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Review

Rethinking Notions of Energy Efficiency in a Global Context

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Abstract: Energy efficiency is, in principle, a simple idea: an output of human value, for example, vehicle-km traveled, divided by the needed input energy. Efficiency improvements are regarded as an important means of mitigating not only climate change, but also other environmental problems. Despite the vast number of articles published on energy efficiency, a few people question whether it is a useful or accurate measure in its present form; nearly all papers are either engineering studies, or address barriers to efficiency improvements. This review addresses this issue via a critical review of the literature, including not only papers on energy efficiency, but those on adjacent areas of research that can help broaden the scope, both geographically and conceptually. These shortcomings are illustrated in case studies of buildings/cities and road passenger transport. The main findings of this review are that (1) energy efficiency inevitably has an ethical dimension, as well as a technical one, in that feedbacks are more widespread than they have generally considered to be, and (2) that conventional efficiency measures omit important energy input items, particularly those concerned with the mining the materials needed for renewable energy plants. The key conclusions are that present efficiency measures are not adequate, and future research is needed to overcome these shortcomings.

Keywords: buildings energy efficiency; climate change; energy efficiency; feedback effects; passive solar energy; renewable energy; transport energy efficiency; urban heat island

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1. Introduction

Humans have always used energy. Initially, it was used to process food, which is needed by all heterotrophs. Fire was discovered and utilized by humans hundreds of millennia ago, and much later, renewable energy sources such as wind and water power were employed. Fossil fuels were even used in small amounts many centuries ago, with peat being the most important one [1]. The concept of energy efficiency and its measurement, however, had to wait until scientific progress had been made in understanding the equivalence of heat and energy and we had developed an accurate means of measuring the calorific value of the various fuels.

Today, energy efficiency is widely regarded as an important means of reducing energy use and, consequently, carbon emissions. Most countries have implemented at least some policies intended to improve energy efficiency, such as efficiency standards for private vehicles and energy ratings for domestic appliances. Both the latest report of the Intergovernmental Panel on Climate Change (IPCC) [2] and the International Energy Agency (IEA) [3] regard energy efficiency as an important means of reducing GHGs and energy use. The European Union has made 'energy efficiency first' the guiding principle for energy policy in achieving the energy transition needed [4].

As a simple illustration of how energy efficiency is presently assessed, consider a coal-fired power station. The simplest efficiency measure is the annual output electricity in gigawatt-hr (GWh = 10^9 Wh) divided by the thermal content of the annual input of coal (in gigajoule (GJ = 10^9 J) into the generating plant. By converting GWH into GJ, the percentage efficiency of the plant can be calculated, which perhaps is 45%. However, this is far from the full story; two important considerations are, first, the embodied energy consisting of the needed to mine the coal, process it, and transport it to the power plant boilers, and second, the need to deal with combustion air emissions. Various oxides of sulfur and nitrogen and particulate emissions are important emissions, all of which can adversely impact the health of humans. In most modern coal plants, scrubbers are installed to remove oxides of sulfur, and particulate traps are used to remove particles. NO_X emissions are being addressed, but they remain a serious health issue, with 97% of the urban population in the European Union (EU) still being exposed to levels exceeding the World Health Organization (WHO) guidelines [5]. The estimated number of global deaths from the transport sector was 385,000 in 2015 [6]. The important point here is that humans' welfare—and thus their values—are considered in efficiency calculations. Accounting for both coal production and pollution control will lower the calculated efficiency, but not significantly.

Once welfare/ethical considerations have been introduced, the logical next step is address to the greenhouse gas (GHG) emissions from power stations. Several articles have recently discussed the dire predicament facing humanity if climate change (CC) is not urgently dealt with (e.g., [7–13]). Raymond et al. [14] have shown that in some parts of the world, the wet-bulb temperature can, on occasion, already exceed the limits of human heat tolerance. Together, these articles and others show that even the survival of humans, or at least human civilization as we presently knot it, is at stake. GHGs can thus be regarded as a second-level pollutant.

For a comprehensive picture of power plant efficiency, the energy costs of removing GHG emissions, mainly carbon dioxide (CO_2), must be included. Various approaches have been proposed for CO_2 removal, including both mechanical and biological carbon dioxide removal (CDR). CO_2 can be removed directly via carbon capture and storage (CCS), which involves using amines to capture the CO_2 emitted, compress it, and then burying it deep underground [15]. Direct air capture (DAC) involves capturing CO_2 from the ambient air. Since its atmospheric concentration is only 0.04%, much more energy is needed for capture than the amount needed for direct capture in power plants. Nevertheless, ambient air CO_2 concentrations are still far higher than the concentrations of particulates, SOx and NOx, in plant exhaust gases. They are also far higher than those of the air pollutants discussed, which have much lower concentrations in plant exhaust gases.

The other possibilities include bioenergy via carbon capture and storage (BECCS), reforestation and enhanced mineral weathering. Biological carbon capture in plants and soils is already practiced to some extent and is regarded as being cheaper than mechanical approaches are, but there are doubts both about its potential and the possibility that it could reduce the albedo in some regions [16]. One proposal, solar geoengineering (SG), would remove the need for completely eliminating GHG emissions, and the proponents claim that it would have costs that are far lower than those of CCS or even biological sequestration, but for several reasons, is not likely to be deployed on the scale needed [17].

As Chatterjee and Huang [18] and Realmonte et al. [19] have demonstrated, there is a lot of uncertainty regarding the energy and monetary costs of DAC, as it has not been tried on a large scale. Additionally, as Lane et al. [15] have stressed, the potential for underground burial, which is needed for CCS, BECCS, and DAC, is also unclear, mainly because the rate at which it can be safely sequestered is very uncertain. This uncertainty means that the energy costs for full carbon mitigation are also uncertain, and hence, so is the real value of the energy efficiency of a coal power station.

As is shown, among the vast and growing research literature on energy efficiency, there are only a handful of authors who have attempted to examine the difficulties surrounding attempts to develop more relevant measures in a world facing increased environmental damage from energy use. Nearly all papers of the thousands published each year (see Appendix A for details) are either engineering studies, or address barriers to efficiency improvements. Both types of research are needed, but the research into social science/ethical questions lags far behind the progress made in engineering research. The key aim of this paper is to fill that gap, so that more informed comparisons can be made.

The rest of this review proceeds as follows. Section 2 surveys the present energy efficiency literature, noting the paucity of articles critically examining this concept, and gives an outline of the approach used in this review. Section 3 discusses the topic in broad terms, concentrating on the need to broaden the boundaries of the energy efficiency concept, both geographically and conceptually.

The next two sections introduce two case studies to illustrate what rethinking the concept could mean in these two high-energy-consumption areas. Section 4 examines cities and buildings, including domestic residences, and demonstrates that energy efficiency studies must look beyond individual appliances to include whole buildings, and beyond that, the city itself, as illustrated by combined heat and power (CHP) systems and the urban heat island (UHI) effect. Section 5 shows the application of the enlarged energy efficiency concept presented here to road passenger transport, especially via private vehicle. Once again, the efficiency of the entire traffic system, rather than just the individual vehicle, must be evaluated. It also uses comparison between internal combustion engine vehicles (ICEVs) and electric vehicles (EVs) to further illustrate real complexities in the energy efficiency concept. Section 6 discusses the implications of the findings in a broader context. Section 7 recapitulates the argument, discusses the limitations of the paper, and also gives directions for future research on the topic.

2. Method for Selection of Papers to Review

The literature on energy efficiency is very large and growing. (See Appendix A for details.) The research by the UK social scientist, Elizabeth Shove, deserves special mention, as they are one of the few researchers who has delved deeper into the concept [20,21].

Because of this dearth of critical articles, it was necessary to review papers on topics with some connection to that which is under investigation in order to gain further insight. The various topics were accordingly examined, included the following:

- Energy services: It is now commonplace that people do not consume energy for the sake of it, but because of the energy services it can provide [22].
- Energy feedback effects: In the form of energy rebound, this is a recognized form of feedback [23], but it needs to be expanded in terms of scope. The energy rebound concept recognizes that improving energy efficiency can lead to the increased use of the higher-efficiency device, such as a cars, or alternatively, increased energy use in other sectors because of the money saved. Steren et al. [24] found that in Israel, the rebound effect of improved car efficiency increased over time, eventually resulting in no fuel savings because of the increased frequency of driving. However, feedbacks can also occur outside nation states or regions (such as the European Union) implementing efficiency improvements, as is discussed in the following section.
- Joint production of goods: In discussing the costs and energy inputs of bioethanol production, for example, it is acknowledged that cattle feed is produced, as well as ethanol, and that energy inputs should be partitioned between the two outputs, thus raising the efficiency of ethanol production [25].
- Cost–benefit analysis (CBA): CBA is useful analogy because it attempts to consider all the (monetary) costs and benefits of a given project, such as a new airport.
- Pollution and its control: As discussed above, air pollution was the first environmental harm recognized as resulting from energy production and use. Pollution control introduces ethical notions into energy efficiency.
- Life cycle analysis (LCA): LCA is important for tracking all the environmental harms resulting from a given process and attempting to quantify them [26,27].
- Earth System Science (ESS): This review adopts an Earth System Science (ESS) approach, which in the context of this paper, has two important aspects. First, the impact of one energy-using device can affect the energy use of other devices sharing the same building or road. Second, all feedback effects must be considered.

- Energy return on investment (EROI). EROI is a vital approach for assessing the energy inputs into energy systems, and its application will usually lead to lower values for energy efficiency [26].

Energy-related statistics were mainly taken from the global energy statistics published annually: BP [28] and the IEA [29]. Historical energy use relied on data from the United Nations [30] and Junker and Liousse [31]. Gross Domestic Product (GDP) data were taken from the World Bank database [32]. For the latest information on CC science and mitigation, the most recent IPCC reports were used [2,33]. Table 1 gives details about the papers selected for the various topics covered in the review.

Table 1. Topics and the relevant references cited in this review.

Topic	References Cited
Energy, etc., statistics	[1,3,28–30,34]
Climate/environmental problems	[2,5–14,31–33,35]
Energy efficiency—general	[4,20,21,36–53]
Energy efficiency—cities/buildings	[54–66]
Energy efficiency—private transport	[67–74]

3. Energy Efficiency: General Considerations

Energy efficiency can be broadly defined as the input energy needed to produce an output of human interest, i.e., the fulfillment of a task, which could be as varied as vehicular passenger-km (p-k), or the production of a tonne of wheat at a farm. However, for efficiency to have meaning, careful consideration must not only be given to the definition of the task being fulfilled, but also to the point in the energy supply chain at which energy is measured.

Figure 1 shows a representative energy supply chain in which primary energy (fossil fuels, nuclear energy, or renewables, such as wind and solar) is transferred to the point at which a task is undertaken. System losses occur at each step in the transformation process. Losses depend on factors, including: resource type and quality; transformation technology, which is limited by theoretical and engineering considerations; operational constraints and demand; the regulation of emissions, safety and so on; the operating environment, e.g., weather. Although they are indicative, the total losses can be significant. Laitner [36] has reported that in the early 2010s, overall, the US was only 14% energy-efficient; so, 86% of the energy used was wasted, suggesting that there is a lot of scope for efficiency gains.

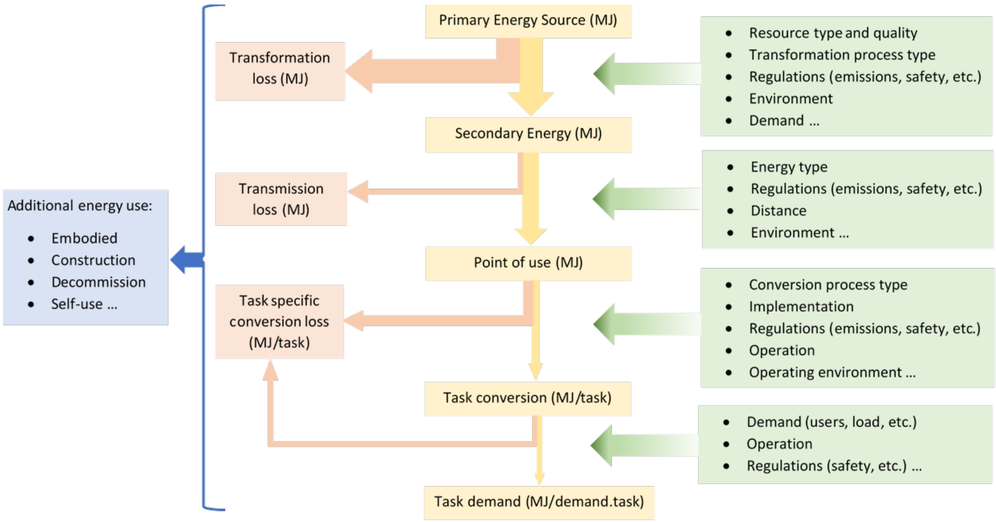

Figure 1. A generalized energy supply chain showing transformation of primary energy into the energy needed to fulfill a task, as measured by demand. Losses are shown on the left; supply chain controlling factors are shown on the right. Arrows are indicative of energy flows. Additional factors for full life-cycle analysis are shown on the far left.

A number of energy researchers regard energy efficient improvements as having the potential to produce large reductions in both energy use and CC mitigation [36–38]. Consider the case of electricity generation from RE sources, which because of their lower GHG emissions, will need to dominate energy supply. For these, location largely determines the resource quality (energy return relative to installed capacity), and in the case of solar power, it is modulated by the weather. The efficiency of the transformation of the primary energy source into secondary energy is technology-dependent. For solar PV, for example, cell and transformer efficiency are among the critical determinants, and a lot of effort has been put into improving these.

However, RE power systems, in general, use greater quantities of material per gigawatt (GW) of power generated [39] than FF power plants do. This is especially the case for the comparatively rare materials needed for PV cells and wind turbine generators [40]. Given the low-capacity factors for wind and PV systems, the amount of materials use per gigawatt-hr (GWh) is even higher. A recent IEA report [41] looked at global demand for various materials if the world was to have zero carbon emissions by 2050. It was found that the demand for certain key materials—including 'lithium, copper, cobalt, nickel and the rare earth elements'—would need to rise by six-fold. Moreau et al. [42] reached similar conclusions, but also found that 'that scarcity relates sometimes more to techno economic supply than to raw material availability'.

Many of these minerals are presently mined in low- or even middle-income countries in tropical Africa or elsewhere, where environmental legislation and its enforcement are often poor. The result is that mine wastes are at best to put in tailings dams, which are often poorly constructed and fail, or, even worse, are not contained at all. As Ali [43] reminds us, 'There's no free lunch in clean energy'. All energy sources, including RE, have environmental side effects.

Ensuring RE generation is not lost to curtailment will require the large-scale use of energy storage systems, such as batteries, which, such as the power plant, must be manufactured and maintained. Transmission losses to deliver energy to the point of use depend on things such as distance, voltage, and the conductor material used. Due to their size and resource quality, solar PV power plants are often located far from load centers and are, in many cases, distant from the existing electricity grid.

The complexity inherent in the energy supply chain has led to the use of different definitions of efficiency. In the case of vehicles, for example, efficiency can be reported as 'tank (or battery) to wheels' (MJ/km) or 'well to wheels' (MJ/km), which take the measurement boundary to the primary energy source. Further inclusions may account for energy (and emissions) embodied in the supply chain, giving rise to 'full life cycle' efficiency. If travel is the task that is to be fulfilled, differences in the way efficiency is measured enable comparisons between fuels, technology, and travel modes. While transport has been used here as an illustration, similar comments can be made regarding the use of energy to produce any output of human interest.

Importantly, the efficiency of an energy-intensive device, such as a vehicle or air conditioner, cannot be properly considered in isolation. Isolation may ignore the effect of the presence of similar devices. Congested roads are known to lower the efficiency of all road vehicles; although to some extent, drivers can have some over control vehicle efficiency via practicing 'eco driving' [44]. On the other hand, if fully automated vehicles (AVs) were to travel on freeways as a platoon, the air resistance level would be lower on the following vehicles, just as it is with wagons on a railway freight train. The complexities of efficiency measurement for ICEVs as compared with those of EVs are discussed in detail in Section 4.

Similarly, it can be argued that the putative gains from national energy efficiency improvements for private road vehicles and large household appliances need to be considered in a global context. The need arises for two reasons, which are illustrated here in terms of private vehicle ownership. The first one arises from the huge disparity in vehicle ownership (considering only vehicles with four wheels or more) between various countries, from over

1000 vehicles per 1000 population (which is, over one per person) in some countries to under 10 in several low-income countries, mainly in tropical Africa [45]. The second one is the signal that the emphasis on energy efficiency—and recently on EVs as a means of raising efficiency and cutting carbon emissions—sends to present and aspiring car owners in all countries. This message is that technical fixes such as energy efficiency or EVs can solve all our environmental challenges [46]; there is no need to consider alternatives, such as giving non-private road travel priority, or emphasizing access over vehicular mobility.

Yet, another way in which the system's boundaries for energy efficiency must be widened is the existence of other global challenges apart from potential fossil fuel depletion and global CC. The initial list by Steffen and colleagues [47] included nine global limits; the crossing of even one of these would have serious consequences for Earth's environment. Both Bradshaw et al. [7], and Dirzo et al. [8] stressed the dangers facing global biodiversity. Dryden and Duncan [48] and Georgian et al. [49] discussed those facing oceans, including acidification and the steady loss of ocean phytomass. Heinze et al. [50] warned that oceans are at risk of crossing several ocean tipping points, including 'warming, ocean acidification, and deoxygenation'. Gross [51] discussed the growing problem resulting from widespread plastic pollution.

Just as a number of studies have looked at the energy costs of avoiding FF carbon emissions, similar assessments could be conducted on the costs of avoiding these other global environmental challenges. Moving away from FFs can ameliorate some of these problems, but it also has the potential to make them worse (see, e.g., [52,53]). Sonter et al. [52] entitled their article: 'Renewable energy production will exacerbate mining threats to biodiversity'. They argued that the increased demand for mining minerals will increase the number of biodiversity threats. They further pointed out that mining potentially covers 50 million km^2 of Earth's surface, with much of it overlapping areas of importance for biodiversity preservation.

4. Energy Efficiency: Cities and Their Buildings

The energy efficiency of entire economies can be readily assessed in terms of its inverse energy intensity, which measures the GDP output per unit of energy for various economic sectors or for regions at various scales: at the city, country, or even world levels. Given that national energy statistics [28,29] and national GDP data from the World Bank [32] are readily available for each year, the national intensities can be compared, and also, the variation in any one country over time. For the entire world, the World Bank data indicate that energy intensity has fallen over time, indicating improved efficiency. Many high-income countries, especially in Europe, have lower energy intensities than the world average. However, this can be misleading, as these countries are often net importers of energy-intensive goods, which lowers their recorded intensity. As already discussed, a global approach is needed for accurate comparisons.

For the rest of this review, we focus on two specific sectors, rather than the overall economy. The energy efficiency of cities and their buildings (as well as energy-consuming devices within buildings), which account for nearly 40% of global energy use [54] and road passenger transport, are considered in turn. All transport accounts for nearly 26% of global final energy demand, and road transport makes up 77% of this value [55]. Importantly, domestic energy use and private transport energy are the only two energy uses that are directly under the control of households.

Overall, cities can partly make their own climate, as evidenced by the UHI effect, which can cause cities to be several °C warmer than the surrounding countryside is [56]. The UHI effect has several causes, but an important one is the heat release from all the city's energy-consuming devices, from power plants to computer laptops. The UHI effect thus exerts an influence on the cooling needed in buildings in warmer months and the heating needs in colder ones. In warmer climates, it may make sense to counter the UHI effect, and higher summer temperatures in general, by applying a reflective surface to the roofs of buildings [57], in order to increase the overall urban albedo, i.e., the fraction of insolation, which is reflected directly back into space. The downside is that the winter heating needs may increase; so, the overall energy efficiency of roof coatings is location-dependent. Reducing the air conditioning needs in warm climates is vital; in Saudi Arabia, for example, it accounts for over two-thirds of buildings' energy use [58].

An alternative approach to countering the UHI effect is to at least partly reverse another important UHI cause: the loss of evapotranspiration cooling resulting from paved surfaces and buildings replacing vegetated surfaces. More urban parks, even 'urban forests', have accordingly been promoted to improve the level of thermal comfort [59]. However, urban parks have another benefit: the increase in the wellbeing of those with ready access to them [60,61]. In summary, urban parks produce joint outputs: one that is readily quantifiable (the temperature decrease in an urban parks relative to the surrounding area), and one that is difficult to quantify the benefit of in terms of an improvement in wellbeing. How to partition any input energy costs (e.g., for watering and maintenance) is, thus, very complex.

Another example of joint outputs is provided by CHP or cogeneration projects, which were mostly located in China and in Europe. Globally, in 2016, about 16% of electricity came from CHP plants, which also provided 11 EJ of heat [62]. These systems were also common in the early days of electricity, but with the rise of very large generating units, which are often located near coal mines, they fell from favor. The emphasis shifted to maximizing the electricity output for a given fuel input, with combined cycle gas turbine plants reaching efficiencies of more than 60%. CHP plants are smaller and situated in residential areas. Some are powered by municipal waste [63], which can produce an additional benefit, as well as heat and power: they can reduce the CH_4 emissions from municipal landfills.

Calculating the energy efficiency of a given device, such as an electric light or a refrigerator, via conventional means may be misleading, as these devices invariably used in the same building with a host of other energy-consuming appliances, such as office or home computers, refrigerators and freezers, and air conditioners. In cold weather, the heat released from all this equipment helps to heat the building. Conversely, in warm weather, they add to the cooling load, unless ways are found to exhaust the heat generated from energy-intensive appliances, such as washing machines and refrigerators, to outside the building in warm weather. Two papers which illustrate the complexity of efficiency calculations and the need to reconsider engineering concepts are provided in references [64,65]. The authors discuss the energy efficiency of water desalination in a Middle Eastern context, where these plants are vital for supplying to cities in these water-stressed countries.

Apartment blocks offer another illustration of the complexities of the energy efficiency measurement in buildings [66]. Apartments kept at lower temperatures during cold months will receive heat flow from adjacent apartments kept at a higher temperature. The lower-temperature occupants experience a higher level of thermal comfort because of the energy subsidy from other apartments.

Further, as Elizabeth Shove [20] has pointed out, defining energy efficiency in terms of energy use per volume (as with freezers) can justify purchasing larger units. The same reasoning applies to buildings; larger buildings are perceived as being more energy-efficient. For dwellings, a more useful index would be energy use per person, but this concept would be difficult to apply to public buildings due to their varying occupancy rates.

5. Energy Efficiency: Road Passenger Transport as a Case Study

The efficiency of ICEVs is usually measured in km per liter of fuel (or, in the US, miles per gallon). This value is based on the refined fuel, and, as noted above, is often termed the 'tank-to-wheels' efficiency. A more comprehensive (and relevant) measure is 'well-to-wheels' efficiency, which is based on primary energy. This approach enables comparison with vehicles using other fuels, such as electric propulsion for both public and private transport. Merely comparing the tank-to-wheels efficiencies of EVs and ICEVs would be misleading, since the higher efficiency of EVs in terms of this measure is offset by the much lower primary-to-secondary energy conversion efficiency for electricity compared with that of oil refining.

Importantly, the propulsion efficiency for all vehicle types has shown steady improvement. For the US, the fuel efficiency of both cars and light trucks more than doubled from 1970 to 2019 [55]. Nevertheless, there are doubts as to whether further gains in the 'well-to-tank' efficiency component can continue. Court and Fizaine [67] have shown how the energy return on investment (EROI) for fossil fuels (FFs) in recent decades has declined over time. This decline will continue as the reserves of economically recoverable petroleum are exhausted; further attempts by oil-importing nations to develop national lower EROI fields because of energy security concerns will also lower the well-to-tank efficiency. So far, the CO_2 emissions from petroleum fuels—bio liquids appear to be no better than these [68]—have been largely ignored in efficiency calculations. For well-to-wheels efficiency, CO_2 emissions can be included by calculating the energy needed to avoid these emissions, for example, via direct air capture, followed by CO_2 burial deep underground.

For electricity production, the efficiency calculations are even more complicated, depending on the energy mix. For fossil fuel power stations, incorporating the energy needed to account for CO_2 emissions is the same as it is above. For RE electricity, the calculations are more complex, mainly because of the energy costs of the materials needed to generate wind and PV electricity. These two primary electricity sources are not only presently the fastest-growing electricity sources, but the International Energy Agency (IEA) [55] also forecast that these sources will supply most electricity in the coming decades. As for CO_2 emissions from fossil fuels, there are notional energy costs for the safe disposal of mining wastes and the remediation of the areas mined.

An important problem with energy efficiency that is usually measured is that the system boundaries are too narrow. A good illustration would be the efficiency comparison between EVs and ICEVs. For use in EVs, the efficient conversion of electricity into vehicle motion depends on the vehicle powertrain and batteries, vehicle design (e.g., shape and mass), and operation (e.g., driving pattern, air conditioner use, etc.) The lower mass-specific energy storage of batteries relative to that of liquid fuels means that EVs are generally heavier than the equivalent ICEVs are. Furthermore, all too often, only propulsion efficiency is considered. However, in colder climates, cabin heating is often needed for the occupant's comfort. The inefficiency of ICEV engines means that engine waste heat is available, but for EVs, additional heating will be needed, perhaps from onboard propane burners [69,70]. The vehicle engine actually produces joint products in the form of two energy services: vehicle propulsion and occupants' thermal comfort.

Driving patterns (i.e., behavior, urban, or freeway driving) can reduce or increase efficiency. Congestion reduces efficiency, particularly for ICEVs, whereas for EVs, regenerative braking can recover some losses. Vehicles' design and use are heavily regulated. Increasing the safety requirements in response to human welfare concerns increases the vehicle complexity (leading to increased embodied energy and emissions); although, technological developments have led to efficiency gains via, for example, use of light-weight materials and enhanced power train efficiency, and for EVs, an increased battery energy density. Although emissions from the use of EVs powered by RE use are almost entirely limited to particulate emissions from tire wear and brake pads, regulations (i.e., standards or guidelines) exist in various forms at national and international levels to manage some, but not all, the pollutants emitted during their manufacture. An important source of EV pollution is safe disposal of used batteries [71,72]. As noted in the power station example discussed in Section 1, should the removal of pollutants require energy, this must be accounted for in system energy flows [27].

The demand for the task can impact efficiency; increasing the vehicle occupancy improves the task specific efficiency if it is measured in units of energy per unit passenger kilometer (MJ/p-k), while also increasing the vehicle mass-based losses (e.g., rolling resistance). Buses may have higher task specific efficiency than passenger vehicles do, but only once the critical occupancy level has been reached.

The efficiency of non-motorized transport—walking and cycling—is also a complex matter. These modes are far more energy efficient than motorized modes are on a secondary energy basis in terms of the fuels used (food vs. petrol or diesel for vehicles). Many countries, however, including some outside the OECD, are suffering from both an obesity crisis and a lack of exercise [73,74]. Given this, it is clear that the energy cost of non-motorized travel for these people (including most residents in the high-income countries) is irrelevant: the more energy we use, the better it is to burn up food calories. Similar ideas apply to ICEV cabin heating; since the energy is freely available, energy efficiency is not an issue, but it would be for EVs used in cold climates.

6. Discussion

The discussion in this paper has shown that measuring energy efficiency is not a simple matter, and it is subject to deep uncertainty for several reasons. Although energy efficiency is simply defined as useful output divided by energy input, both the numerator and the denominator of this equation may be subject to large uncertainties. It is argued in this paper that both are too narrow. Figure 1 shows all the factors that must be considered. The output too often focuses on a single device, such as a refrigerator. Nevertheless, simple efficiency measures, such as passenger-km/MJ or vehicle-km/MJ for vehicles, have their uses, for instance, as a means of comparing the efficiency of different car models. However, their limitations as policy instruments to reduce energy use or carbon emissions in the entire world, or even in just one country, need to be recognized.

Energy inputs often do not fully consider the total energy input costs, especially those incurred overseas. Most analyses assume that minerals (and energy) will be sourced from overseas if they are not locally available, or can be obtained more cheaply than the cost of local production. However, national security considerations make this assumption increasingly irrelevant. The need to mine lower-quality grades for security reasons will lead to higher energy inputs. These considerations lead to an over-estimation of the real energy efficiency. It follows that policies based on this misleading information may increase energy use, rather than decrease it—or worsen pollution if remedial energy costs are ignored—at least from a global perspective.

It may even be next to impossible to determine true energy efficiencies in all cases. Consider nuclear power: although safety measures, such as encasing the reactor vessel in reinforced concrete housing, is widely used, and its energy cost is included as an energy input, the risks of nuclear proliferation under the cover of a civilian nuclear program cannot be given as the energy cost, and in any case, these risks are deeply contested. Similarly, the readily exploitable reserves of fossil fuels are contested, as is the potential for various RE sources [34]. In these latter two cases, the energy input costs would rise if lower-quality fuels have to be used, thus lowering the energy efficiency.

In Section 3, it was argued that feedback effects of private road transport could easily negate any improvements made in technical energy efficiency, not only because of the rebound effect, but also by the uptake of vehicle ownership in presently low-level car-ownership countries. In brief, high-level ownership countries provide a template for other countries. Certainly, the steady rise in both global primary energy and the resulting CO_2 emissions over the last three decades [28], despite steady improvement in efficiencies at the appliance level, seems to highlight this. As Stoddard et al. [35] have pointed out, we are yet to bend the 'global emissions curve' for tackling CC.

7. Conclusions

The key conclusion of this review is that the present assessments of energy efficiency are inadequate in that the boundaries of the topic need to be expanded both conceptually (particularly in regard to social science/ethical considerations) and geographically. Doing so will have important implications for energy efficiency assessments, as illustrated in this review, for two important energy-consuming sectors, buildings/cities and private road transport.

The limitations of this paper also indicate the directions future research needs to take. The key limitation is the absence of numerical data incorporating new ideas, for instance, in transport, in contrast to the plentiful—if incomplete—data on appliance or vehicle efficiency. Much more work is also needed on materials for RE power generation, including the quantities needed for an entirely carbon-free energy system, whether materials availability is likely to be a future problem for PV and wind turbine manufacture, and, particularly, a means of assessing the energy needed for the full environmental restoration of affected areas because of the pollution emitted from the mining these materials.

However, given the needed entry into energy efficiency of ethical concepts, which will be contested, we may never have a complete, readily agreed upon numerical answer to the problem. Nevertheless, we will have a better guide of the comparative energy efficiencies of the different options available, and so, we can make better decisions.

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Nomenclature

AVs	automated vehicles
BECCS	bioenergy with carbon capture and storage
BTS	Bureau of Transportation Statistics
CBA	cost–benefit analysis
CC	climate change
CCS	carbon capture and storage
CDR	carbon dioxide removal
CH_4	methane
CHP	combined heat and power
CO_2	carbon dioxide
CO_2-eq	carbon dioxide equivalent
DAC	direct air capture
EIA	Energy Information Administration
EJ	exajoule (10^{18} joule)
EROI	energy return on investment
ESS	Earth System Science
EU	European Union
EV	electric vehicle
FF	fossil fuels
GDP	Gross Domestic Product
GHG	greenhouse gas
GJ	gigajoule (10^9 joule)
Gt	gigatonne = 10^9 tonne
GW	gigawatt (10^9 watt)
GWh	gigawatt-hr (10^9 watt-hr)
ICEV	internal combustion engine vehicle
ICT	Information and communication technology
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LCA	Life cycle analysis
MJ	megajoule (10^6 joule)
Mt	megatonne (10^6 tonne)
OECD	Organization for Economic Cooperation and Development
OPEC	Organization of the Petroleum Exporting Countries

ppm	parts per million (atmospheric)
p-k	passenger-km
PPP	purchase parity pricing
PV	photovoltaic
RE	renewable energy
SG	solar geoengineering
t CO_2/cap	tonnes CO_2 per capita
TWh	terawatt-hour (10^{12} watt-hr)
UHI	Urban Heat Island
USD	US dollars

Appendix A

Putting the term 'energy efficiency' into the Scopus database revealed a total of around 265 thousand papers with that term in the title, abstract or keywords, with over 24 thousand in 2022 alone (see Figure A1). Although isolated papers stretch back a century, the research interest appears to have accelerated after the oil crises of the 1970s, with papers from the early 1970s to the late 1980s being above the logarithmic trend line. Adding the term "AND 'critique'" to energy efficiency returned a mere 72 papers, or under 0.03%. The inspection of all these papers showed that nearly all were irrelevant to rethinking the topic needs. When the term 'barriers' was substituted for 'critique', over 4900 articles were returned, but again, they were nearly all were concerned with overcoming the perceived barriers, not with looking deeper into what energy efficiency means.

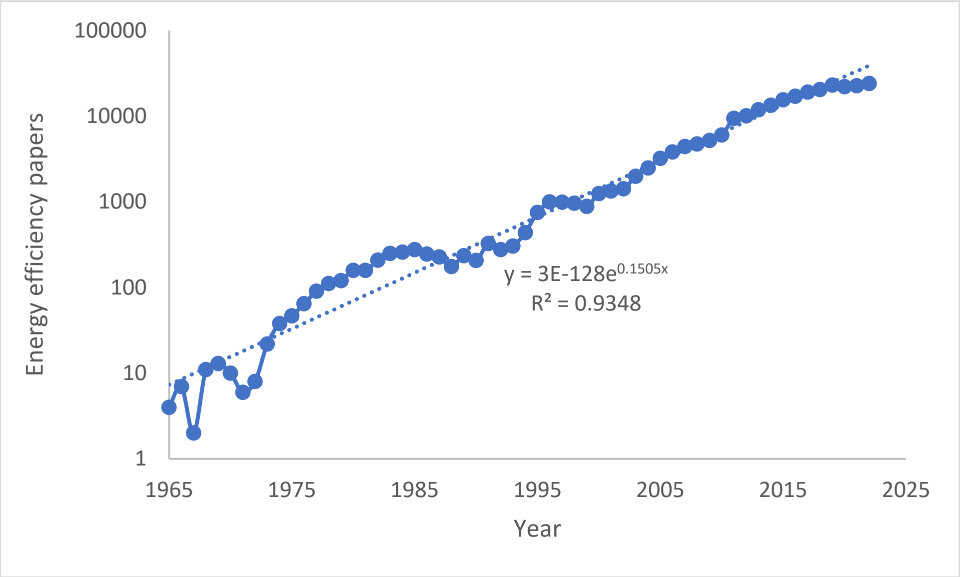

Figure A1. Annual energy efficiency papers in the Scopus database, 1965–2022. Note log scale for *y*-axis. The dotted line represents the exponential line of best fit, with a high R^2 value of 0.97.

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