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THE SCOPE OF INNOVATIVE DESIGN IN ENHANCING ENERGY EFFICIENCY

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ABSTRACT

Most official energy forecasts regard major energy efficiency improvements as a key means of reducing energy use and associated greenhouse gases. This paper examines past and current energy efficiency improvements in various sectors and concludes that absolute energy reductions are very difficult to achieve in a growth-oriented global economy with continued population rise.

Keywords: climate change, energy efficiency, domestic energy use, economic growth, equity, feedback effects

Abbreviation	
CO_2	carbon dioxide
EIA	Energy Information Administration (US)
EROI	energy return on energy invested
GHG	greenhouse gas
GDP	Gross Domestic Product
GW	gigawatt (10^9 watt)
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
MJ	Megajoule = 10^6 joule
OECD	Organization for Economic Cooperation and Development
RE	renewable energy
SUV	sports utility vehicle
TTW	Tank-to-Wheels
TWh	terawatt-hour (10^{12} watt-hour)
WTT	Well-to-Tank

1. INTRODUCTION

Improving energy efficiency is often seen as an important means of reducing both absolute annual levels of energy use and the greenhouse gas (GHG) emissions from fossil fuel combustion. The difficulty here is how to achieve this aim? One promising direction is to transition to sustainable modes of consumption and production, which is gaining a lot of interest from the research community, with a niche focus on technological innovation to help find solutions to socio-technical challenges of today and tomorrow [1].

Energy analyst Amory Lovins [2, 3] has long argued that improving energy efficiency can not only dramatically cut energy use but can also save money. For example, he has argued that with possible reductions to the road load, coupled with electric drive, '1-2 litre gasoline equivalent/100 km fuel economy' is achievable [3]. He has coined the term 'negawatts' for these energy savings, pointing out that energy savings are equivalent to new energy output capacity.

Cullen et al [4] have detailed the potential savings possible from more careful design of household appliances, vehicles, buildings etc. Overall, they have estimated that globally, 73% of existing energy use could be saved by such design changes.

Recent energy forecasts from both official sources and energy companies also see efficiency as an important means of at least stemming global energy growth [5-9]. All predict large annual decreases in *energy intensity* (as measured by primary energy per dollar of GDP), but not enough to offset rising global GDP. BP [5], for example, forecast energy intensity falling by nearly 2% annually over the period 2017-2040.

These organisations also predict continued rises in energy-related CO_2 emissions, but given the increase in extreme weather events the world is presently experiencing, drastic action is needed. As we enter an age of smart systems and machine learning, emerging technologies are primed for sustainability to make systems both cost- and resource- efficient [10, 11]. But the journey towards sustainability may not be as clear cut as is often assumed.

The central puzzle is this: if energy efficiency can be achieved by designing smarter systems that really have the very large potential shown by Lovins [2,3] and Cullen [4], why hasn't it become the main approach for climate change mitigation? This paper is an attempt to answer this question.

2. BARRIERS TO EFFICIENCY IMPROVEMENTS

Realising the potential for energy efficiency will involve overcoming a number of obstacles, including the inertia of existing practices, and sunk costs in existing equipment such as vehicles. These are discussed in detail in the following sections.

2.1 Energy is not the only efficiency metric

In general terms efficiency is a ratio of some desired output to the various inputs, both measured in compatible units. Efficiency is to be maximised, since inputs have some cost. There are, however, a number of other humanly desirable efficiency metrics besides energy efficiency. These include *land use* efficiency, important where land has a real or imputed rent as in agriculture, where it is termed yield (tonnes/hectare). Other efficiencies are *capital* efficiency, measured as the monetary rate of return (%) on some commercial undertaking, and *labour* efficiency (output per hour of labour). '*Time* efficiency' (speed of transport for example) is also important, since the number of hours per day is fixed for all of us.

The problem for energy efficiency improvements arises because these can often be in *conflict* with each other. Thus, traditional agriculture was usually much more energy efficient than industrial agriculture, but had both lower yields per hectare and lower output per worker [12]. Ship freight is far more efficient in terms of tonne-km per megajoule (MJ), but is no use if deliveries must be made overnight. Similarly walking is more energy efficient, but slower, than vehicular travel. And in growth-oriented market economies, energy efficiency usually takes second place to rates of monetary return.

2.2 Energy efficiency gains don't necessarily reduce total energy use

At the level of a given device, such as a motor vehicle, it is possible to have large improvements in energy efficiency for that device, but still have global growth in primary energy consumption for all such devices (for example, all motor vehicles). Indeed, this is what has actually occurred in recent decades. There are several reasons for this puzzling outcome.

1. There is global growth in the number of energy-using devices, as ownership levels of cars, refrigerators, air conditioners etc, continue to rise. Even in OECD countries, some growth in car ownership is still occurring, as is air travel. In countries outside the OECD, there is a huge unmet demand for cars, domestic white goods and air travel. Growth in white good sales will be helped by the global decline in real prices of these energy-using appliances [13, 14]. Sales of air conditioning units are likely to rise even faster as the frequency of heat waves increases.

In some low-income countries, per capita levels of electricity consumption and vehicle ownership are just a few percent of OECD country levels [6, 15]. In the extreme case, electricity use per capita in Iceland is *three orders of magnitude* larger than that for poor countries like Haiti or Eritrea [6]. Even if *per capita* energy levels fell, it could still be negated by continued global population growth.

2. Another major reason for continued energy growth is the shift to higher performance devices or greater intensity of use. With cars, this has taken the form of increased energy needs for accessories (air conditioning, power steering), better acceleration characteristics, and a shift to larger vehicles such as sports utility vehicles.

For instance, Automated Vehicles are a popular emerging technology being explored by many companies as the future of transport, because of the potential for increased efficiency and reduced human error. But while it may seem logical to expect a reduced impact on the environment, the efficiency and productivity gains for individuals will likely lead to higher levels of vehicular transport and so increased energy consumption. Until the transition to renewable energy is complete, fossil fuel consumption for transport and energy generation will continue to have an environmental impact [16].

The example of the US is instructive. In 1970, cars accounted for 82.6% of all highway vehicle-km, and '2-axle, 4-tyre vehicles' i.e. SUVs) for only 11.1%. By 2015, the figures were 46.7% and 43.1% respectively [17]. Both cars and SUVs registered efficiency improvements, but the less efficient SUVs gained a greatly increased market share.

Large screen TV replace conventional sets, largely negating any efficiency gains. Compact fluorescent lighting is far more efficient (in terms of lumen/watt) than incandescent bulbs, but the number of lights has multiplied with the rise of security and advertising lighting. And, of course, in transport overall, car (and air) travel have largely replaced the more energy efficient public transport and non-motorised modes.

3. In a growth-oriented market economy, new energy-using products and services are constantly being developed. Sometimes they replace former household non-powered devices by powered ones, as with vacuum cleaners, dish washers, lawn mowers, leaf blowers and hedge clippers. This mechanisation of formerly manual tasks is still continuing. Other products are entirely new, such as bitcoin 'mining', which is highly energy-intensive [18], or bottled water, which (partly) replaces energy efficient reticulated water with water in small plastic bottles delivered by small trucks. There is now even talk of 'space tourism'. If this ever became widely adopted it would greatly increase transport energy use.

4. Feedback effects can also undo any efficiency gains [16]. In energy studies the term used is 'energy rebound'. Rebound is an example of 'unintended consequences' which are endemic in society. Improving the efficiency of a device such as a car, for example, has the effect of lowering the costs of car operation (measured as cents per vehicle-km). If car travel is elastic, overall car travel will rise, thus offsetting much of the energy savings. Even if, in this example, car travel is inelastic, travel costs will be reduced, allowing householders more money to spend on non-travel goods and services, with further associated energy costs.

2.3 Socio-economic barriers to improving efficiency

There is a large literature on obstacles to improving energy efficiency, especially at the household level [e.g. 19-22]. These include the low payback time households want from purchase of energy-efficient appliances and vehicles, and their lack of knowledge of the energy use of various household appliances.

Another reason why saving energy may not be a key concern—for both households and businesses is the present low money cost of energy. According to Fouquet [23] real energy prices in Europe in 1750 were several times higher than they are today, even though per capita incomes were only a fraction of those today. Generations of households, especially in the West, have grown up with cheap energy for transport and domestic energy. Further, as shown in Section 2.1, energy efficiency is not the only efficiency measure that is important in modern economies.

One increasingly popular method for reducing GHG emissions, partly by improving energy efficiency, is to impose carbon pricing. Already, about 20% of global commercial energy use is already subject to carbon taxes [24] of varying, but generally low severity. As shown by the recent demonstrations in France, increases in energy prices will not be popular.

Further, even given the social changes necessary for their successful introduction at levels which would make a real difference to GHG emissions, the reductions would mainly come from reduced use of domestic equipment and personal vehicles, rather than improvements in energy efficiency. The main reason is that household appliances, and especially vehicles, have long useful lives. Householders will either use them less for example by partly switching to public transport or non-motorised modes), or use them at lower intensity (such as resetting room temperature controls) as an alternative to purchasing the new, more energy efficient appliances or vehicles. Lower income households are particularly likely to the adopt conservation as an alternative to purchasing new equipment.

2.4 Increased energy costs of producing energy

Overall energy efficiency consists of two components. The first is what for transport vehicle efficiency is called the 'Well-to-Tank' (WTT) efficiency, the second is the 'Tank-to-Wheels' (TTW) efficiency. However, the terms can be generalised for other energy-using sectors. Overall efficiency is the product of these two efficiencies. Although device efficiency (TTW), as already discussed in Section 2, may continue to improve, it will be offset by possible rises in the conversion of primary energy (such as fossil fuels in the ground) to secondary energy (such as petrol or electricity) i.e. rises in the WTT efficiency. A related term for WTT efficiency is the energy return on energy invested (EROI).

A good example of declining WTT efficiency is the steady move to unconventional fossil fuels such as polar and deep-water oil, and particularly oil sands. Brandt [25] has demonstrated the much larger energy costs for delivering a litre of shale oil-derived petrol to a car tank compared with conventional oil. Murphy [26] has shown that even for conventional oil, the energy costs per barrel have risen over time for both the US and the world as a whole.

It is not only fossil fuels that are experiencing declines in generalised WTT energy costs per unit of energy—the same is true for renewable energy (RE) sources. For hydro and geothermal power, there is evidence that the annual electricity output (TWh) per installed gigawatt (GW) is falling worldwide [27]. Other factors that will tend to increase RE conversion energy costs are declining quality of RE resources (e.g. wind speeds) as output rises, the need for energy storage as intermittent RE sources (chiefly solar and wind) come to dominate energy production and, for bioenergy, competition for input resources (fertile well-watered soils) from agriculture [28, 29].

3. DISCUSSION AND CONCLUSIONS

Some researchers consider than nearly an order of magnitude improvement in overall energy efficiency is possible. If this translated into equivalent overall energy savings, it would largely solve the climate change problem, and would do so at a cost much lower than alternative mitigation options. For transport it would further greatly reduce air pollution and fears about national energy security.

However, as discussed in Section 2, there are a number of reasons why achieving absolute energy reductions with energy efficiency is proving very difficult with merely innovative & alternative solutions. What then, are the alternatives for achieving deep reductions in GHG emissions? As discussed elsewhere [27-30], technical fixes including non-carbon fuels, carbon dioxide removal and geoengineering, even if they do work as planned, will likely provide too little, too late.

In conclusion, research into new forms of satisfying basic human needs like food, energy and transport, is increasingly geared towards sustainability. Although the impetus for innovation and design might not always be limited to environmental sustainability, the need for cost-efficient and resource-efficient systems is deeply rooted in the concept of ecological preservation, and thus innovation toward financial and social sustainability is consistently moving towards environmental sustainability too. This journey toward sustainable systems involves redesigning existing infrastructure, which itself has a considerable impact on the environment. Unfortunately, not all innovations geared towards sustainability have an immediate benefit for the environment. At the same time, many innovations already exist to limit our environmental impact, but they have not been tapped because of social regulations, customs, cultural inertia and lack of awareness or social stimulus towards eco-preservation.

We will need to look beyond the innovative designed technical solutions, and taking a more wholistic view, look more to social changes supported by policy changes needed to produce the deep cuts in GHGs necessary for climate change mitigation.

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