Study

The implications of switching to a pattern of demand consistent with very high use of energy from renewable sources that produce work are explored in a scenario for the UK supplied entirely from wind and solar. It should be noted that this is not intended to be a policy proposal. The UK has other sources of indigenous renewables, including hydropower and biomass. However, these are somewhat limited, compared to the solar and wind resources. And, of course, a zero carbon energy system can be achieved in other ways than relying 100 % on renewables, by utilising either CCS or nuclear energy. However, it is clear that wind and solar are currently both significantly cheaper than competing options. So a future energy system that is dependent entirely on wind and solar is unlikely, but one that is dependent predominantly on these resources seems very likely.

For the purposes of developing a transparent scenario of demand, it is necessary to make some simplifying assumptions. It is assumed that demand changes from the current pattern in a manner that is dependent only on three factors: first, general efficiency improvements and conservation independent of the low carbon transition; secondly, conversion to electricity and/or hydrogen; and thirdly, efficiency changes that result from this conversion. The precise quantitative changes assumed are set out in the appendix and discussed briefly in the following paragraphs.

General efficiency improvements, conservation impacts and increases in service demands are assumed to follow trends of the last decade, which have resulted in reductions in demand, even against a background of a growing population and economic growth. For most end uses, it is assumed that demand falls 20 % by 2050 (i.e. about 0.5 % annually) as a result of these changes. There are exceptions. On the one hand, demand for cooling and computing are projected to double and triple respectively, reflecting expected trends in growth in demands for these services. On the other hand, larger efficiency improvements are projected in end uses where inefficiency remains most obvious; 33 % for light vehicles and 50 % for space heating and appliances. Overall, these are more modest changes than many proponents of efficiency would suggest are achievable and significantly lower than in some recent scenarios (e.g. Grubler et al, 2018). Relatively conservative assumptions are used here to avoid these changes obscuring the effects of the transition that is the main focus of the paper.

It is assumed that all energy at the point of use is derived from electricity directly or from hydrogen generated by electrolysis. Most analysis has assumed that hydrogen may be cheaper to manufacture from natural gas with CCS (e.g. CCC, 2016), but electrolysis becomes more attractive as the share of variable renewables rises in electricity generation (Philibert, 2017). Other zero carbon fuels are possible and arguably preferable in some uses, but more complex assumptions would again risk obscuring the main goal of the analysis.

Conversion to electricity is assumed to allow for significant improvement in efficiency; by a factor of three for water heating (using heat pumps), a 25 % improvement in industrial drying (using higher temperature heat pumps), and a factor of three for cars and other light vehicles (electric vehicles).

Electricity is assumed to be used for all end uses with the exception of those demands that are difficult to electrify: space heating, industrial processes, heavy vehicles, shipping and aviation. In these cases, it is assumed hydrogen is used, generated from electricity with 80 % efficiency. The transport demands are assumed to converted entirely to hydrogen. In heavy road vehicles the loss of efficiency through electrolysis is assumed to be more than offset by the use of more efficient conversion in the vehicle. Industrial process demands are envisaged to convert to a 50:50 mixture of electricity and hydrogen, with no impact on overall efficiency.

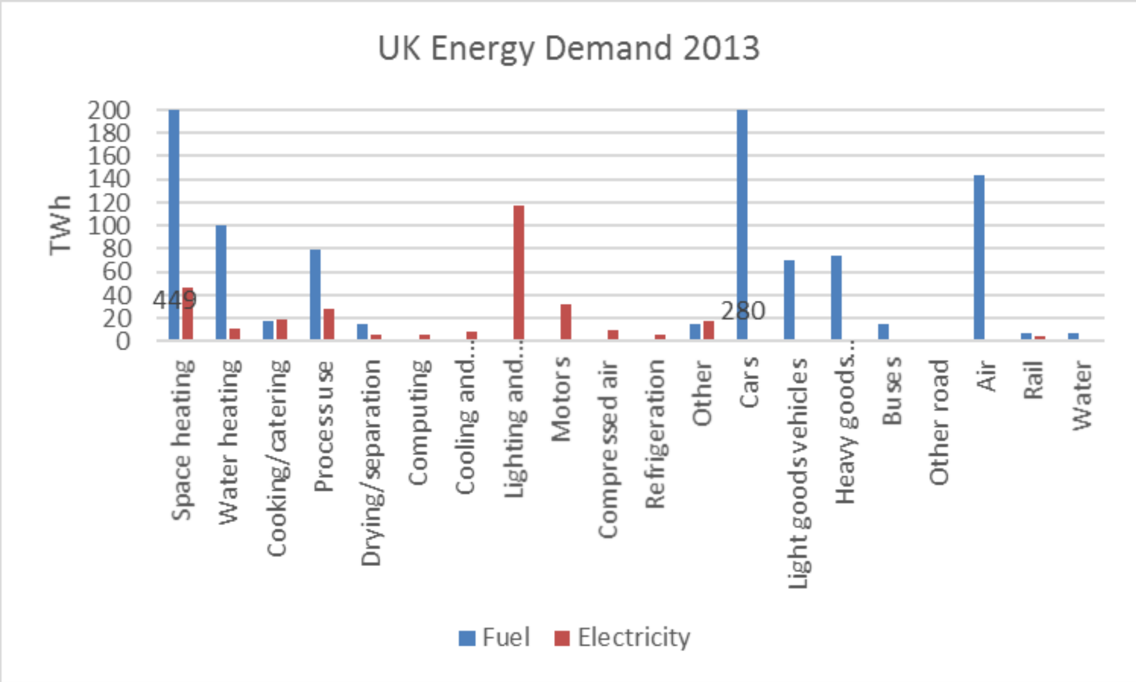
Space heating is assumed to derive all of its energy from hydrogen, in order to avoid a large increase in peak demand on the electricity system, which is potentially a serious issue in decarbonised heating (Eyre and Baruah, 2015). However, this achieved through a mixture of high efficiency hydrogen CHP (fuel cells) and electric heat pumps, with the output of the former matching the input to the latter, which is known to be an efficient system solution (Cooper et al, 2013). Making reasonable assumptions about fuel cell and heat pump efficiencies it allows electricity, via electrolytic hydrogen, to be used at approximately 150 % efficiency for space heating.

The overall impact of these changes is shown in Figure 3 using data set out in the Appendix.

The overall impact is to reduce final energy demand by approximately 50 %. The majority of the effect (32 %) is due to the assumed changes in conversion efficiency, with a smaller impact from business as usual efficiency and conservation. This is in addition to the reduction in primary energy demand achieved by eliminating the heat losses in thermal power generation, which are currently ~20 % of primary energy use. The total impact on primary energy demand is therefore a 60 % reduction.

The implications for energy supply are very significant. Current UK final energy use is ~1,600 TWh/year, but this does not need to be replicated in decarbonised energy required to move to a zero carbon system. In fact only ~800 TWh/year will be needed. This is a factor 5 less than the demand assumed in early work that purported to show a 100 % renewable UK was infeasible (MacKay, 2015), and which has been very influential in the UK. Making the (arbitrary) assumption that this will from a 50:50 wind solar mix, at typical UK load factors it would require approximately 120 GW of wind and 400 GW of solar. These would be significant investments by any standards, but could easily be accommodated physically even in a densely populated country like the UK.

More challenging are the assumptions about decarbonised fuels, in this case hydrogen, of which it assumed that ~400 TWh is required, largely for space heating, aviation, industrial pro-



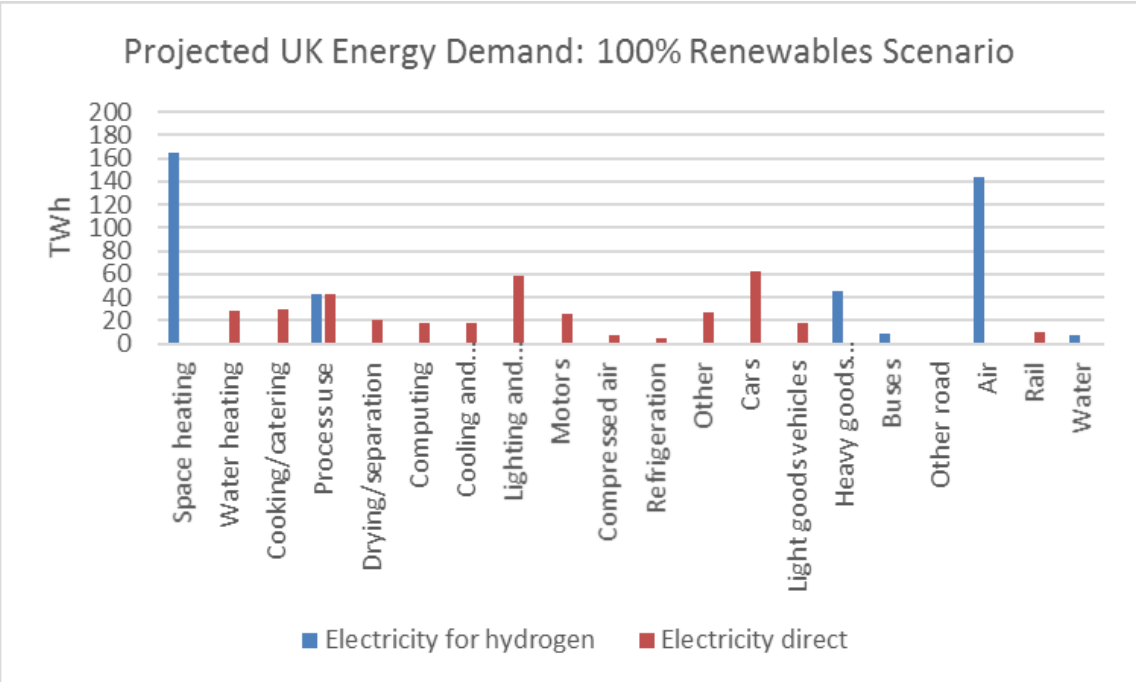


Figure 3. Energy use by fuel type in the UK. Comparing 2013 actual data with the 100% Renewable Scenario.

cesses and heavy goods vehicles. This would require in excess of 80 GW of electrolyser capacity, assuming that batteries could balance diurnal loads.

In the scenario set out here, demand would be significantly winter peaked, due to space heating demand; whereas supply would be summer peaked due to the use of solar. The implied inter-seasonal storage is ~130 TWh (Eyre, 2019). One benefit of such a significant role for hydrogen (or other easily storable fuel) would be that it helps to address the gap in long term energy storage left by eliminating the role of fossil fuels. The inter-seasonal storage demand might be reduced by changing the balance of wind and solar resource used, but the need for significant new inter-seasonal storage capacity seems to be an almost inevitable outcome of a zero-fossil fuel system in a climate with significant space heating demand.

The results set out above depend on the choices being made for energy conversion technologies at the point of energy use. In this scenario, it is assumed that:

- electric vehicles are the dominant technology for cars and light goods vehicles,
- heat pumps are used for the provision of low temperature heat from electricity, and
- hydrogen conversion uses fuel cells, for both CHP in buildings and motive power in heavy vehicles.

These are the high efficiency options. Clearly, none of them is inevitable. The analysis above avoids the human factors known to be critical in energy efficiency. They are implicitly included in 'business as usual' demand change, but not elsewhere. This is acknowledged as a weakness of this paper and points to the need for a more detailed analysis of the socio-technical issues involved in transitioning from low efficiency to high efficiency conversion. If this is not done there are potential risks. Incumbent manufacturers might be quite happy to see the continuation of electric resistance heaters for space and water heating and conventional low temperature industrial processes. And some potential new technologies focus on low efficiency options such as synthetic carbonaceous liquid fuels for vehicles and hydrogen boilers. 'Efficiency first' will matter at least as much in the context of changes driven the energy transition as in existing systems.

Treatment of conversion efficiencies in global carbon models

There are concerns that the integrated assessment models that have historically dominated assessment of climate policies are flawed in their treatment of both efficiency generally and the conversion gains identified above in particular. A review of the literature for the buildings sector, in the context of the last IPCC mitigation report (Lucon et al, 2014), identified that integrated assessment models systematically under-estimate the potential for efficiency improvement when compared to more technically detailed sectoral models. Despite this, the integrated assessment model findings tend to be widely quoted as IPCC findings.

A comprehensive analysis of the treatment of these issues in energy modelling is outside the scope of this paper. However, preliminary analysis indicates potentially severe problems. For example, outputs from the POLES model that is widely used by the European Commission indicate that the efficiency gains identified above that are likely to arise from decarbonisation are not fully captured by this model. Figure 4 sets out the trends in final energy final energy use and carbon emissions trends in an ambitious decarbonisation scenario. To maximise consistency with the UK analysis above, data chosen is for the OECD countries and a scenario with high efficiency gains, and no use of nuclear or CCS. Carbon emissions fall rapidly: ~60 %, ~80 % and ~90 % by the years 2030, 2050 and 2100 respectively. Final energy use also falls rapidly initially by ~30 % by 2030, but thereafter improves little. This is entirely inconsistent with the analysis above, where the gains in efficiency due to improved conversion efficiencies would be expected in the later stages of the energy transition.

Similar concerns apply to other well-known energy scenarios. For example, in the Shell Sky scenario (Shell 2019), which designed to be consistent with meeting a global 1.5 °C target, final energy use in Europe falls by less than 10 % by 2050. Most implausibly, given the analysis above, final energy use rises in both road transport and residential heating, where the potential conversion efficiency gains is most significant.

It is clear that more research is needed on the treatment of end use conversion efficiencies in at least some global models. At best, there are some unexplained discrepancies with would be expected from the thermodynamic and technical arguments set out above. At worst, the models that are widely used to inform global climate policy are fundamentally flawed and not fit for purpose in addressing an energy transition in which the roles or work and heat are radically changed.

Discussion

The potential for conversion efficiency gains arises because of the shift in the dominant energy sources expected in the energy transition from those that produce heat to those that produce

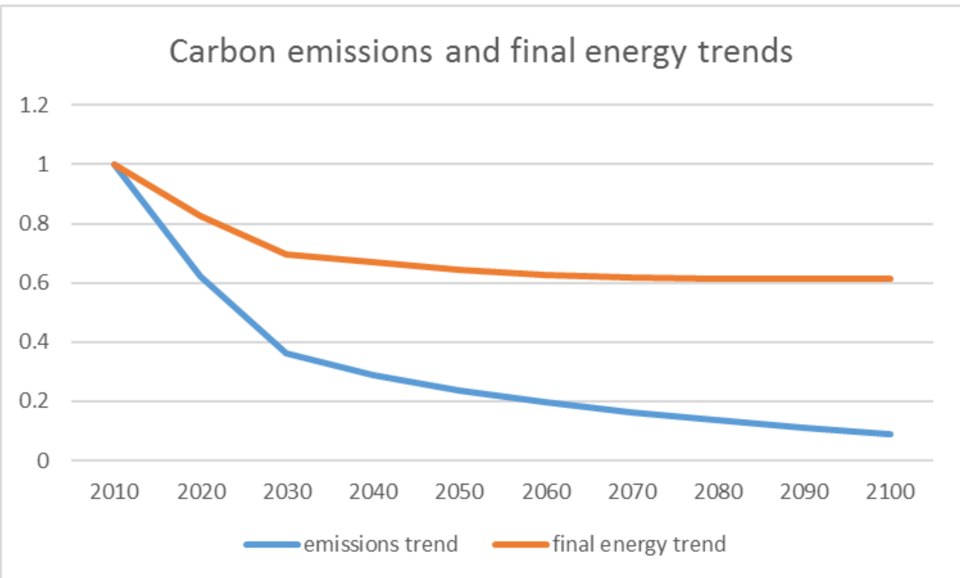


Figure 4. Example global model output of final energy and carbon emissions trends for an ambitious decarbonisation scenario. POLES model run for OECD, EMF 27 comparison exercise, EERE variant. Author calculations with data IPCC scenario data downloaded from http://www.iiasa.ac.at/web/home/research/researchPrograms/Energy/IPCC_AR5_Database.html.

work. In most energy systems that have existed since the industrial revolution it has been necessary to convert heat to work, with significant energy losses, some of them unavoidable. In expected future energy systems, the main conversions will be from electricity to work, with high efficiency, and work to heat, where efficiencies exceeding unity are possible.

In essence, the conversion efficiency potential gains are a simple result of the fact that the second law of thermodynamics allow greater efficiencies in conversion of work to heat that *vice versa*. An alternative exposition of the same argument is that 'energy' is a misleading metric, with which to cover both work and heat (and heat at different temperatures). An alternative would be to use 'exergy' (Dincer and Rosen, 2012). In a set of exergy statistics, the numerical values associated with heat and fuels would be lower than their energy equivalents. The heat related components of a Sankey diagram would shrink. This would allow machines such as turbines and engines to have theoretical (but not practical) efficiencies of 100 %. And heat pumps efficiencies would be unable to exceed 100 %, as ambient heat has no exergy. In the absence of a shift to exergy as a metric, existing energy metrics will have to be used, but the implications are that efficiency gains and demand reductions (measured as energy) seem very likely.

In the longer term, energy statistics do need to be reconsidered. Current choices of what is measured become more obviously problematic as the use of renewable energy increases. In European climates, most buildings gain ~25 % of their useful heat and a greater fraction of their light from ambient, largely through windows. This is not recorded in energy statistics, for the understandable reason that it is not measured. And it is not measured because it is not traded. Similarly, the energy inputs to wind turbines and solar panels are not measured, with the unintended effect that only the output is known. Actual renewable energy conversion efficiencies and losses are therefore not recorded. Indeed, with some minor exceptions, energy statistics are essentially a measure only of energy that is bought and sold. As the use of (free) renewable energy increase, this may become increasingly problematic.

Conclusions

The relationship between improved energy efficiency and the low carbon energy transition is usually conceptualised as the former having a significant impact in delivering the latter. However, there are significant feedbacks due to the fundamental re-shaping of energy systems implicit in the transition. In particular, 'work producing' renewables are substituting for 'heat producing' fossil fuels. Initially, the impact is a reduction in (thermal) losses from power generation. However, as the transition proceeds, 'work producing' renewables will substitute for other end uses, probably either via electricity or fuels produced from electricity. The type and scale of energy conversion processes therefore changes radically. In particular, conversion of 'electricity to heat' and 'electricity to fuel' become important, with significant changes in conversion efficiencies in both the upstream energy sector and across a wide range of energy uses.

The scale of this effect has not been adequately identified in the literature. The paper has developed a simple illustrative scenario for the UK, in which all energy is generated from wind turbines and solar photovoltaics, and final energy is delivered either as electricity or electrolytic hydrogen, depending on what is plausible for each end use. The impact of changes in energy conversion at the point of use is predominantly positive and very significant. It is estimated to reduce UK final energy demand by ~32 %. Coupled with ongoing improvements in other sources of energy efficiency, it is estimated that this could reduce UK final energy demand by 50 %. This is additional to the system efficiency benefits of eliminating thermal power generation. The estimated impact on primary energy demand is therefore a 60 % reduction from current levels.

These changes are well-captured by many global energy and climate models and scenarios, which do not show reductions on demand consistent with the expected effects of conversion efficiency improvements. There is a need for careful analysis of energy demand modelling of the low carbon transition, in particular to ensure that models take account of the likely benefits of moving to an energy system dominated by the production of work. There is a risk that many influential models are fundamentally flawed in addressing the energy transition.

There are important implications for policy. Analytical techniques need to be fit for purpose, and this can only be achieved by recognising that the transition involves some fundamental structural changes. To the extent that existing models are flawed, policymakers expectations of the shape and scale of future energy systems need to be recalibrated. Energy demand in Europe will continue to fall, as the potential for efficiency will not 'run out', but rather will be reinforced by the transition. Efficient conversion technologies, such as electrolysers, hydrogen storage, fuel cells, heat pumps and electric vehicles, will be critical and need to be prioritised. The temptation to retain inefficient options (boilers, resistance heaters, internal combustion engines) that are inconsistent with a 'work driven' system needs to be avoided.

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Appendix

Table 1. Assumptions and calculated energy demand for the zero carbon UK scenario.

	2013 actual demand (TWh)			2050 changes assumptions (%)			2050 projected demand (TWh)		
End Use	Fuel	Elec	Total	Demand reduction	H_2 share	Conversion efficiency	Elec direct	Elec for H_2	Total
Space heating	449	47	495	50 %	100 %	67 %	0	165	165
Water heating	101	11	112	80 %	0 %	32 %	29	0	29
Cooking/catering	17	19	36	80 %	0 %	100 %	29	0	29
Process use	79	28	107	80 %	50 %	125 %	43	43	85
Drying/separation	15	6	21	80 %	0 %	125 %	21	0	21
Computing	0	6	6	300 %	0 %	100 %	18	0	18
Cooling and ventilation	0	9	9	200 %	0 %	100 %	18	0	18
Lighting and appliances	0	118	118	50 %	0 %	100 %	59	0	59
Motors	0	32	32	80 %	0 %	100 %	26	0	26
Compressed air	0	9	9	80 %	0 %	100 %	7	0	7
Refrigeration	0	6	6	80 %	0 %	100 %	4	0	4
Other	16	18	33	80 %	0 %	100 %	27	0	27
Cars	280	0	280	67 %	0 %	33 %	62	0	62
Light goods vehicles	70	0	70	80 %	0 %	33 %	18	0	18
Heavy goods vehicles	75	0	75	80 %	100 %	75 %	0	45	45
Buses	15	0	15	80 %	100 %	75 %	0	9	9
Other road	2	0	2	80 %	0 %	50 %	1	0	1
Air	143	0	143	80 %	100 %	125 %	0	143	143
Rail	8	4	12	80 %	0 %	100 %	10	0	10
Water	8	0	8	80 %	100 %	125 %	0	8	8
Total	**1,277**	**312**	**1,589**	**0 %**	**0 %**	**0 %**	**371**	**413**	**784**