



# From using heat to using work: reconceptualising the zero carbon energy transition

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**Abstract** Recent evidence indicates that the key sources of energy for the zero carbon transition will be renewable electricity sources. The most rapidly expanding sources, photovoltaics and wind produce work, as electricity, directly rather than via heat engines. Making the assumption that these will be the dominant sources of energy in a future zero carbon system, the paper makes two new related and innovative contributions to the literature on the energy transition. First, it shows that the energy transition will be more than just a shift away from carbonaceous fuels, and that it is more usefully thought of as including a systemic shift from heat-producing to work-producing energy sources. Secondly, it shows that this enables very large improvements in the conversion efficiency of final energy, through the use of electricity and hydrogen, in particular in heating and transportation. The paper presents a thought experiment showing a reduction in final energy demand of up to 40% is likely from this effect alone. Technical standards and product regulation for end use conversion efficiency and/or service delivery efficiency seem likely to be key policy instruments.

**Keywords** Energy transition · Thermodynamics · Energy efficiency · Final energy

## Introduction

The goals set out in the Paris Agreement almost certainly require the global energy system to move to close to zero emissions, as other emission sources may be harder to abate (Masson-Delmotte et al., 2018). This transition is normally thought of as a shift from carbon-based fuels to zero carbon fuels. This is understandable, but not an adequate approach to understanding a systemic transition. Not only will primary energy sources change, so also will the ways that they are converted and used. In particular, the direct use of fossil fuels in buildings, transport and industry will need to end, and this has significant implications for the types of final energy used and the efficiency of both upstream and downstream conversion processes.

There is an increasing consensus that the lowest cost sources of zero carbon energy will be renewable electricity sources (RES), and that bioenergy, solar photovoltaics (PV), wind energy and hydroelectricity are likely to be particularly important (Grübler et al., 2018; Gielen et al., 2019). With the exception of biomass, these generate electricity directly rather than via combustion and heat engines. Hydropower has been an important source of electricity in favourable geographies for over a century and provides 16%

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of global electricity (IEA, 2020a). The economics of PV and wind have been transformed in less than a decade, with typical generation costs falling by 82% and 39% respectively in the decade to 2019 (IRENA, 2020a).

There is therefore increasing evidence that global energy will rely on RES. They will initially substitute for other, largely fossil fuel, electricity generation. However, the later stages of the transition are less straightforward. Electricity currently provides less than 20% of global final energy (IEA, 2020a), and therefore a zero carbon energy transition will also involve the decarbonisation of other end uses. Most analysis shows that this will require electricity to substitute for fossil fuels in many other end uses, notably in transportation and heating in buildings and industry (IEA, 2018a). The energy transition can therefore not be achieved without fuel switching in the large number of energy end uses that provide the energy services on which modern life depends.

Most analysis of the transition shows that improvements in energy efficiency will play a role in the energy system change by reducing energy demand below ‘business as usual’ levels (Edenhofer et al., 2014; Masson-Delmotte et al., 2018). Many projections see energy efficiency improvements mitigating but not reversing global energy demand growth. However, detailed analyses show that the global technical potential for efficiency improvement is very large (Cullen & Allwood, 2010; Cullen et al., 2011). Recent analysis shows that global energy demand could be reduced, even whilst delivering goals for

energy access, poverty alleviation and decent living standards (Grübler et al., 2018).

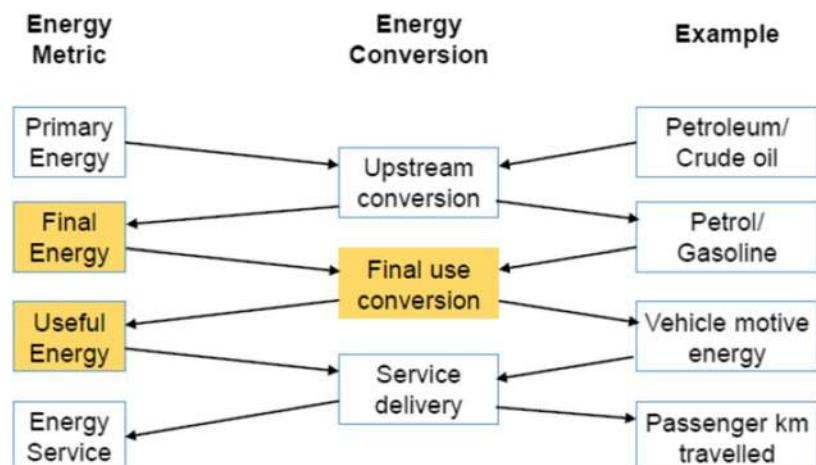
In summary, it is broadly accepted that there is a major role for energy efficiency improvement in the transition, but that the scale of energy demand reduction is disputed. The dominant conceptualisation is that demand reductions will alter the scale of the decarbonisation challenge, and therefore the amount and cost of the zero carbon energy supply system needed.

This paper will argue that this is not a satisfactory conceptualisation. Given the systemic nature of transition, and in particular the need for fundamental changes in the type of energy used in transport and heating, the flows of energy in the global economy need to change substantially. Changes in the fuels used, and the efficiency of their use, are not just an enabler of the transition, but rather a defining characteristic.

The phrase energy efficiency is potentially confusing in that it is used in both physical and economic analyses of energy use. In the latter case, there is a very large literature on the scope for improving economic productivity through the use of higher efficiency technologies and techniques (see e.g. Ayres and Warr, 2010; Kümmel, 2011; Kümmel, 2013; Laitner, 2015). In this sense of energy efficiency, the phrase ‘energy productivity’ is often used synonymously. This paper does not seek to add to that literature, but focusses on the physical analysis of energy efficiency.

Even within this restricted use, the term ‘energy efficiency’ is, confusingly, used with respect to

**Fig. 1** Conversion steps in the production of energy services from primary energy, highlighting the focus of the paper



individual processes, sectors and whole systems. Figure 1 sets out the framing and terminology used in this paper. The energy efficiency of the whole system may be improved in three broad ways: firstly, by increasing the efficiency of conversion of primary energy into the final energy delivered to energy users ('upstream conversion efficiency'); secondly, by increasing the efficiency of conversion of that final energy into useful energy at the point of use ('final energy conversion efficiency'); and thirdly, by techniques that allow more energy services to be delivered by the same useful energy ('service delivery'). The latter two categories are often combined in the phrase 'end use efficiency', but are conceptually distinct.

Upstream conversion efficiencies are affected by the transition to RES, in particular through the phasing out of thermal power stations using fossil fuels. However, this paper focusses on the processes highlighted in Fig. 1, i.e. the conversion of final energy into useful energy. As the remainder of the paper shows, these efficiencies are also likely to be affected significantly by the energy transition.

The paper does not explicitly address other contributions to end use efficiency improvement (service delivery), for example through material resource efficiency, transport modal shift and building insulation. This is not because these approaches are not important, indeed it is well-established that they, but because their potential is less likely to be affected by the shift to RES.

The paper poses two research questions:

- What are the broad qualitative changes to energy flows in the global economy that will happen as a result of the energy transition? and
- What are the likely quantitative effects of these on final energy conversion efficiencies and, through these effects, on energy demand?

The 'The thermodynamics of the zero carbon energy transition' section analyses the shift in energy flows that will happen as a result of a shift from fuels that provide heat to RES that provide work, showing that this is a critical issue for the overall energy system. The following two sections undertake a thought experiment on the implications of this change for end use conversion efficiencies and therefore for global

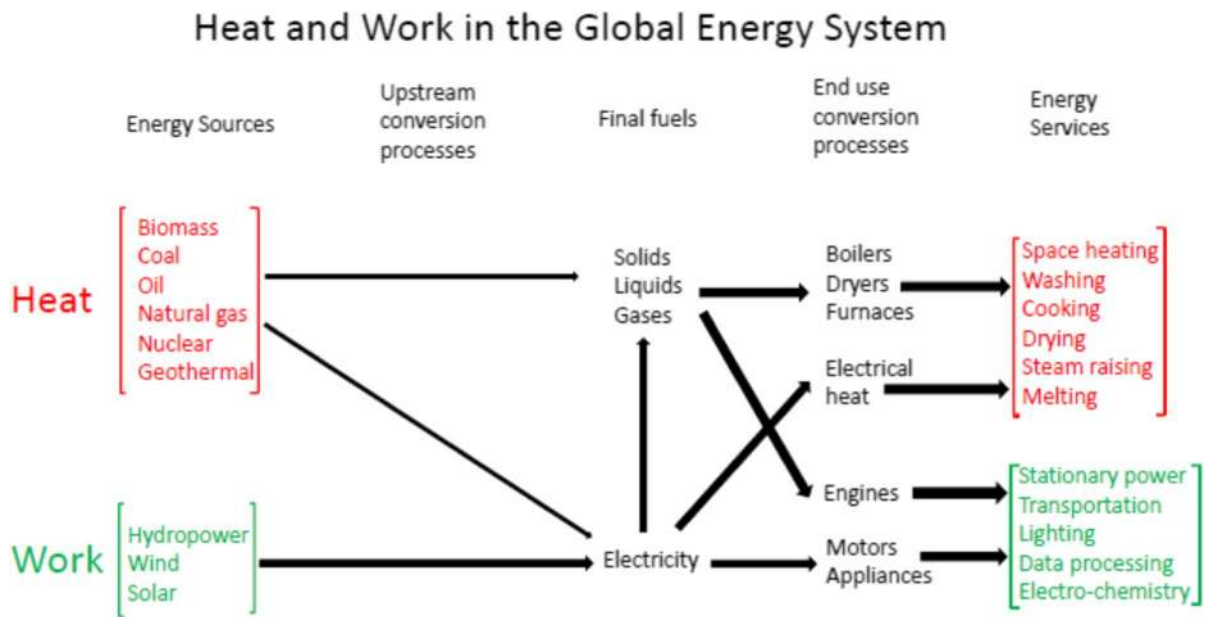
final energy demand. The 'Quantification methodology' section sets out the methodology for the quantitative assessment, and the 'Quantification results' section the results of the analysis. The 'Discussion' section discusses some implications for the zero carbon energy transition and the 'Conclusions' section provides key conclusions.

### The thermodynamics of the zero carbon energy transition

Most energy analysis uses the concept of the 'energy system'. Whilst precise definitions differ, the critical understanding is that there are complex links between the ways that different energy sources are converted and transported to provide energy services. Although heat and work are conceptually different, they are strongly linked, and therefore a systems approach is helpful. A common tool to illustrate the point is the Sankey diagram (Sankey, 1898), which shows energy flows from energy sources to energy services.

A highly simplified and non-quantitative Sankey diagram of the global energy system is shown in Fig. 2. In this case, rather than showing fuel types or carbon contents, the diagram makes a distinction between heat and work, both for the energy sources and the energy services provided. Fossil fuels, and some other energy sources, tend to provide heat, as does nuclear power and some RES such as biomass and geothermal energy. Other RES tend to provide work. Most notable in this category are hydropower and the 'new renewables', solar photovoltaics and wind, which have experienced dramatic recent cost reductions (IRENA, 2020a, 2020b). Some energy services require heat, most obviously those associated with space heating, water heating, cooking and many industrial processes; many other energy services, notably movement, require work.

The ability to inter-convert between heat and work is characteristic of modern energy systems, and the constraints on these conversions described in the discipline of thermodynamics. In principle, any mix of energy services can be met by any mix of any energy sources, but often only by utilising heat/work conversions. A more detailed and nuanced analysis of the relationships of different energy sources and energy services to work is provided in Appendix 1.



**Fig. 2** A stylised Sankey diagram of the energy economy

In pre-industrial societies, the systems of provision for heating services and work were largely separate. Heat was largely produced from wood and was used for cooking, thermal comfort and services requiring hot water, as well as a few other specialised applications such as metal working. Work was provided, largely for motion, from different systems, mostly from the physical labour of humans (hence the name work) or by domesticated animals, with hydropower and wind power in specialised applications, such as milling grain.

The technological changes of the industrial revolution allowed the two systems to connect. This was principally by allowing heat to be converted into work, initially in the late eighteenth century using steam engines, but then from the late nineteenth century by the two dominant technologies of modern energy supply, the internal combustion engine and the turbo-generator. Both provide work from combustible fuels using a heat engine. The former is principally used for decentralised motive power, mainly in transportation. The latter, driven by steam turbines and more recently gas turbines, has become the main source of electricity generation, with electricity then distributed to provide a multiplicity of energy services, including motive power. The science of these conversions has been understood through the

discipline of thermodynamics since the mid-nineteenth century.

The combination of internal combustion engines and thermal electricity production has enabled the delivery of modern energy services anywhere on the planet, at least in principle. Energy use has multiplied many-fold and fossil fuels have become the main source of energy. Figure 3 shows a stylised version of such an industrial, fossil fuelled energy system. Fuels are combusted to produce heat as in pre-industrial societies. What the industrial revolution changed fundamentally was that heat was also converted to work to provide transportation, stationary power and other energy services.

The change to low-carbon, and ultimately zero carbon, energy systems seems highly likely to be a transition as fundamental as the changes of the industrial revolution. Current evidence indicates that the cheapest forms of low-carbon electricity will be renewable rather than nuclear and/or fossil fuels with carbon capture and storage (CCS). Already fossil fuels are being displaced from electricity generation by renewables (IRENA, 2020a). Whilst very high levels of variable RES create new challenges for system operators (Jones, 2017), these look soluble, allowing a transition to zero carbon electricity (NGESO, 2020).

### Heat and Work in a Fossil Fuel Energy System

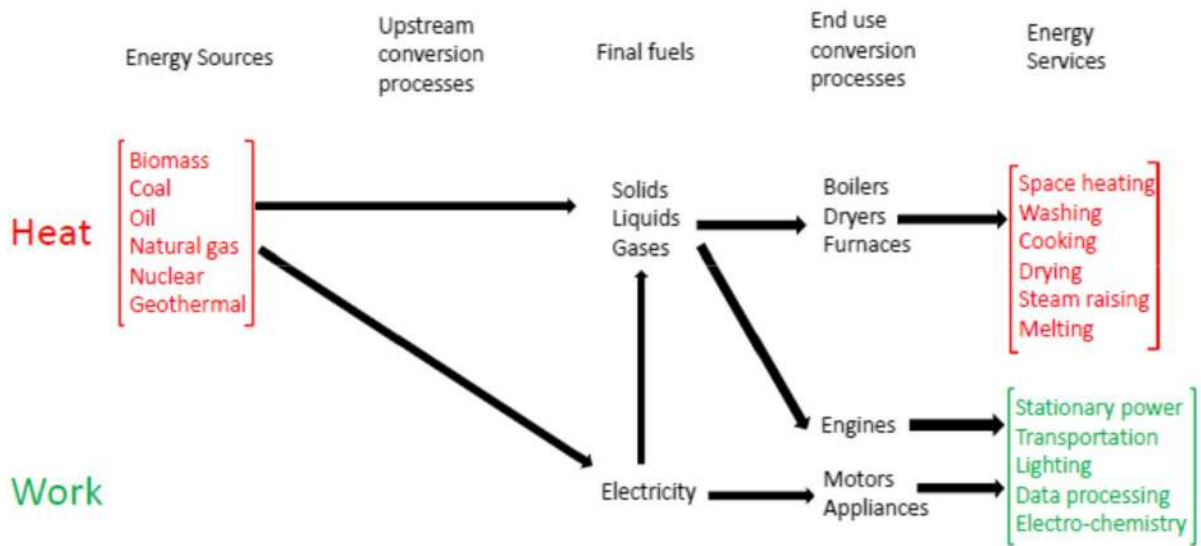


Fig. 3 A stylised Sankey diagram of an industrial economy

A zero carbon energy system will need electricity decarbonisation to be followed by the substitution of fossil fuels elsewhere in the energy system, i.e. for heating, transport and industrial processes. The heat-producing renewables—bioenergy and geothermal

energy—may make a contribution. However, most evidence points to this being limited. Use of bioenergy is constrained by land availability, competition for other uses of biomass (notably for food) and relative costs (Smith et al., 2013). The global resource of

### Heat and Work in a Renewable Electricity System

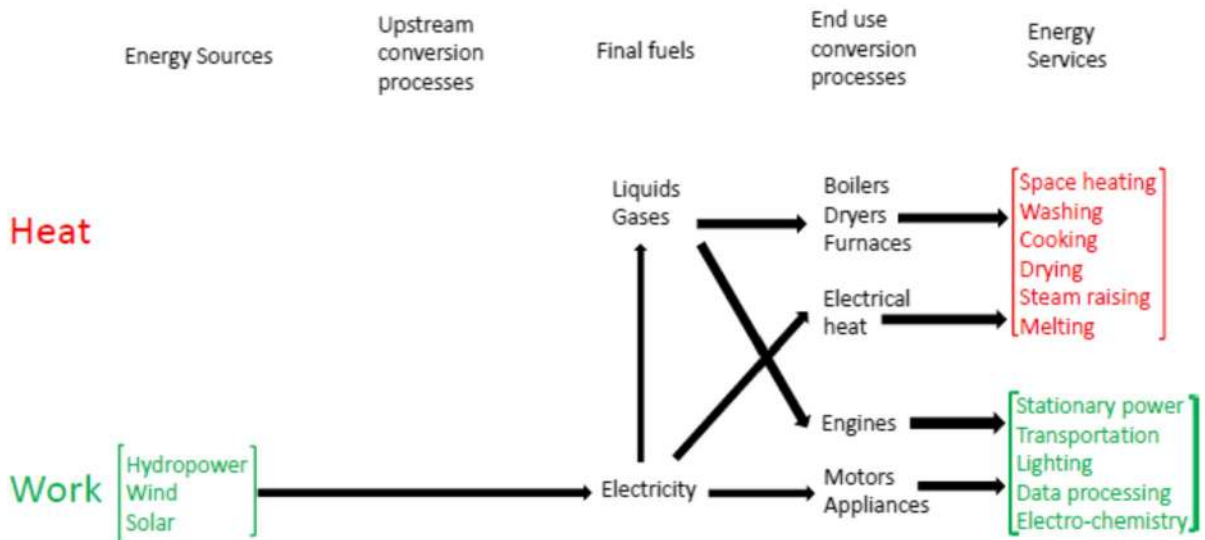


Fig. 4 A stylised Sankey diagram of 100% renewable economy



geothermal energy is very large and economic in specific locations, but it is not expected to be competitive in most large, densely populated areas (Goldstein et al., 2011). If this analysis is correct, the main work-producing renewables (solar, wind and hydropower) will need to become the major fuels for transportation and heating, as well as the services currently provided by electricity. The dominant flows of energy in such a 'post-transition' energy system will then be as shown in Fig. 4.

This wider role for electricity in low-carbon economies (Edmonds et al., 2006; Sugiyama, 2012) has become better understood as more ambitious carbon mitigation targets have been established and has been summarised by the IPCC (Edenhofer et al., 2014). The idea that the whole world's energy can be supplied from renewable energy is not new (see e.g. Lazarus, 1993), but only more recent studies of 100% renewable energy systems (e.g. Lund & Mathiesen, 2009; Jacobsen et al., 2015; Hansen et al., 2019a; Hansen et al., 2019b) rely heavily on renewable electricity and therefore electrification. Increasingly, it is understood that there are therefore major challenges around the conversion of the 80% of global final energy use that is not currently electrified. Analyses of sectoral electrification have been undertaken for transport (e.g. McCollum et al., 2014), buildings (e.g. Deason & Borgeson, 2019) and industry (e.g. Lechtenböhmer et al., 2016). These studies show the potential for increased efficiency through electrification at the level of the individual process and sector.

Some non-academic literature has framed the overall process as a move away from combustion (Lovins, 2013; Patterson, 2014). However, the change is arguably even more fundamental. As shown in Figs. 3 and 4, it is a reversal of the changes that occurred during the industrial revolution. Instead of energy services that require work being provided from fuels via combustion and heat, energy services that require heat will be provided from energy sources that provide work. The whole architecture of energy systems will change, away from converting heat into work, towards converting work into heat.

The scale and rate of change are, of course, likely to vary as a function of resources, investment and politics. However, once the assumption that work-producing renewables will become dominant is accepted, this broad conclusion is unavoidable. Perhaps surprisingly, there is no literature that conceptualises the whole energy transition in this way.

Work-producing RES are already replacing heat-producing fuels, predominantly fossil fuels, in electricity generation. This reduces primary energy demand by eliminating heat losses in thermal power generation. However, it has no direct impact on final energy demand.

With the conceptualisation of a shift from heat-producing to work-producing energy sources, the zero carbon energy transition may be thought of in three subsequent steps, each with implications for the efficiency of final energy conversion, and therefore the scale of final energy demand.

First, without fuels to supply heat engines, end uses of energy requiring work will be converted, where possible, to electricity. The early stages of this step of the transition are already beginning, in particular with electric vehicles substituting for internal combustion engines. As electric motors have a much higher efficiency than heat engines, this change decreases final energy use substantially.

Second, without fuels to produce heat, electricity will also be used for heating. At temperatures below 100 °C, this can also be achieved with a significant reduction in final energy use to supply the same useful energy. This is because electric heat pumps can achieve efficiencies well in excess of 100% (see Appendix 2 for a discussion of the counter-intuitive idea of efficiencies that exceed 100%).

Thirdly, it will be necessary to substitute fossil fuels with other options, in cases where electricity use is not a viable alternative. The precise limits to electrification are not agreed, but seem likely to include at least some aviation, shipping, road freight and manufacturing process applications (CCC, 2018a; IEA, 2019). There may also be practical economic limits for the large, seasonally peaked energy service of space heating (Eyre & Baruah, 2015).

There is a variety of options for alternative carbon-free energy vectors. Hydrogen is the most obvious and most extensively studied (Philibert, 2017). The current dominant production route, using steam reforming of methane, is not carbon neutral, and often referred to as 'grey hydrogen'. It can be converted into a low-carbon vector, 'blue hydrogen', by adding carbon capture and storage to the reformation. Hydrogen can also be produced from water by electrolysis (Brandon & Kurban, 2017). This 'green hydrogen' is likely to be the major route in an energy system dominated by work-producing RES.

The electrolytic conversion process can approach 100% efficiency in theory, but in practice involves an efficiency penalty. However, conversion of hydrogen chemical energy to work using fuel cells enables it to be used more efficiently than fossil fuel in heat engines. The theoretical maximum electrical efficiency of a hydrogen fuel cell (determined by the ratio of the Gibbs free energy to the enthalpy) is 83% and achievable efficiencies exceed 50%. These are significantly higher than in a heat engine, where the theoretical efficiency is the Carnot limit and materials limit feasible operating temperatures and therefore the efficiency of conversion to work (Lutz et al., 2002). In summary, hydrogen may be used more efficiently than fossil fuels at the point of final energy conversion, because the chemical energy may be converted directly into work rather than heat.

All three stages will tend to increase conversion efficiencies at the point of final energy use, and thereby reduce global final energy demand. The size of the combined effect for the global energy system is investigated in the next two sections. Likely impacts on primary energy use are more complex due to the additional upstream conversion inefficiencies in the third stage and are addressed in the ‘[Discussion](#)’ section.

## Quantification methodology

The principles of the quantification methodology follow from the analysis of the previous section.

For the purposes of this thought experiment, it is assumed that energy is generated entirely from work-producing RES. This is not intended to be a prediction or even a realistic scenario. Even in a 100% renewables scenario, bioenergy and geothermal may be expected to make a contribution. However, as set out above, it is widely expected that a zero carbon global energy system will be supplied largely by work-producing RES. It is therefore a reasonable first approximation, on which to base an assessment of the impact of the zero carbon transition on the end use conversion technologies needed.

Global energy demand, using a base year of 2020, is estimated from available sources. It is divided into different categories of energy use designed to provide different energy services (e.g. boilers for space

heating, high-temperature industrial processes, heavy road freight transport). The extent of disaggregation is determined by the level required to make reasonable allocations into the three categories set out in the previous section, i.e.

- Energy services delivered by work and that can be electrified
- Energy services delivered by heat that can be electrified
- Energy services that cannot practicably be electrified.

Detailed assumptions about current global energy use are set out in [Appendix 3](#). For each category, current global energy use is split into electricity and heat-producing fuels.

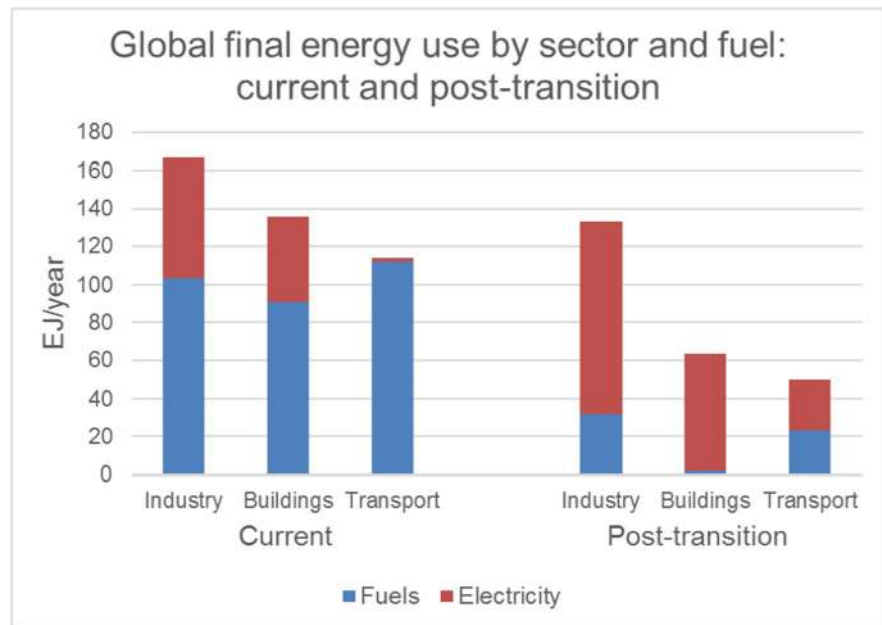
The literature on energy efficiency is reviewed to identify existing efficiencies in both electrified and non-electrified cases. Detailed assumptions about conversion efficiencies are set out in [Appendix 4](#). The same process is repeated for the same set of energy services delivered in a zero carbon system, using a mix of electricity and electrolytic hydrogen as the zero carbon vectors to supply final energy demand. The differences in efficiency are applied to current global final energy demand to calculate the size of global demand reduction.

In order to ensure transparency, other efficiency options (e.g. building insulation, vehicle aerodynamics, industrial process control) and energy service demands (e.g. for material resources, thermal comfort or mobility) are held constant. This is not, of course, realistic, as the potential for these to change is very large (Grübler et al., 2018). But this thought experiment approach enables calculation of the effect of supply mix changes on final energy conversion efficiencies without being obscured by these other effects.

## Quantification results

The overall impact of the changes from converting the whole energy system, with a constant level of energy services and useful energy demands, to an efficient work-driven system is approximately a 40% reduction in final energy demand (see [Fig. 5](#)) from 416 to 247 EJ/year. The major efficiency gains are in buildings

**Fig. 5** Changes in global final energy demand due to a shift to using work



and transport where demand reductions exceed 50%. These are primarily due to converting building heating from fossil-fuelled boilers to electric heat pumps (EHPs) and from switching transport propulsion from internal combustion engines (ICEs) to electric vehicles (EVs). Energy demand reductions in industry are smaller (20%), as set out in Appendix 4, reflecting the high efficiencies already achieved in energy intensive industry sectors and the difficulties in switching some demands to electricity, especially where fuels play some other role such as a feedstock or chemical reducing agent.

Demands that are not electrified are assumed to be provided by hydrogen. The change in the split between electricity and fuel for each major type of process is shown in Table 1. The share of electricity use doubles in industry (38% to 76%); almost triples in buildings (33% to 97%) and rises more than 30-fold in transport (less than 2% to 54%). Overall electricity provides 189 EJ (77%) with hydrogen the remaining 57 EJ (23%). These compare to the current figures of 110 EJ (26%) for electricity and 306 EJ (74%) for other fuels. In other words, fuel use falls to well under 20% of existing levels, whilst electricity use rises by 70%.

The detailed results are dependent on the precise assumptions set out in the appendices. In particular, the results depend on the assumptions about the energy supply mix and the conversion technologies deployed at the point of energy use.

The major finding that energy services will be delivered much more efficiently in a 100% work-powered global energy system is robust, provided that EHPs largely replace boilers for low-temperature heating services and EVs largely replace ICE for light vehicles.

In essence, the efficiency gains are a direct result of the fact that the second law of thermodynamics allows greater efficiencies in conversion of work to heat than vice versa. An alternative framing is that ‘energy’ is a misleading metric, with which to cover both work and heat (and heat at different temperatures). The analytical option of ‘exergy analysis’ is discussed in Appendix 2. However, the key conclusion of this paper is robust against shifting to exergy analysis. In either framework, the important point is that a unit of work energy will generally provide more useful energy and energy services than a unit of heat energy.

Two major simplifying assumptions made in the thought experiment warrant some consideration: first, that there is no deployment of energy efficiency measures other than the final use conversion efficiency improvements driven by the change to a work-based energy system; and secondly that the demand for energy services is unchanged. Of course, neither of these is a realistic scenario.

Firstly, there remains significant scope for improvement in the energy efficiency with which energy services are produced from useful energy, for example in building insulation and vehicle design. The technical potential for such changes has been estimated to be 73%



**Table 1** Final energy by process type and fuel: current and post-transition (EJ/year)

	Current			Post-transition	
	Fuels	Electricity	Traditional biomass	Fuels	Electricity
<b>Industry</b>					
High-temperature process	47.2	15.9		31.6	22.1
Low-temperature process	24.2	6.7		0.0	26.1
Drying and separation	12.0	1.7		0.0	4.7
Motors, drives and lighting	0.6	31.4		0.0	32.0
Space heating	8.2	3.8		0.4	3.1
Other	11.6	3.6		0.0	12.9
<b>Total industry</b>	<b>103.8</b>	<b>63.1</b>		<b>32.1</b>	<b>100.9</b>
<b>Buildings</b>					
Space heating	38.4	2.2	3.2	2.0	10.4
Water heating	24.1	4.3	0.0	0.0	10.7
Cooking	0.0	4.1	25.1	0.0	6.0
Lighting, cooling and appliances	0.0	34.3	0.0	0.0	34.3
<b>Total buildings</b>	<b>62.5</b>	<b>44.8</b>	<b>28.3</b>	<b>2.0</b>	<b>61.4</b>
<b>Transport</b>					
Vans	14.0			0.0	3.2
HGV	15.7			4.7	4.2
Car	40.2			0.0	9.4
Bus	13.9	0.7		2.1	5.8
Motor cycle	1.5	0.2		0.0	0.5
Rail freight	1.6	0.5		0.0	1.2
Rail passenger	0.8	0.4		0.0	0.8
Aviation	11.1			5.4	1.4
Marine	13.0			10.9	0.6
<b>Total transport</b>	<b>111.8</b>	<b>1.8</b>		<b>23.1</b>	<b>27.0</b>
<b>Total all sectors</b>	<b>278.1</b>	<b>109.8</b>	<b>28.3</b>	<b>57.2</b>	<b>189.3</b>

(Cullen et al., 2011). End use efficiency improvements, in the broadest sense, are therefore not restricted to those shown in Table 1 and Fig. 5. More substantial improvements are possible by combining the conversion efficiency improvements discussed in this paper with other energy efficiency techniques.

Secondly, demand for energy services seems very likely to rise in order to meet rising living standards, especially in the Global South. On the other hand, there are large opportunities for higher-income energy users to reduce consumption of energy services without lower welfare (Ivanova et al., 2020). Combining these effects requires more detailed socio-technical analysis. Doing this for the whole world is complex; the most comprehensive analysis shows that a sustained effort to reduce energy demand whilst enabling all of the UN Sustainable Development Goals to be met can reduce

final energy demand by approximately 40% (Grübler et al., 2018). The similarity of this 40% reduction number to the conversion efficiency improvement calculated above is a coincidence. The implication is that the projected rise in global energy service demands can be balanced by improvements in the production of energy services from useful energy. The large rises in conversion efficiencies in moving to a work-based energy system then drive the 40% reduction.

The analysis uses the simplifying assumption that renewable energy is produced as electricity, with direct use of fossil fuels replaced by either electricity or electrolytic hydrogen. To the extent that bioenergy and, perhaps, geothermal heat might contribute to renewable energy supply, this constraint is too limiting. The best uses of limited biomass resources in a low-carbon transition remain disputed (CCC, 2018b)

and may be very dependent on local resources. Analysis of the issue is outside the scope of this paper, but some production of heat and liquid fuels from bioenergy is likely, and it would be expected to substitute for some of the electrolytic hydrogen projected in the results above. This will tend to increase final energy demand, as biofuels can generally be used less efficiently than hydrogen at the point of final energy use. On the other hand, upstream conversion losses associated with hydrogen production would be reduced. More research is needed on the overall impact of a realistic share of bioenergy on the analysis.

The results imply a growth in use of hydrogen to 57 EJ/year. This is four times the existing level of annual global hydrogen production from all sources of 14.4 EJ (IRENA, 2020b). Producing this entirely by electrolysis, assuming an electrolyser efficiency of 80%, which is the median of a major review (Parra et al., 2019), would require 70 EJ/year of electricity, i.e. over 60% of total current global electricity production. It would need at least 2500 GW of electrolysis. This vastly exceeds current electrolyser capacity, although it is rising quickly with new investment expected to exceed 1GW/year in 2023 (IEA, 2020b). For the reasons explained above, in practice, use of heat-producing renewables in some applications would be expected to reduce the scale hydrogen demand.

## Discussion

### Policy implications

Critical assumptions in the analysis are that EHPs provide most low-temperature heat, EVs predominate in the light vehicle fleet and hydrogen is used primarily in fuel cells in heavy vehicles. These are the high-efficiency options. Based on current analysis, they appear to be the economic options in a zero carbon system. However, it is well-established that a variety of market failures mean that economically optimal technologies are frequently not deployed (Brown & Wang, 2015; Eyre, 1997). Without policy intervention, some actors in equipment supply industries are likely to market electric resistance technology or hydrogen boilers for low-temperature heating and alternative fuels in ICEs for vehicles. Policy decisions, in particular regulatory standards for heating

systems, vehicles and appliances, will continue to be important in ensuring high-efficiency options are used.

In the context of the transition to technologies that use work instead of heat, technical standards and product regulation can be very powerful. The analysis above shows that efficiency standards for heating and vehicles can be approximately a factor of 3 stricter than those currently in place for fossil fuel use. These standards could be set for either or both of the final energy conversion efficiency or the wider service delivery efficiency, e.g. for an electric vehicle, either motor efficiency (%) or vehicle efficiency (kWh/km). Setting standards at a level that can only be achieved by well-designed EHPs and EVs effectively will require both the use of final energy that can be used efficiently (electricity or hydrogen) and end use product designs that achieve that efficient use. For this reason, they will be more effective than traditional product policy, which only affects product design. Such standards therefore have the potential to be pivotal in the energy transition.

Interactions between energy service demands and energy efficiency improvements should also be considered. Two may be significant: the impact of embodied energy and economic rebound effects.

Investment in more efficient technologies may increase embodied energy, and therefore industrial energy use. The methodology used in the analysis above treats industrial energy use as independent of the material input for efficiency improvement, and therefore analysing the size of this effect is outside the scope of the paper. It is a significant effect in a few cases, notably for EVs, where manufacturing emissions are currently double those of an ICE vehicle (Wolfram & Wiedmann, 2017). In principle, these lifecycle considerations could be included within product standards and regulations. However, any such adjustment would be a second-order effect compared to differences between operational energy use in ICEs and EVs.

By treating demand for energy services as fixed, the methodology also neglects any rebound effects from improved energy efficiency. Direct rebound effects are typically 10–30% (Sorrell, 2007). And historical economy wide effects have been found to be larger (Brockway et al., 2021), which follows from the importance of exergy efficiency in the economy. However, rebound effects specific to the

improved conversion efficiencies addressed here are unknown. Rebound is driven by energy cost reductions, increased incomes and higher levels of economic productivity, not physical metrics. Many of the conversions envisaged will not lead to significant energy cost reductions, as they involve switching to higher-priced fuels, and therefore historical relationships may not be reproduced. In any event, rebound cannot be addressed by technical standards. To the extent it is judged undesirable, it requires economic disincentives.

#### Implications for primary energy demand

The analysis above relates to final energy demand, not primary energy. However, it is straightforward to make a preliminary assessment of the effects described above of primary energy demand. International Energy Agency data shows that, in the current global energy system, 70% of total primary energy supply (TPES) is used for final energy use (IEA, 2020c). The remaining 30% is lost in various upstream conversion processes. The main loss (20% of TPES) is in thermal power generation, with 8% in other fuel industry processes (largely in coal conversion to coke and oil refining). Losses in electricity transmission and distribution are 1.6% of TPES (approximately 10% of electricity generated). In a fully work-based energy system, these numbers will be very different. Losses in thermal power generation and fuel industry processing will be eliminated. As electricity becomes the dominant energy vector, distribution losses would be expected to rise to approximately 10% of TPES.

The other new source of upstream conversion losses will be in hydrogen production. Assuming an 80% efficiency in electrolysis, with 23% of final energy delivered as hydrogen, these conversion losses will be 5% of TPES. As explained above, these might be reduced if bioenergy replaces some uses of hydrogen. Depending on the resources used to balance electricity systems with high levels of variable resources, there may also be additional losses in upstream electrochemical storage and electricity generation from stored hydrogen. However, total upstream losses seem very likely to be smaller than in the existing global energy system. A 40% reduction in final energy demand will therefore be reflected in a reduction in primary energy demand of at least 40%.

#### Timescales of change

The analysis compares the current global energy system with that after a complete transition to work-producing energy sources. The time taken to achieve this is not explicit in the analysis. There is no expectation that different aspects of the transition will have similar timescales. Indeed, it seems very likely that, for example, the adoption of EVs in some developed countries will be more rapid than the complete phase-out of traditional cooking fuels in the Global South. The results are simply a comparison of starting conditions and a projected future end state. However, the overall reconceptualization does have implications for the timescales of the transition. The timescales for different technology transitions are very variable, providing some encouragement that system change by mid-century is plausible (Sovacool, 2016). However, it is clearly also true that large-scale transitions of the type seen in industrial revolutions have tended to be slower (Grübler et al., 2016). The revised conceptualisation set out in this paper shows that the zero carbon transition has the character of an industrial revolution in that it is a complex, multi-stage process, involving multiple technologies, infrastructure systems and many actors. This tends to support arguments that a very rapid complete transition is probably unrealistic.

#### Conclusions

The energy transition is normally conceptualised as a shift from fossil fuels to zero carbon energy sources, with the role of energy efficiency limited to reducing the scale of demand for energy, and therefore the amount of decarbonised energy required. This paper has shown that this is a seriously inadequate representation of the changes in energy systems implied by the transition to zero carbon. Recent evidence shows that the key energy sources are likely to be ‘work producing’ renewables. As these replace ‘heat producing’ fossil fuels, the changes in the energy system are more profound than simply fuel switching. They constitute a systemic change on the scale of the changes observed during the industrial revolution.

Substitution of fossil fuels by renewables is only the first stage of the transition. To achieve a zero carbon energy system, it needs to be followed by changes that enable ‘work producing’ renewables to supply energy services not currently supplied by electricity. The dominant energy conversion processes in the global energy system will therefore be

different. In particular, electricity will be converted to heat and other zero carbon fuels. The transition as a whole cannot adequately be conceptualised as independent processes of shifting to zero carbon fuels and improved energy efficiency. The two have strong positive synergies.

The paper presents a thought experiment on the implications for global final energy conversion efficiency in an energy system in which all energy is supplied by work-producing energy sources. It assumes that all final energy is supplied as either electricity or electrolytic hydrogen, but the broad conclusion is robust to inclusion of some other renewable energy sources. Both electricity and hydrogen can be used more efficiently than the other fuels that dominate final energy use, and this is a very significant effect. Making transparent and plausible assumptions about the end use conversion processes used, the paper finds that there is a very large increase in the overall efficiency of final energy conversion. Total useful energy to deliver the same energy services is reduced by approximately 40%, with the main effects in buildings and transport. Holding other drivers of final energy demand constant, this will have a proportional effect on global final energy demand. A similar impact on primary energy demand is likely.

Technical standards and product regulation for end use conversion efficiency and/or service delivery efficiency seem likely to be key policy instruments. They have the potential both to ensure product designs that use energy efficiently and to drive the transition to final energy sources that enable such use.

### **Appendix 1 Heat and work from energy sources and in energy services**

Energy services can be divided into two categories: firstly those that are essentially delivered by heating (raising the temperature of something), and secondly those that are delivered by some other form of energy (e.g. electrical or mechanical work).

In buildings, raising the temperature of the building, heating water and the variety of different forms of cooking are all forms of heating services. In industry, there are a large number of processes that depend on heating to a wide range of different temperatures. In contrast, in transport there are few heating-related services. Services in industry and buildings that are traditionally only provided by electricity tend to be work-related, notably the provision of motive power through electric motors, but also increasingly information

services. In transport, the service itself can only be provided by work, but has typically relied more on local conversion of fuels in internal combustion engines.

There are some services which are a little more complex to categorise. Space cooling is, in principle, a heating service, but it predominantly supplied by refrigeration systems driven by electric motors. For the purposes of this analysis, it is therefore classified as a work-related service. Similarly, the heat required for hot water in washing machines and dishwashers is predominantly supplied by electricity. The analysis also treats lighting as a work-related service. The oldest lighting technologies, candles and oil lamps, used combustion, but modern lighting devices require electrical work, either to achieve the high temperatures needed for incandescence in the visible spectrum or in modern devices, such as light-emitting diodes (LED) and fluorescent lamps, to convert electricity selectively into photons in the visible spectrum.

Some industrial processes are also complex to categorise within this simple heat/work binary division. Notably, electrochemical reactions, by definition, require work in the form of electricity, but may also require heat, for example in the Hall-Héroult process for primary aluminium manufacturing. We classify these as work related, due to the essential role of electricity. In some other electricity using processes, notably electric arc steelmaking, electricity is a heat-producing fuel. In other cases, such as petrochemical and ammonia production and primary steel-making, fossil fuels provide a chemical reagent as well as heat. In this paper, they are categorised as requiring heat, and the accounting process set out in Appendix 4 below requires the replacement of fossil fuels by some other combustion fuel.

For the purposes of this paper, we also make a binary division of energy sources into those that provide work and those that provide heat. In the current global energy system, fossil fuels are the dominant producers of heat. Biomass also provides heat via combustion and geothermal energy exists as a heat source. In addition, the energy from nuclear fission, although originating as high energy particles and photons, has only ever been captured as heat. Where these energy sources are required to provide work, this has been done through heat engines of various kinds. In some cases, it has proved an efficient option to use these fuels for combined heat and power (CHP), i.e. to use heat rejected from the heat engine to provide heating services.

Most other forms of renewables produce only work, usually in the form of mechanical work. These include power from wind turbines, hydro-dams, waves and tidal energy.

Solar energy can be used to provide work or heat. Examples of the latter include ‘passive solar gain’ for space heating, ‘active solar heating’ of water and ‘concentrating solar power’ for electricity generation using heat engines. However, the rapid growth in solar energy has been driven by the use of photovoltaics, which convert solar energy directly into electrical work (the inverse process of LED lighting). For the purposes of this paper, we therefore treat solar energy as a source of work.

## Appendix 2 Energy efficiency and its metrics

The term energy efficiency does not have a universally agreed definition. Like any form of efficiency, it can be conceptualised as the ratio of a ‘useful output’ to a ‘total input’, but these terms are not defined or used consistently.

The broadest and commonest definition of ‘useful output’ is the energy service delivered. This enables incorporation of all the technical and social changes that might be utilised to improve the efficiency of energy service delivery, including for example modal switch in transport, materials utilisation efficiency in industrial production, and insulation of buildings to reduce heat loss or gain. However, energy services are frequently difficult to measure and, in some cases, even to define. For some important energy services, such as thermal comfort and mobility, the appropriate metrics are not specified in terms of energy units, and therefore the metric of the efficiency of their delivery (e.g. passenger km per Joule for mobility) are service specific. This prevents meaningful aggregation across different service categories.

In the context of this paper, the definition of energy efficiency is more straightforward, as the types of efficiency improvement considered are confined explicitly to the efficiency of conversion devices for different forms of final energy use, for example the substitution of boilers by heat pumps and internal combustion engines by electric motors. These devices have better-defined inputs and outputs, both measured in energy units. In essence, the output metric of energy service in broader definition of energy efficiency is replaced with ‘useful energy output’. The measure of efficiency is therefore the ratio of useful energy output to final energy input, a dimensionless ratio, normally quoted as a percentage.

There are limits to achievable efficiencies as a result of the second law of thermodynamics. Indeed, the key findings of this paper—that work may generally be converted to heat more efficiently than heat may be converted to work—result largely from that law. In some cases, for example in heat pumps and refrigerators, this enables work to be used at efficiencies of greater than 100%, as the work is used to pump heat, to or from ambient, and the conventional definition of ‘energy input’ excludes ambient heat and coolth.

So, whilst both heat and work are measured in energy units, they are not generally of equal value. An alternative framing that addresses this inequality is exergy analysis (Moran & Sciubba, 1994), where exergy is a measure of the ability of an energy source to do work. Exergy therefore has a numerically equal value to that for energy when work is measured, but a smaller numerical value for energy as heat, with the degree of ‘down-rating’ dependent on temperature. Various authors have preferred exergy analysis when investigating the scope for technology improvement within current energy systems (Hammond & Stapleton, 2001). In exergy analysis, heat engines, e.g. turbines and internal combustion engines, have theoretical maximum efficiencies of 100%, compared to a much lower value in energy analysis. And the maximum efficiency of a heat pump cannot exceed 100%.

Exergy analysis is well-established in thermodynamics and has a long history ecological economics (Georgescu-Roegen, 1993). However, it is scarcely used in energy economics and policy. Almost all global and national data sources, models and policy analyses are constructed in terms of energy, not exergy. In this paper, we use energy analysis, primarily for that reason. It would be possible to reconstruct the analysis in exergy terms. The numerical values in the results would be different. Energy sourced from heat would have lower relative numerical values than that sourced from work, and the energy services requiring heat would have lower relative numerical values than those requiring work. The shift in the global energy economy described in this paper, from heat-producing energy sources to work-producing energy sources, would appear partly as a change in these relative values, rather than increased conversion efficiencies. But the reality represented would, of course, be the same. The key conclusion of the paper would be still be that the final energy needed to provide the same energy services is lower from a work-based system than a heat-based system.



### Appendix 3 Current global energy use assumptions

#### Industry

Assumptions about current energy use in industry are shown in Table 2.

Total industrial energy use is taken from Low Energy Demand scenario for 2020 by Grübler et al. (2018). The split across between different major industrial sectors is taken from Fig. 2 of Cullen and Allwood (2010).

Reliable data for the splits by process type and fuel within each industrial sub-sector are not available at the global level. To estimate these for this paper, we have used UK data (ECUK, 2020) as the default. This implicitly assume that global practice within each sector is similar, which is a reasonable assumption in most cases. Where UK data does not conform to the sectoral split in Table 2, we have made supplementary assumptions as follows. UK data does not distinguish between steel and non-ferrous metals. We assume that the aluminium industry uses 40% of the electricity and 10% of the other fuels of the total metals sector, based on Energy Information Administration data (EIA, 2014). Within the steel industry, the fuel split is 79% fuels and 21% electricity, based on the work of He and Wang (2017). UK data on paper is aggregated with printing and publishing and therefore not representative of the global paper industry. The paper industry split between drying and separation and other low-temperature process therefore uses data on paper mills and pulp mills from Lawrence et al. (2019).

Petrochemicals account for about 12% of global oil use (IEA, 2018b), and therefore about 4% of global primary energy use. In this analysis, it is implicitly assumed that oil used as a feedstock may be substituted in the same way as oil used for energy in the chemical sector. This is a significant simplification, but not a major uncertainty in the context of the whole analysis.

#### Buildings

Total energy demand in buildings in 2020 and the shares of fossil fuels, electricity and traditional biomass are taken from the same Low Energy Demand scenario (Grübler et al., 2018). In order to estimate the energy use in different process types, total demand is first split into separate contributions from residential and non-residential, assuming the former is 74.3%

**Table 2** Current global industrial energy by sub-sector, process type and fuel (EJ/year)

	High-temperature process			Low-temperature process			Drying and separation			Motors, drives and lighting			Space heating			Other			
	Fuels	Electricity	Total	Fuels	Electricity	Total	Fuels	Electricity	Total	Fuels	Electricity	Total	Fuels	Electricity	Total	Fuels	Electricity	Total	
	Steel	31.9	8.5	40.4	0.0	0.0	0.0	0.0	0.0	1.7	0.0	1.7	0.0	0.0	0.0	0.0	0.0	3.6	1.3
Chemicals	1.8	0.2	2.0	5.4	0.7	6.1	3.0	0.4	3.3	0.0	6.7	0.5	0.1	0.6	0.6	0.6	2.1	0.2	2.3
Minerals	11.0	2.0	13.0	0.8	0.2	1.0	0.8	0.1	0.9	0.0	1.5	0.2	0.0	0.3	0.3	0.3	1.2	0.2	1.4
Paper	0.0	0.0	0.0	3.0	0.0	3.0	4.8	0.0	4.8	0.6	2.6	0.8	0.0	3.2	0.8	0.8	1.2	0.0	1.2
Food	0.0	0.0	0.0	5.9	1.4	7.3	0.7	0.2	0.8	0.0	2.2	0.0	0.0	2.2	0.0	0.0	1.3	0.3	1.7
Aluminium	2.3	5.0	7.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.0	0.0	0.8	0.0	0.0	0.3	0.6	0.9
Other	0.3	0.2	0.5	9.1	4.4	13.5	2.7	1.1	3.8	0.0	15.9	6.7	3.7	10.4	10.4	10.4	1.9	0.9	2.9
<b>Total</b>	<b>47.2</b>	<b>15.9</b>	<b>63.2</b>	<b>24.2</b>	<b>6.7</b>	<b>30.9</b>	<b>12.0</b>	<b>1.7</b>	<b>13.7</b>	<b>0.6</b>	<b>31.4</b>	<b>8.2</b>	<b>3.8</b>	<b>12.1</b>	<b>11.6</b>	<b>12.1</b>	<b>11.6</b>	<b>3.6</b>	<b>15.2</b>

**Table 3** End use process split of energy use in buildings

End use	Residential	Non-residential
Space heating	32.0%	33.0%
Water heating	24.0%	12.0%
Cooking	29.0%	0.0%
Lighting	4.0%	16.0%
Cooling	2.0%	7.0%
Appliances/ICT	9.0%	32.0%

(Lucon et al., 2014). These are then each split into the different end use processes using the shares shown in Table 3 (Lucon et al., 2014).

The end use fuel is assumed to be 100% electricity for lighting, cooling and appliances. Electricity use in cooking is assumed to be 3% of total building demand, with the remainder of cooking energy use from traditional biomass. The remaining traditional biomass demand is assumed to provide space heating. The shares of electricity for space heating and water heating are assumed to be 5% and 15% of the total for each end use. This ensures that the total share of electricity in the sector as a whole corresponds to the overall fuel mix assumed.

## Transport

Data on transport energy use by mode and fuel type are taken from the Supplementary Information of Khalili et al. (2019) and set out in Table 4.

End use demands smaller than 0.1EJ/year have been neglected. End use devices are assumed to be internal combustion engines for fuel and electric motors for electricity. Total energy use is consistent with the same Low Energy Demand scenario (Grübler et al., 2018) as the other sectors.

## Appendix 4 Future energy conversion assumptions

This section sets out the methodology used to calculate future final energy demands. Current energy demands by process type and fuel (see Table 1 and Appendix 3) are the starting point. For simplicity and transparency, it is assumed that there are no changes in energy services demands and no changes to energy efficiency other than in conversion processes from final energy to useful energy.

**Table 4** Global transport energy use by fuel and mode (EJ/year)

	Fuel	Electricity
<b>Road</b>		
Light goods vehicles	14.0	
Heavy goods vehicles	15.7	
Cars	40.2	
Buses	13.9	0.7
Motor cycle	1.5	0.2
<b>Rail</b>		
Rail freight	1.6	0.5
Rail passenger	0.8	0.4
<b>Aviation</b>		
Aviation freight	0.1	
Aviation passenger	11.0	
<b>Marine</b>		
Marine freight	12.7	
Marine passenger	0.3	
<b>Total</b>	111.8	1.8

All end uses are supplied by either electricity or hydrogen. Electricity is assumed to be the preferred zero carbon end use fuel in most applications. Hydrogen is used for those demands judged from the existing literature to be difficult to electrify. These include industrial processes, heavy vehicles, shipping and aviation, and some space heating.

Detailed assumptions are set out below in Table 5. This documents the conversion factors used for each combination of sector and process type (e.g. ‘industry, high temperature process’). Table 5 is essentially a set of  $2 \times 2$  matrices that document the conversion factors used to calculate post-transition energy demands, split into fuel and electricity, from the pre-transition fuel mix. As an example, the quantity of (non-electric) fuels used in industrial high-temperature processes falls to 67% of its pre-transition level, 13% of pre-transition direct fossil fuel appears as electricity post-transition and the remaining 20% is the final energy efficiency gain. For the same set of processes, all the energy currently provided by electricity is unaffected.

‘Pre-transition fuels’ are predominantly fossil fuels; ‘post-transition fuels’ are assumed to be hydrogen. For the buildings sector, an additional current fuel type is considered: traditional biomass. But there is no traditional biomass in the final fuel mix, and

**Table 5** Conversion factors between current and future fuel and electricity use

Sector and process	Pre-transition energy	Fuel	Electricity
<b>Industry</b>			
High-temperature process	Fuels	67.0%	13.2%
	Electricity	0.0%	100.0%
Low-temperature process	Fuels	0.0%	80.0%
	Electricity	0.0%	100.0%
Drying and separation	Fuels	0.0%	33.3%
	Electricity	0.0%	41.7%
Motors, drives, lighting	Fuels	0.0%	100.0%
	Electricity	0.0%	100.0%
Space heating	Fuels	5.3%	23.2%
	Electricity	0.0%	32.3%
Other	Fuels	0.0%	80.0%
	Electricity	0.0%	100.0%
<b>Buildings</b>			
Space heating	Fuels	5.3%	23.2%
	Electricity	0.0%	32.3%
	Traditional biomass	0.0%	25.8%
Water heating	Fuels	0.0%	36.4%
	Electricity	0.0%	45.5%
	Traditional biomass	0.0%	36.4%
Cooking	Fuels	0.0%	62.5%
	Electricity	0.0%	100.0%
	Traditional biomass	0.0%	7.5%
Lighting, cooling and appliances	Fuels	0.0%	100.0%
	Electricity	0.0%	100.0%
	Traditional biomass	0.0%	100.0%
<b>Transport</b>			
Vans	Fuels	0.0%	23.3%
	Electricity	0.0%	100.0%
Heavy goods vehicles	Fuels	30.1%	26.6%
	Electricity	0.0%	100.0%
Cars	Fuels	0.0%	23.3%
	Electricity	0.0%	100.0%
Bus	Fuels	15.3%	36.6%
	Electricity	0.0%	100.0%
Motor cycles	Fuels	0.0%	23.3%
	Electricity	0.0%	100.0%
Rail freight	Fuels	0.0%	40.0%
	Electricity	0.0%	100.0%
Rail passenger	Fuels	0.0%	45.0%
	Electricity	0.0%	100.0%
Aviation	Fuels	48.4%	12.4%
	Electricity	0.0%	100.0%
Marine	Fuels	83.6%	4.5%
	Electricity	0.0%	100.0%

therefore the conversion matrices are  $3 \times 2$  for this sector.

In industry, it is assumed that changes in high-temperature process conversion efficiency are dominated by those in the steel sector. Currently electric arc furnaces produce only 25% of steel globally, but this is very variable across countries ranging from 50% in most OECD countries to only 10% in China (He & Wang, 2017). Electric arc furnaces use only 40% of the final energy of the blast furnace process route. We assume that the global industry shifts to the current process mix of the OECD. Production of iron by hydrogen direct reduction has a similar energy consumption to blast furnace production (Vogl et al., 2018).

Low-temperature processes in industry are very largely dependent on steam. Process change as a direct outcome of the energy transition is therefore unlikely (although the changing costs of different fuels may lead to innovation). The change envisaged here is therefore a shift from fossil fuel to electric boilers with a 20% conversion efficiency improvement.

Drying and separation processes at temperature below 120 °C are amenable to conversion to heat pumps using existing technology. It is assumed that 80% efficient boilers and 100% efficient electrical technologies are replaced with heat pumps with a coefficient of performance of 240% (Arpagaus et al., 2018).

It is assumed that space heating changes are achieved consistent with those in the buildings sector set out below. Changes in other end uses are assumed to reflect those in low-temperature process to ensure a conservative assessment of potential.

In buildings, space heating is the largest energy user in cool and temperate climates. From an efficiency perspective, the ideal solution is to use high-efficiency heat pumps. However, there are concerns that 100% substitution may not be economic due to the very large peak in winter electricity demand it could cause (Eyre & Baruah, 2015). We therefore assume that some hydrogen contribution will be needed. We assume that existing fuels are replaced by 90% electricity and 10% hydrogen. We assume a long term achievable efficiency of 310% based on air source heat pump data from the cold climate of northern China (Zhang et al., 2017), replacing fossil fuel boilers with an 80% efficiency and 100% efficient

electric resistance heating. For hydrogen use, we assume an efficiency based on a gas-fired heat pump (Critoph et al., 2020). Where traditional biomass is replaced, we assume 80% efficient (for space heating) traditional biomass stoves (Geller, 1982) are replaced with air source heat pumps.

For water heating in buildings, it is assumed that direct use of fossil fuels, electric resistance heating and traditional biomass are entirely replaced by electric heat pumps with an efficiency of 220%, which is the median value of a recent field study (Willem et al., 2017). Where the current fuel is traditional biomass, it is assumed to be used with an efficiency of 14% (for water heating) based on Geller (1982).

The paper assumes that cooking is completely electrified and that this efficiency is 80%, which is characteristic of a modern electric hob (Hager & Morawicki, 2013). Traditional biomass displaced is assumed to be used with an efficiency of 6% for cooking (Geller, 1982).

Lighting, cooling and appliances are already completely electrified. Further efficiency improvements can be expected, but none is assumed here to be the result of the transition.

In transport, it is assumed that electrification occurs in all modes to a greater or lesser extent. The likely penetration of electricity and the emission factors for different vehicle types are taken from a recent comprehensive review (Khalili et al., 2019).

It is assumed that light vehicles (cars and vans) are completely electrified. Internal combustion engine vehicles (ICE) with a fuel consumption of 0.782 kWh/km are replaced with battery electric vehicles (BEV) with a fuel consumption of 0.182 kWh/km.

For heavy vehicles it is assumed that only 50% of total vehicle distance travelled can be electrified, with the remaining 50% supplied from hydrogen fuel cell electric vehicles (FCEV). Fuel consumption data assumed are for ICE 3.51 kWh/km, for BEV 1.87 kWh/km, and for FCEV 2.11 kWh/km.

Bus fleets are assumed to be 80% electrified, with only long distance buses powered by hydrogen fuel cells. Fuel consumption data assumed are for ICE 4.09 kWh/km, for BEV 1.87 kWh/km, and for FCEV 3.12 kWh/km.

Rail transport is currently the most electrified transport mode. We assume that the transition will stimulate a continuation of this trend through to full electrification. Specific energy consumption for rail

freight engines is 0.04 kWh/tkm for electricity compared to 0.1 kWh/tkm for diesel engines. For passenger railways, the equivalent figures assumed are 0.09 kWh/pkm for electric trains and 0.2 kWh/pkm for diesel.

Aviation is generally assumed to be difficult to electrify, because of the weight of batteries and high power requirements. However, recent work shows that journeys of less than 2000 km might reasonably be electrified (Schafer et al., 2019). In this paper, we assume electrification of 33% of total air travel with the remaining 67% converted to hydrogen. Using data on passenger aircraft, the fuel consumption data assumed are 0.54 kWh/pkm for conventional planes, 0.2 kWh/pkm for electric planes and 0.39 kWh/pkm for hydrogen.

Marine transport remains an important mode for freight. It is widely seen as a difficult mode to electrify with more attention focussing on hydrogen and ammonia as zero carbon options. Here, we assume that electrification is limited to 10% in short distance trips such as ferries. Using data on marine freight, the fuel consumption assumptions are 0.042 kWh/tkm for ICEs, 0.019 kWh/tkm for electric ships and 0.039 kWh/tkm for hydrogen-powered ships.

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#### Declarations

**Conflict of interest** The authors declare no competing interests.

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