

Review

# Energy Efficiency or Conservation for Mitigating Climate Change?

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**Abstract:** Given that global energy use today is still dominated by fossil fuels, there is an urgent need to rapidly reduce its use in order to avert serious climate change. However, the alternatives to fossil fuels—renewable and nuclear energy—are more expensive, and have so far done little to displace fossil fuels. Accordingly, reducing energy use must play an important part in both averting climate change and avoiding the depletion of high energy return easily recoverable fossil fuel reserves. This paper examined both the potential and barriers to the adoption of energy reduction measures, with particular attention to domestic energy and passenger transport. The main finding was that energy efficiency approaches alone are unlikely to deliver anywhere near the energy reductions needed in the limited time available. Instead, most energy reductions will have to come from energy conservation, involving less use of energy-using devices, including private vehicles. Achieving such reductions will require changes in lifestyles, especially for residents of OECD nations.

**Keywords:** car travel; climate change; domestic energy; energy efficiency; energy conservation; equity; fuel prices

## 1. Introduction

Climate researchers sometimes conceptualise the global warming problem by means of the ‘carbon budget’ (or ‘carbon pie’). The carbon budget refers to the gigatonnes of carbon (GtC) in the form of carbon dioxide (CO<sub>2</sub>) that can be safely released into the atmosphere before seriously disruptive climate change occurs. In 2018, global carbon emissions from fossil fuel and industry alone were estimated at 10.1 gigatonnes of carbon (GtC) or 37.1 Gt CO<sub>2</sub> [1]. In 2007, Broecker [2] wrote that for every 4 Gt of fossil carbon burnt, the CO<sub>2</sub> atmospheric concentration rises by one part per million (ppm), resulting in the carbon budget size shrinking by 70–80 Gt per decade. Estimates for the current size of the budget vary, but according to a 2017 *New Scientist* article, ‘Climate scientists had estimated that this means we can emit no more than 70 (GtC) after 2015 [3]. At current emission rates, we will pass this threshold by 2022’. Other estimates put it as high as 200 Gt, but several researchers think it is smaller than usually modelled, because climate sensitivity is higher than usually calculated [4] and/or because the carbon budget for the 1.5 and 2 °C Paris targets will be ‘lowered by natural wetland and permafrost feedbacks’ [5].

The amount of fossil fuel carbon that can be burnt as fuel is also limited in another way: by limited reserves of fossil fuels (FFs). Although such reserves are usually regarded as several times the climate limit [1], such figures ignore the energy return on energy invested (EROI) which will progressively shrink as non-conventional FFs, such as oil sands, must be tapped and their environmental costs

eventually factored in [6,7]. Even if such corrected reserves are still much larger than the climate change carbon budget, it is still the case that FFs are not a long-term solution for global energy supply.

The authors and others have earlier shown [6,8–14] that the potential for environmentally sustainable renewable energy (RE) is also limited and may well be much lower than current global primary energy use. For RE to replace fossil fuels, there would need to be high technical potential, high energy return on energy invested [6,8], no shortage of available land [10,13], low energy losses for energy storage of intermittent RE, low costs and few environmental problems with very large-scale expansion [8]. These conditions are unlikely to be met [6,10–14]. Since the remaining possible energy source, nuclear power, is not expected to contribute more than a minor share of primary energy [8,15], it follows that not only must the use of fossil fuels be drastically cut, but the same is true for overall energy use. Present approaches for fossil fuel reductions are clearly not working: both primary energy and fossil fuel CO<sub>2</sub> emissions are again growing strongly—FF-derived CO<sub>2</sub> grew 2% over 2017 values in 2018 [1].

Energy use depends on the task and the efficiency with which it is undertaken. For example, in transport, the task could be described by the total number of passenger kilometers (p-km) travelled by private cars, and efficiency by the ratio of the task to the total energy (MJ) used by private cars (p-km/MJ). Therefore, cutting energy use can be achieved by either reducing the task through conservation measures or by reducing the energy consumed by the devices used to undertake a given task. Hence, energy can be cut by

- Using devices less intensively, for example, by driving each car less each year
- Reducing the number of energy using devices
- Improving the efficiency of some or all of the energy using devices used to undertake the task
- Using devices that have less energy embodied in them, for example a bicycle rather than a car.

Although listed separately, these factors can be coupled, particularly with embodied energy. Since size (either volume or mass) will scale with embodied energy, for many tasks, reduced embedded energy will lead to increased energy efficiency. The lower mass of a bicycle per unit passenger, for example, gives rise to reduced embodied energy and greater energy efficiency than a car. Similarly, using fewer energy using devices will ultimately mean less embodied energy, and this may give rise to increased efficiency; reducing the number of private cars, for example, may lead to an increase in car occupancy rates. Thus, while energy embodied in devices can be significant, and therefore need reduction, this reduction can either be brought about by conservation measures or as a direct consequence of improved energy efficiency. This is particularly the case for the sectors that are the focus of this paper: personal road transport and domestic energy use.

Researchers have studied intensively from a social psychology viewpoint how to influence households to reduce their energy consumption (see for example [16,17]). Most Organization for Economic Cooperation and Development (OECD) survey respondents claim to be concerned about the environment in general and about climate change in particular. However, this concern does not seem to translate into actions to cut greenhouse gas (GHG) emissions, where deep cuts are urgently needed. What are much less studied are the '*natural experiments*' which the detailed national statistical data from various countries allow. Countries (and sub-national units) vary by income per capita, income inequality, energy prices, transport regulations, climate, household size, degree of public transport use and population density, among other factors. This paper makes use of this data to explore both the barriers to using less domestic and transport energy and what can be done to overcome them in OECD, and to a lesser extent, non-OECD countries. (Note that non-OECD countries also include most former Soviet Union countries and OPEC nations, as well as all low-income countries). The overall aim was to examine both the prospects for, and barriers to, deep reductions in both energy sectors and the corresponding GHG emissions. These sectors were selected because households are directly responsible for energy use in residences and passenger transport energy, especially from private road vehicles. These sectors also allow a discussion on the scope for psycho-social barriers to energy

efficiency; with the industrial, agricultural and freight energy sectors, efficiency improvements are more likely to be dominated by economic reasons.

The rest of the paper is organised as follows. Section 2 examines the past and present global energy consumption by both energy sector and region (OECD versus non-OECD). Section 3 examines both the potential for energy reductions and possible barriers. New approaches to cutting energy use by using the latest information technology (IT) advances are considered in Section 4. In Section 5, the effect of energy prices on both energy efficiency and energy use overall is explored. Section 6 asks whether energy efficiency improvements can ever result in large *global* energy reductions. Since several earlier sections have questioned the potential for improvement, Section 7 explores energy use and conservation in a wider context. Finally, Section 8 provides a summary of the argument and discusses the implications of the paper for energy policy.

## 2. Global Energy Use Patterns

Table 1 shows total final consumption (TFC) and total primary energy supply (TPES) for the world as a whole, as well as the OECD and non-OECD groupings of countries for both 1973 and 2016. Although growth in TFC has occurred in all energy sectors, it has been especially rapid in transport. The category ‘other TFC’ is predominantly for energy use in residences and commercial buildings. For both regions and the world, the return on TFC from TPES, expressed as TFC/TPES, has reduced since 1973, largely because of increased electrification of TFC.

Worldwide, both the passenger transport energy used and the task have risen greatly over the period 1900–2016—by as much as a factor of 225. Estimates vary, but in 2016, global travel was probably around 45 trillion p-km [18]. Cars are now the dominant form of passenger transport worldwide, accounting for over 50% of all travel. In recent decades, ownership growth has been strongest outside the OECD [19], especially in China, which is now easily the world’s largest producer of private vehicles [20]. Commercial air travel has grown rapidly since the 1950s, and in 2016, it had a roughly 17% share of the global travel market. Air travel was expected to double over the years 2018–2037 [18,21].

**Table 1.** Energy statistics (in EJ) for 1973 and 2016, Organization for Economic Cooperation and Development (OECD), non-OECD, and the world.

Region	OECD		Non-OECD		World	
Year	1973	2016	1973	2016	1973	2016
Industry TFC	40.2	33.4	24.2	82.2	64.5	115.6
Transport TFC	29.2	52.0	16.2	63.4	45.4	115.4
Other TFC *	48.8	68.7	37.1	101.8	85.9	170.5
TFC	118.3	154.1	77.5	247.2	195.8	401.5
TPES	157.1	221.5	99.1	356.4	256.2	578.0
TFC/TPES	0.753	0.696	0.782	0.694	0.764	0.695

\* mostly buildings, but also includes agriculture and non-energy uses. Source: [22].

Since 1900, growth in domestic energy use has been far slower than that for transport, partly because of the progressive replacement of wood, coal and town gas by natural gas and electricity in OECD countries. A full list of OECD countries is given in [22]; all other countries are non-OECD. Total domestic energy use *per household* fell in all regions from 2000 to 2017, and ExxonMobil [23] forecasted this global trend to continue until 2040. In Europe and North America, *electricity* consumption per household was flat or falling from 2000 to 2017, with further declines expected until 2040. In all other regions, however, household electricity use is growing rapidly, a trend that is also expected to continue. Globally, only electricity use per household was forecast to grow; the use of all other energy sources will fall [23].

In absolute terms, ‘other TFC’ energy use in primary energy terms has still grown rapidly, as shown in Table 1, largely driven by the rise in global household numbers. Fuel wood is still an important

component of household energy TFC, accounting for 37 EJ in 2016 [23]. Even the poorest households use much of this low-efficiency fuel, so that household energy for cooking (and water heating) is comparable or even greater than that in OECD households. Absolute fuelwood use is expected to fall and be replaced by more efficient fuels, which will moderate growth in household energy use from rising appliance ownership, especially in Africa.

### 3. Energy Efficiency Improvement: Potential and Barriers

The published literature demonstrates the apparently great potential for improvement in the energy efficiency for all sectors of the economy, including passenger transport and household energy use [24–30]. Some researchers have even claimed that many energy efficiency improvements will pay for themselves, i.e., have negative cost. Therefore, the high historical energy growth rates for both sectors discussed in Section 2 are somewhat puzzling. The following two subsections discuss each of the two sectors in turn, and consider both the potential and barriers to energy efficiency improvement, such as the socio-economic factors encouraging or hindering the purchase and use of more energy efficient devices.

#### 3.1. Transport Energy Efficiency Potential

Lovins [24] has claimed that with a shift to electric drive vehicles combined with reductions in road load (the sum of vehicle inertial, air and rolling resistances) an approximately five-fold efficiency improvement is possible compared with equivalent conventional vehicles. Creutzig et al. [28] argued that all vehicular travel energy (including air) could be halved by 2050, even with some global demand growth, but this level of reduction would require a carbon tax of some \$US460 per tonne of CO<sub>2</sub> by 2050.

Others e.g., [31,32] have stressed that in practical terms, the scope for improvement is far more limited, especially for conventional internal combustion engine vehicles (ICEVs). Although the fuel efficiency of petrol cars is improving, diesel cars are generally more fuel efficient. However, concerns about NO<sub>x</sub> and particulate emissions from diesel vehicles has led several global cities to plan banning them, beginning in 2025 [33]. Going further, many countries are looking to eliminate new sales of *all* ICEV cars (or even all ICEV vehicles) entirely by the year 2030 [33,34].

Electric vehicles (EVs) look like the obvious replacement for ICEVs, and worldwide sales are now increasing rapidly. Forecasts made in 2018 predict several hundred million EVs globally by 2040 [35,36]. For comparison, the global car fleet was over 1.1 billion in 2017, and OPEC [19] projected a total of almost two billion by 2040. EVs are more energy efficient than equivalent conventional ICEVs, partly because of regenerative braking and lower accessory power demand. However, this benefit is partly cancelled out by the high embodied energy costs for EVs compared with equivalent ICEVs—mainly because of battery energy costs [37]. If passenger car ICEVs are phased out over the next two decades, the prospects for *all* ICEV fuels, including bioliquids and natural gas, are poor. Improving ICEV engine efficiencies would then be a dead end, except possibly for heavy vehicles where progress to find a replacement power system is well behind that for passenger vehicles.

Some researchers see, e.g., [38,39] believe that fully automated vehicles (AVs) could markedly improve energy efficiency, for several reasons. First, cars could thus be driven in the most ‘eco-efficient manner’, saving fuel. Second, cars could thus travel much closer together on roads so that air resistance on following vehicles would be reduced. Third, improved safety resulting from elimination of driver error—a contributory factor in most traffic accidents—would allow redesign of vehicles with present safety and manual control features removed. The resulting lighter vehicles would be more fuel-efficient.

Others, however, have argued that car fuel use could rise overall. With no need for drivers, the pool of possible car owners would be enlarged. Travel costs comprise money and travel time costs. With AVs, travel time cost would fall, since drivers could use their time for other purposes. Furthermore, the present time-use advantage of public transport would be lost, initiating a possible shift back to less efficient car travel. In summary, future vehicles could well be EVs, which should

improve fuel efficiency (in terms of vehicle-km per unit of primary MJ), but fully AVs are unlikely to lead to further energy reductions. Indeed, such vehicles are still decades away, and may never replace driver-controlled vehicles [40,41]. Finally, if only partly automated, the energy efficiency advantages would be largely lost.

One important barrier to the adoption of more fuel-efficient cars is the initial purchase cost. Lower-income households tend to own older, less fuel-efficient cars on average, so the reaction to a fuel price rise may be simply to drive less. Smaller, more fuel-efficient cars have been available for decades, but as shown below, the current trend in OECD countries is to purchase larger vehicles. An important reason is that vehicles are bought with maximum passenger loadings in mind, not the average load of typically 1.5 persons per car, and increased vehicle size can provide increased safety in mixed traffic. Another factor slowing fuel efficiency improvement is a trend toward more power-consuming auxiliaries, such as power steering, air conditioning and entertainment systems, and enhanced vehicle performance. Finally, car ownership and driving confer psychological benefits in terms of prestige and vehicle control; these will be greater for larger and more expensive vehicles.

In contrast to the claimed potential reductions from improved efficiency, the scope for energy reductions from social-psychological interventions has been seen as minor [29,42]. In a business-as-usual (b-a-u) world, the potential may indeed be small. Consider a major ‘TravelSmart’ trial conducted in the early 2000s in Perth, Western Australia, primarily aimed at providing personalised information about alternative modes to households. It was introduced into different local government areas (LGAs) at different times, allowing a natural experiment. Comparison of LGAs with TravelSmart intervention and matching LGAs in Perth yet to have the intervention showed no lasting significant effects on shifting motorists to alternative modes [43]. Overall, research suggests that in a b-a-u world, social psychological interventions of any type are of only minor value in affecting the large reductions in transport energy needed to combat further climate change [42].

### 3.2. Domestic Energy Efficiency Potential

The potential for domestic energy efficiency improvements differs from that for transport in several different ways. Whereas energy use in passenger transport is confined to devices, all of which provide a similar task, domestic energy use covers a multiplicity of tasks, including space heating and cooling, water heating, refrigeration, cleaning of clothes, dishes and rooms, lighting, and operating domestic appliances like TV sets and computers. Additional energy is needed to operate a variety of devices outside the home, such as lawn mowers.

Table 2, drawn from the 2014 IPCC report, gives estimates for the range of energy efficiency gains possible for various household and commercial buildings energy use functions. (For energy reductions from behavioural change for each end-use, the IPCC [29] found substantial but generally lower potential than was the case for energy efficiency improvement. Savings would come from actions such as lower thermostat settings in winter, shorter showers, full loads for clothes washing, etc.).

**Table 2.** Potential for efficiency improvements (%) for various building energy uses. Source: [29].

End Use Task	Efficiency Potential (%)
Heating	30–80
Hot water	60–75
Cooling	50–75
Cooking	25–80
Lighting	75–100
Refrigeration	40
Dishwashers	17+
Clothes washers	30
Clothes dryers	50+
Office computers & monitors	40

Pattanayak et al. [44] have claimed that 'Three billion people rely on traditional stoves and solid fuels'. Given the very low efficiency of traditional stoves in low income countries (as low as 5%), there is clearly a great scope for energy efficiency (and indoor air quality) improvement. Improved efficiency could be achieved by redesign of traditional stoves, or by shifting to modern energy sources, electricity and gas. However, the authors showed that cost is not the only barrier to their introduction, stressing, among other factors, the importance of matching the technology to local needs.

#### 4. Information Technology and Energy Reductions

A number of studies have assumed that application of the new information technology (IT) can significantly reduce energy use [45,46]. For vehicular travel, IT can potentially help in two ways. First it can directly substitute for travel: telework, telemedicine and on-line shopping are examples. The most successful use is for on-line shopping, but even here, it accounts for only a few percent of all consumer purchases by value. Its impact on travel has been negligible, because most shopping trips are for a variety of items. Buying some of them on-line does not necessarily reduce shopping trips [45]. Furthermore, items purchased on-line—apart from items like software—still have to be physically delivered to the customer's address, so that any savings in passenger travel energy are at least partly replaced by a rise in freight energy costs, such as for home delivery of prepared meals. Teleworking can also make a car available for household members who would not normally have a car available. In fact, recent research has found that at present, IT has ambiguous effects on travel behaviour [47,48]. It can lead to travel substitution in some cases, but the rise of social media connectedness can also generate increased travel. Rebound effects may also be important for reducing travel savings [49].

'Smart transport' promises further travel energy reductions. However, some of its applications, such as those that optimise parking spaces or traffic flow on city highways and streets, while helpful for *individual* motorists, may well simply encourage more use of cars at the expense of more efficient alternative modes. Research has shown that higher average traffic speeds in cities is strongly correlated with higher levels of city-wide per capita p-km and energy use [45,50].

Apart from smart transport, 'smart cities' and even 'smart homes' are promoted as another way in which IT could reduce energy [51–53]. Proponents of Smart Home Technology claim that a 30% reduction in household energy is possible [54]. At first glance, this seems reasonable; Lesic et al. [55] have documented householder misconceptions of energy use, such as over-estimating electricity consumption of low-energy appliances and underestimating that of high-energy use ones. Moreover, householders lack information on possible energy savings from specific actions. Surely, IT can address these information shortcomings?

However, as reported by Herrero et al. [54], according to a recent review by Hargreaves et al. [56], 'there is little evidence that smart home technologies will generate substantial energy savings and, indeed, there is a risk that they may generate forms of energy intensification'. Herrero et al. added that such energy intensification could come about through 'pre-warming domestic spaces before residents come home, raising comfort expectations or encouraging the adoption of additional energy-using technologies'. They further reported that many households have difficulty in using the new technology.

One possible reason for overestimating the savings from smart home technology is that (many) householders themselves already exhibit some smart behaviour. They do not, for example, attempt to maintain a year-long target temperature setting of (say) 20 °C, but turn it down or off when absent, and when the weather is mild. They turn off lights when not needed. The base rate chosen for energy savings is thus set too high [54].

Smart meters, capable of giving much more information on use to the householder than traditional meters, are already used in several countries. Again, to date, the results have been disappointing. [42]. Nevertheless, IT could be an important part of both transport and domestic energy reduction in cities if and when governments decide that energy use must be drastically cut for climate change mitigation.

## 5. Energy Prices, Energy Efficiency and Conservation

There is much controversy over the relative effectiveness of non-monetary vs. monetary interventions for enhancing environmentally friendly behaviour (EFB). Non-monetary interventions, in turn, can be divided into government mandates—such as energy efficiency standards for vehicles or insulation standards for homes—and social psychological interventions. The research of de Groot and Steg [57] and Asensio and Delmas [58] has suggested that non-monetary are superior to monetary approaches for promoting general EFB. The reasoning is that if the monetary benefits of more efficient vehicles are lost—as can happen with reductions in fuel price—the motivation for EFB is also lost. Indeed, Fowlie and colleagues [59] found that in the US, a home weatherization program was not cost effective for householders.

However, the global interest in carbon pricing suggests that cost-based approaches for energy and thus carbon reductions cannot be ignored. Although the above suggests a variety of ways for effecting energy reductions, this section is restricted to examining how price increases for fuels affect transport and household energy consumption.

### 5.1. Transport

For transport, a large number of policy measures are available to governments at either the local, regional, or national level. Those directly affecting the cost of passenger travel include

- Road user charges
- Road fuel taxes
- Structure of motoring cost changes
- Subsidies for alternative fuel vehicles
- Parking prices (and controls)
- Free public transport.

In most OECD countries, diesel fuel is much cheaper than petrol, with the exception of the US, and to a lesser extent, Australia, Canada and the UK [22]. Given the greater efficiency of similarly sized diesel vehicles, the cost difference per vehicle-km is actually greater, even if diesels are generally more expensive to manufacture. This lower effective cost explains the much greater take-up of diesel for cars in continental Europe. If diesel passenger vehicles are phased out, car fleet vehicle efficiency could stagnate or even drop for some years.

Car travel per capita is generally much lower in countries with higher fuel prices. Most of the variation in fuel prices is the result of varying fuel taxes, which would seem to indicate that higher fuel taxes are effective in lowering car travel demand. Furthermore, EU countries levy purchase taxes based on rated grams CO<sub>2</sub> per vehicle-km, with higher rates for higher emission vehicles [60]. With the exception of oil-exporting Norway, most countries with high fuel taxes are also those with low fossil fuel reserves [1,22]. In Norway, the combination of high petrol taxes (which includes a CO<sub>2</sub>-based *fuel* tax) and close to 100% of electricity generated from hydropower [1] has resulted in the world's highest penetration of electric vehicles [61].

Of course, it is possible to achieve any desired level of fuel reduction if fuel prices are raised sufficiently high, perhaps by means of a carbon tax. However, such price increases will disproportionately disadvantage lower-income households—at least for transport in high car ownership OECD countries. Australia's large cities illustrate this equity problem. Incomes closer to the city centres are generally higher than in outer suburbs. Car ownership shows the opposite trend because of both higher speeds for outer suburban travel (thus increasing the convenience of car travel) and a relative lack of public transport, especially fixed rail [50]. Therefore, outer suburbs have high ratios of cars—and travel costs—to income [62].

For the US, low energy costs do partly compensate for the unequal income distribution. However, in many countries of the world, car ownership is below 20 per thousand population, and most travel is

done on foot or by public transport [63]. Thus, higher fuel prices represent much less of an equity issue in these countries. Given the more efficient transport modes already used in such countries, there is reduced prospect for improved energy efficiency for personal transport relative to the OECD countries.

Another method for reducing energy use is to change the *structure of costs* for motoring. Fuel costs for motoring are often a minor share of the total costs of owning and operating a car. It is possible to shift costs such as vehicle insurance, registration and driving licence fees onto fuel costs, while keeping total costs on average unchanged. Again, in cases where lower income households drive more km than the average, this approach could prove inequitable. An additional compounding factor is the difficulty of taxing the fuel used by EVs since these may be charged at any available outlet. It is likely that regulators will need to find new ways to tax vehicles once EV ownership reaches a critical value.

## 5.2. Domestic Energy

In contrast to transport, few policy instruments are available to governments to cut domestic energy use, possibly because unlike transport, which mainly takes place on public rights of way, dwellings are private spaces. The useful life of dwellings is several times that for vehicles, which hampers the introduction of energy-saving innovations. Moreover, given that annual road fatalities number about 1.2 million worldwide, with millions more injured, governments feel they have a mandate to exercise greater control. For households, policies that have been adopted include efficiency ratings for appliances and minimum insulation standards for dwellings.

Like transport, variations in national domestic energy prices—largely reticulated electricity and natural gas (NG)—again allow a natural experiment to be conducted. However, given the importance of space heating in higher latitude zones, comparisons are best done between countries or regions with similar climates (and comparable living standards) but different energy prices. In 2017, domestic NG prices in the US were less than half of those in other high-income OECD countries. Also in 2017, US domestic electricity prices were higher than those in Canada or Norway, but again less than those in most other income-comparable OECD countries [22]. Domestic energy use ‘in Denmark, Germany and Sweden was appreciably lower than that of the US, despite having generally colder climates’ [61]. Average climate was roughly assessed by comparing the latitudes of population centroids for each country.

As for transport prices, equity considerations are important. Lower income households spend a higher share of their disposable income on utility bills than higher income ones [42], even though this share is still very modest by historical standards [64]. Higher domestic energy prices in Europe compared with the US are partly mitigated by more equitable income distribution. Changing the structure of domestic energy costs is another option. At present, in Australia, at least, low energy consuming households are perversely penalised by the high proportion of fixed costs in their fuel bills. (And if renting, they are unlikely to have domestic solar PV, and would not upgrade insulation, or heating/cooling system efficiency etc.)

## 6. Does Energy Efficiency Improvement Result in Energy Overall Savings?

An important question is the level of *global* energy savings possible with efficiency improvements. Several factors act to limit or even negate overall energy reductions:

- Energy efficiency rebound
- Global growth in air travel, and ownership/use of private vehicles and domestic appliances
- Shift to less efficient transport modes
- Continued mechanisation of household tasks
- Increasing primary energy needed for each unit of final energy.

Improving the energy efficiency of any device does result in lower operating costs for the consumer. However, this lower cost means that consumers can now either afford to use these devices more, or alternatively, purchase other (energy-using) goods or services with the savings. This so-called *energy*

*rebound* offsets to some extent the energy savings from efficiency gains. For transport, Munyon et al. [65] have found empirical evidence for this in the US: increasing vehicular fuel efficiency by 1% led to a 1.2% increase in vehicle-km.

Although rapid growth in car ownership has occurred in non-OECD countries in the last two decades, the 2017 global level was still only 146 cars per 1000 population [19]. In wealthier OECD countries, it was nearly four times higher. With a near-doubling of the global car fleet expected shortly after 2040, the potential for significant global fuel increases, even with efficiency gains, is evident, and has been forecasted by OPEC [19], ExxonMobil [23], and BP [66].

Not only do non-OECD countries on average have far lower per capita levels of vehicle ownership or air travel than OECD countries, but also much lower levels of domestic appliance ownership. For the US, Desroches et al. [67] have shown that real costs for such appliances fell by about three-fold over the years 1970–2010, with further price falls expected. Weiss et al. [68] have also documented real cost reductions for large domestic appliances, as well as energy efficiency improvements. The huge unmet demand in lower income countries for appliances such as air conditioners, together with falling costs, suggests that any energy efficiency gains will be swamped by greatly increased demand. A related reason for increased domestic energy use in all countries is the progressive replacement of human by mechanical energy for domestic tasks, and in OECD countries, for garden tasks as well.

Another possible reason why reliance on vehicle efficiency improvements is unlikely to deliver the absolute reductions in transport energy needed is that new modes of transport may still arise—or be resurrected. Plans for super-sonic plane travel are being revived [69]. NASA is even planning to allow two trips each year by ‘private astronauts’ to the International Space Station, starting in 2020 [70]. Similarly, if the past is any guide, novel household appliances will continue to appear.

In recent decades, each transport mode has seen steady improvements in fuel efficiency [71]. However, at the same time, the less-efficient transport modes increased their share of the total travel task. Therefore, in terms of market share, the train replaced non-motorised travel, and was, in turn, replaced by the car [72]. In recent decades, air travel has shown rapid growth: growing nearly eight-fold from 1977 to 2017 [21]. Even within the private vehicle market, sports utility vehicles are gaining market share over lighter conventional cars in North America, the European Union and Japan [73–75]. Even in China, now the world’s largest auto manufacturer, the average weight of light duty vehicles is rising [76]. Improving the seat occupancy rate is another method for improving energy efficiency on a p-km per MJ basis. Although it has improved for air travel in recent decades, the opposite is true for car travel, the result of rising multiple-car ownership in households and declining household size [45].

In the future, another barrier to achieving overall energy reductions will be the rising costs of converting primary energy (for example, crude oil or coal) into useful fuels such as petrol or electricity. Energy efficiency of lighting is measured by lumen/watt of electricity, vehicles efficiency by vehicle-km/MJ, and it is possible for these efficiency measures to improve at the same time as overall primary energy use in these sectors is constant or even rising. Any large-scale move to non-conventional fuels such as Canada’s oil sands, or the need for carbon capture and storage (CCS) in the case of fossil fuel-fired electricity plants, would increase the energy costs of energy [8,77].

## 7. Looking Beyond Efficiency

Shove [78] is critical of the concept of (technical) energy efficiency and doubts that it can, by itself, lead to energy reductions. She argues that ‘efficiency strategies reproduce specific understandings of ‘service’ (including ideas about comfort, lighting, mobility, convenience), not all of which are sustainable in the longer run’. Max-Neef et al. [79] have made the important distinction between basic human needs (shelter, food, sociality, etc.) and the way we humans satisfy such needs—the satisfiers. While basic human needs are a given, the choice of satisfiers can be met in a variety of different ways, including non-commercial ones [80]. Hence, we need to ask the questions: what human needs are we trying to satisfy with transport and domestic energy consumption, and are there more sustainable ways of meeting them?

### 7.1. Transport

For transport, nearly all discussions focus on using less energy to deliver the same or more *mobility* (in terms of vehicular p-km). The importance of very high mobility is rarely questioned. Given that transport overall has a 29% share in global final energy use in 2016 [22], this high energy use has to change. We need to look beyond mobility and ask what service mobility is meant to provide. The answer is, of course, *access* to activities outside the house: accessing work, school, shops, friends, etc. [50]. True, mobility is potentially much easier to measure than access, which has an inevitable subjective component. Is it possible to achieve a desired level of access with much lower levels of (vehicular) mobility?

Urban travel per capita has risen several-fold in most OECD cities outside the US since the 1950s, with car travel accounting for all the net increase. What did this hypermobility [81] achieve in the way of access? Australian data indicate that journey to work or school travel distances have not risen for decades, and the combined share of total population at work or school has also changed little [50,62]. Hence, most of the travel increase was for non-discretionary trips, including social and shopping trips. This large increase in personal travel levels suggests that, in OECD countries at least, households have become locked into high-travel lifestyles. Yet, before the rise of the car in various countries, households did not regard lack of access to activities as a particular problem. It is the *convenience* of car travel that has led to today's hypermobility [50]. If such convenience was reduced—and given its unwanted side effects like traffic accidents, air pollution, noise and community disruption—accessible cities could be created at much lower personal travel levels.

One approach is to reverse the usual priority of transport planners, with non-motorised modes favoured over vehicular modes, and public transport over private car travel. As shown by the list in Section 5.1, some policies do try to at least partly overcome the dominance of car transport. Non-motorised travel was the dominant mode until early in the 20th century, and is the most energy efficient of all travel modes. Public transport is typically several times more energy efficient than car travel, depending on occupancy rates, and is also much more land-use efficient [50,82]. Car-sharing could be a backup to the preferred modes—Spangenberg et al. [80] reported that in Germany, the car was only used for about 29 min per day. Its primary purpose, it would seem, is to occupy space that could be otherwise used.

### 7.2. Domestic Energy

As is the case for transport, we need to ask what services domestic energy is meant to provide. In general, the answer is to provide occupants with a comfortable, safe and sufficiently illuminated environment, to enable personal hygiene and the cleaning of clothes, dishes and rooms, for food preservation and cooking, and for entertainment, instruction and social activity.

The most important energy use is for domestic heating and cooling—in the US in 2017, it accounted for some 51.4% of final domestic energy use [83]. Energy efficiency of buildings is assessed per m<sup>2</sup> of floor space. But occupants, not rooms, need to maintain temperature within a certain range for thermal comfort. For warm climates (and summers in temperate zones), *acclimatisation* can markedly affect personal comfort for a given temperature. Residents of warm climates can feel comfortable at 34 °C [84], but acclimatisation is undermined if people continually move between air-conditioned spaces and outside. Appropriate clothes—in both homes and workplaces—can also help maintain personal comfort [85].

The urban heat island effect results from a combination of factors, including urban heat release and the increase of non-evaporative surfaces. It acts to reduce heating needs in the warmer months, but raises cooling needs [86,87]. On the other hand, efficiency improvement methods, such as reflective wall coatings, will decrease summer cooling loads but raise winter heating needs [88]. Most building energy losses occur through the walls and windows [89], and retrofitting can reduce these losses. However, it is necessary to balance the energy/monetary costs of such retrofitting with the resulting energy/monetary cost savings [90].

The stress on efficiency also implicitly assumes that *active* energy will be used. But for heating and cooling buildings, as well as lighting, *passive* solar energy can supplement or even largely supplant active means, as has been the case for many centuries with vernacular architecture. It is difficult to separate passive solar energy consumption from energy conservation, as it involves active and intelligent occupant participation. Occupant behaviour can make a large difference to household space heating and cooling costs [91–93]. This could involve opening and closing doors, windows and curtains/blinds at various times of the day for light and temperature control. Intelligent homes need intelligent occupants.

## 8. Discussion and Conclusions

### 8.1. Discussion

Although surveys consistently show high support for environmental values, this seldom translates into energy use reductions [94]. In general, three conditions are necessary for meaningful reductions. Steg [95] has listed these as adequate *knowledge* (for example, of public transport alternatives to the car), *motivation* to change, and *ability* to make the changes necessary (viable alternatives must be available to the household). Clearly, at present, one or more of these conditions are not being met in either sector.

Given that results of various interventions to date have proved disappointing, there is clearly a need to go beyond a b-a-u perspective when considering energy conservation. An important justification for the present stress on energy efficiency is that it requires minimal social change. What circumstances could ever bring about political support for the changes needed for deep energy conservation? Implementing such changes presently looks like an impossible task; in OECD countries at least, high-energy living patterns are deeply entrenched. However, we will need to question the high energy consumption lifestyles already practiced by OECD countries and seemingly aspired to by the rest of the world [96].

Given that daily temperatures can vary by tens of °C, the one °C or so increase since pre-industrial times is barely noticeable. But what is already noticeable for a rising share of the world's people is an increase in the frequency and severity of extreme weather events [97,98]. Lawton [99] has pointed out that in as little as a decade, the climate could change in unpredictable ways. Such changes could make the general public more amenable to more robust action on climate change mitigation.

For transport, there are already early signs that the ICEV, and perhaps even cars themselves, are being called into question [9,24], independent of climate concerns. Fundamental changes could include policies which restrict the convenience of car travel [50]. For example, restrictions could be placed on parking availability, speed limits could be greatly lowered and inner-city areas could be converted to pedestrian only precincts. Such changes would have multiple benefits: energy and GHG emission reductions, less air pollution, traffic noise, traffic accidents, more personal exercise and more urban land available for other purposes because of reductions in land devoted to carparks and roads.

### 8.2. Conclusions and Future Research Needs

Reducing energy use itself is important because fossil fuels account for most energy used in the world today, and it will take decades for the world to fully shift to non-FF energy sources [100,101]. The carbon budget remaining for us before serious climate change occurs decreases with each year of inaction. Furthermore, even if RE could supply the levels of energy expected in future, it will be more expensive than FFs. Given that passenger transport and domestic energy account for a major part of global final energy consumption [22], the need for deep energy cuts in these sectors is evident.

Increasing the efficiency of all energy-using devices, or reducing their use by any means—energy conservation—are the two approaches for reducing energy consumption. In this paper, it was shown that the net reductions that can be expected from energy efficiency improvements alone are at best quite modest, mainly because of the large expected rise in air travel and ownership of cars and domestic appliances, particularly in non-OECD countries.

Surveys suggest, at least for OECD countries, that only minor potential for transport energy savings can be expected from social/psychological interventions [102]. For domestic energy, conservation is viewed as having considerable potential (much larger than for transport energy efficiency), but the behavioural changes needed would be significant. Although, as argued above, the barriers to the adoption of energy efficient equipment can be significant, they are minor compared with the challenges facing the adoption of lower energy lifestyles. Setting fuel and electricity prices sufficiently high would encourage energy reductions, in the short term by conservation and in the longer term by purchase of more efficient devices. However, data from current energy prices [22] and energy use in various OECD countries, suggest that very large price increases would be needed, especially for transport fuels, with obvious equity implications.

Another approach is urgently needed to supplement technical energy efficiency improvements. Given the large number of energy-using devices in OECD households, there is no single approach that will dramatically lower domestic energy use. Nevertheless, we need to look first at OECD countries such as Japan, which have both much lower ownership of high using energy devices—such as refrigerators/freezers—than, for example, in the US [42,83,103]. The OECD countries could also learn from their own low-energy past and even get inspiration from practices in presently low-energy use countries.

The socio-political changes needed for deep energy conservation are significant, but the reality of a deteriorating climate could shift public opinion. Although the policies might appear to have little chance of adoption, transport changes previously thought unthinkable are already being seriously considered [9].

A vast amount of research on energy efficiency of both vehicles and buildings has been published. However, the potential for passive solar energy in buildings could be explored further. There is also much research published on the social psychology of adoption of energy efficient equipment and conservation measures, but nearly all this previous research assumes that minimal change in lifestyles are needed. More research is needed on both the mechanics of social change, and the development of policies for deep conservation.

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## Abbreviations

b-a-u	business-as-usual
BEV	battery electric vehicle
CCS	carbon capture and storage
CO <sub>2</sub>	carbon dioxide
EFB	environmentally friendly behaviour
EIA	Energy Information Administration
EJ	exajoule (10 <sup>18</sup> joule)
EROI	energy return on energy invested
EV	electric vehicle
FF	fossil fuels
GHG	greenhouse gas
GJ	gigajoule (10 <sup>9</sup> joule)
Gt	gigatonne (10 <sup>9</sup> tonne)
GtC	gigatonne carbon
ICEV	internal combustion engine vehicle

IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LGA	local government area
Mt	megatonne (10 <sup>6</sup> tonne)
MW	megawatt (10 <sup>6</sup> watt)
NG	natural gas
OECD	Organization for Economic Cooperation and Development
OPEC	Organization of the Petroleum Exporting Countries
p-km	passenger-kilometre
ppm	parts per million
RE	renewable energy
TFC	total final consumption
TPES	total primary energy supply

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