Reinventing energy efficiency for net zero

Introduction

Although not widely known, historically, energy efficiency has delivered the largest share of greenhouse gas mitigation. In recent decades, more than 90% of the progress in breaking the relationship between carbon emissions and economic growth globally has come from reducing the energy intensity of the economy (IPPC 2014), i.e. from energy efficiency in its broadest economic sense – increasing the economic value created per unit of energy used.

A significant part of this relied on replacing fossil fuel technologies with more efficient technologies based on or using fossil fuel directly. Energy efficiency improvements of this kind, i.e. the creation of the same level of energy services with less final energy, have been, and continue to be, supported by public funding programmes, policies, and regulations.

But the goalposts have shifted dramatically in recent years. The recognition of the scale of the climate crisis means that full decarbonisation of the economy rather than partial reduction of emissions is now the target. Instead of just using fossil fuels more efficiently we will need to stop using them altogether. Major changes are underway moving from sources of heat to sources of work, most importantly via electrification of end-uses previously not served by electricity (Eyre 2021). At the same time, the costs of renewable energy sources and storage have plummeted (IRENA 2021) and are expected to continue to fall further. And new types of energy carriers, such as hydrogen, are emerging to replace fossil fuels in 'difficult to electrify' applications.

This has significant implications for the role of energy efficiency. Energy efficiency is not a good in itself, only through delivering some social benefit, such as improved energy security, economic efficiency and reduced environmental impacts. The emphasis on these different outcomes as a justification for energy efficiency has changed over time (Mallaburn and Eyre, 2014). In many cases, improved energy efficiency is cost effective and therefore, by definition, has an economic benefit. But with increasingly ambitious aims, this cannot always be guaranteed, e.g. for deep refurbishment of buildings. In recent years, energy efficiency proponents tend to have focussed most on carbon emissions reduction. Until the transition to zero-carbon fuels is complete, as efficient use of fossil fuels clearly continues to have a value for carbon reduction. But ultimately, in a zero-carbon energy system, however efficiently they are used, fossil fuels become obsolete and energy efficiency no longer reduces emissions. In this conceptual paper, we assess whether and how energy efficiency can and needs to be reinvented to be compatible with efforts to address the climate crisis.

Through a narrative review we identify a number of areas that require a reconsideration of the role of energy efficiency framed around five challenges including the need for full decarbonisation, the falling costs of renewable energy, electrification, flexibility and the emergence of hydrogen. Our work builds on previous analysis by Grueneich (2015) who sets out five challenges to energy efficiency in the context of reducing emissions by 80% in California. These include the need to scale energy efficiency faster and further, the need to diversify the sources of energy efficiency, measuring and ensuring persistence of energy savings, alignment of energy efficiency with a carbon reduction agenda, and utilising energy efficiency as a power system resources in the context of small-scale variable renewables.

Notably the analysis by Grueneich (2015) was carried out in the context of a reduction of emissions by 80% rather than full decarbonisation. Extending this work, we develop a number of policy recommendations, suggesting that energy efficiency needs to continue to play an important role but can only do so if we rethink its place in the race towards full decarbonisation.

Challenge number one – full decarbonisation

At the time of writing 136 countries in the world had adopted a net zero emissions target representing 90% of global gross domestic product (Net Zero Tracker 2022). Stabilising the climate requires net emissions to fall to zero, and meeting the Paris goal of limiting global temperature rises to "well below 2°C and pursuing efforts to … 1.5 degrees" requires rapid reductions in the next two decades. Scenarios compatible with these goals foresee the near-full decarbonisation of the world economy by 2050 (e.g. IEA 2021). This means that energy-related emissions from the combustion of fossil fuels will need to fall close to zero in all sectors (Sachs et al. 2016). This does pose a challenge for traditional energy efficiency programmes that rely on improving the efficiency of fossil fuel use as it improves the very technologies and processes that will need to be phased out.

In the buildings sector, significant energy savings and emission reductions have been obtained through replacing inefficient heating systems with more efficient heating systems, but still using fossil fuels. This has been well-documented in a number of countries, for example in the UK where condensing boilers were first supported by energy efficiency programmes and eventually made mandatory (Elwell et al, 2015). Recent pan-European analysis found that the majority of European countries continue to actively support the installation of fossil fuel heating systems on grounds of energy efficiency (Tognetti 2020), partly driven by energy savings targets established by the European Union's Energy Efficiency Directive.

In the transport sector, vehicle efficiency improvements have been driven by product standards, typically applied as a manufacturer corporate average, such as Corporate Average Fuel Efficiency standards in the USA (Greene et al, 2020) and CO_2 Performance Standards (Regulation 2019/631 and its predecessors) in the EU (Paltsev et al, 2018). Forthcoming requirements for zero carbon emissions (at the point of use) will principally result in a shift to battery electric vehicles (BEVs), which are typically three times more energy efficient than internal combustion engine (ICE) vehicles. The policy framework for net zero is therefore, itself, a major driver of efficiency improvement. However, it will be important to retain use of efficiency standards, initially for ICE vehicles to minimise direct emissions as they are phased. Subsequently it will be important to ensure adoption of BEVs that are efficient, as inefficient BEVs would drive up electricity use unnecessarily, increasing consumer costs and slowing the speed of electricity sector decarbonisation. Energy efficiency standards for BEVs will therefore be an important policy tool.

In the industry sector, all processes need to be decarbonised. Where fossil fuels are currently used directly, this will involve switching the energy carrier, possibly involving entirely new processes. Energy efficiency will continue to play a role in reducing emissions from industrial processes but efforts to make fossil fuel-based processes more efficient will become obsolete unless combined with close to 100% effective carbon capture and storage. In some cases, complete switching to renewable electricity has already been demonstrated, e.g. for ammonia (Nayak-Luke et al 2018). However, because some processes require very high temperatures and/or the use of chemical reducing agents, the potential for electrification will be more limited compared to the buildings and transport sectors (Azevedo et al. 2021). In these cases, use of hydrogen is more likely, notably for steel production (Pimm et al, 2021).

So for all three sectors it will be necessary to move away from improving products and processes reliant on fossil fuels towards replacing them with zero carbon alternatives that are also efficient at the same time. Often the costs of zero carbon alternatives are higher than comparable fossil fuel-based technologies (heat pumps are a good example which are more expensive compared to gas boilers). Through research and development, innovation and scaling up deployment the costs of those technologies can be reduced as evidence from other technologies such as solar, batteries and wind shows clearly. Public finance to provide incentives and investment support also play a critical role for ensuring that zero carbon alternatives are economically viable.

To summarise, a continuation of policy support for incremental energy efficiency improvements through the replacement of existing fossil fuel-based technologies with more efficiency equipment that also relies on fossil fuels is problematic for a number of reasons. First, it does not achieve the long-term required emission reduction. Whilst energy efficiency can significantly reduce and has reduced carbon emissions, as long as the more efficient technologies installed continue to run on fossil fuels, this does not bring down emissions to zero or near zero. Second, continued support of more efficient fossil fuel-based technologies leads to lock-in and lost opportunities to switch to technologies that are compatible with climate neutrality. And finally, investments made in more efficient fossil fuel technologies are investments not made in alternative technologies that involve fuel switching. As Naimoli and Ladislaw (2020, p. 3) argue "energy efficiency upgrades may delay the conversion to zero-emissions technology because of the additional capital costs on top of those that went into the efficiency upgrades".

Challenge number two – Falling costs of renewable energy sources

Energy efficiency has been promoted in many jurisdictions as part of efforts to achieve least cost planning, an approach that involves examining all demand-side (e.g. energy efficiency, demand response, storage) and supply-side resources (e.g. generation) to meet a given level of energy service provision (Moskovitz 1991). In Europe, the concept of least cost planning has inspired the Efficiency First principle which "prioritizes investments in customer-side efficiency resources (including end-use energy efficiency and demand response) whenever they would cost less, or deliver more value, than investing in energy infrastructure, fuels, and supply alone" (Rosenow et al. 2017, p. 72). Both least cost planning and Efficiency First are based on the premise that often the cheapest energy is the energy we do not use.

However, the costs of solar and wind, which are the main scalable renewable energy sources, have plummeted over the last decade, and renewable electricity can now be produced at much lower cost than ever before. This, in turn, challenges the notion that energy saving technologies are always the lower cost option to reduce carbon emissions. Levelised costs for utility scale solar have fallen rapidly to just 0.057 $/kWh, on-shore wind costs are now 0.039 $/kWh and offshore wind costs are 0.084 $/kWh (IRENA 2021) representing cost reductions since 2010 of 85%, 56% and 48% respectively. Of course there are associated costs for system integration of renewables such as the need to build out the electricity network, invest in low carbon dispatchable generation, balancing, and storage. However, analysis shows that only with relatively high levels of penetration do these system costs contribute a significant share to the total system levelised costs of energy (Ueckerdt et al. 2013). And making demand more flexible is part of the package of measures that can reduce these costs.

Energy efficiency is still often the cheapest form of emission reduction as some of it has a negative cost, because the cost savings outweigh the capital investment costs even at these prices for renewables. In some cases, notably for light-emitting diodes (LED), the same sort of rapid cost reduction is happening. However, for more costly energy efficiency measures, the point at which decarbonising energy supply becomes cheaper than avoiding an additional unit of energy is moving in favour of renewable energy. Given the scale and pace of change needed, major investments in both will be required. This approach points to net zero goals being delivered principally through energy demand reduction and renewable energy (Grubler et al, 2018; Barrett et al, 2021).

However, in the long-term, in a 100% RES economy, additional energy efficiency no longer reduces carbon emissions. This does not mean it has no value, simply that in the absence of the need for emissions reduction, it will be economic, social and energy security goals that become pre-eminent. So proponents of energy efficiency will need to look to other arguments, for example the benefits that energy efficiency delivers for lower household bills, job creation, economic competitiveness, thermal comfort and energy security. This should not be a surprise, as the dominance of carbon reduction in energy efficiency discourse is relatively recent. These other arguments have been central motivators of policy at other times, even within the last 50 years (Mallaburn and Eyre, 2014).

Challenge number three – Electrification

Electrification is widely seen as a key pillar of full or near full decarbonisation of different sectors, with the electricity used is based on renewable energy and other zero or close to zero carbon sources (IEA 2021). This is because the main low-cost zero-carbon supply technologies, notably wind and solar photovoltaics, produce electricity, and therefore electrification increases the share of total energy use for which they can compete.

Electrification reduces carbon emissions through two, conceptually distinct but interacting, effects. The first is by fuel switching to electricity from direct use of fossil fuels. Of course, this only reduces emissions where the carbon content of electricity is lower than that of the fuel it replaces. Historically, this has been unusual due to the dominance of fossil-fuelled electricity generation, but it will become the norm if the global economy transitions to being powered largely by renewable electricity.

Secondly, electricity can usually be used more efficiently than fossil fuels, in many cases by a large factor. Key technologies are heat pumps for space and water heating and electric vehicles. In both cases, the energy conversion efficiency improvement at the point of use is a generally a factor of three or more compared to the dominant current technology (boilers and internal combustion engine vehicles respectively). This enables electricity to be used to reduce emissions even in systems where electricity carbon content remains relatively high. This 'efficiency effect' is therefore larger than the 'fuel switching effect' in reducing carbon emissions. Moreover, it has huge implications for the energy efficiency of the global economy as a whole. Alone it will produce an improvement of ~40% (Eyre 2021).

In addition, the process of electrification may well indirectly drive some other energy efficiency improvements. Heat pumps operate more efficiently in heating systems with lower flow temperatures, and improved insulation can assist achieving this without increasing radiator size. Similarly, there are synergies between vehicle electrification and other efficiency techniques, such as light-weighting and aerodynamics, given user concerns about the range of battery electric vehicles.

The IEA (2021) has modelled a global pathway for net zero by 2050 and their modelling suggests that almost half of all energy demand will be based on direct use of electricity up from currently only 20%. The shares in the industry, transport and buildings sector are expected to be 46%, 44% and 66% respectively. There is broad agreement that these are well within what is technically possible, for example Eyre (2021) estimates technical potentials for these three sectors as 76%, 54% and 97% respectively.

There are three key messages for energy efficiency policy. The first is that the process of electrification itself will generate an energy efficiency improvement larger than any other prospective change. The second is the long-term potential of energy efficiency will depend on the efficiency of the electrified technologies, and therefore attention needs to switch to these. More efficient electrified technologies will enable renewables to take a larger share of the energy market more quickly. And they will mitigate the inevitable increases in electricity demand produced by the transition. The third is therefore that energy efficiency, not carbon efficiency, is the key metric for these technologies.

Challenge number four – Flexibility

As more and more end-uses are electrified and it increasingly matters not only how much energy is used but also when it is used. This is because in many locations at the moment and in the short to medium-term the carbon emissions of the power grid vary widely over the course of a day, between weeks and seasons. Saving a unit of electricity during peak hours on a day with little renewable generation delivers significantly more carbon savings and environmental benefit than saving the same unit during hours of excess renewable generation. But the timing of energy savings matters not only for carbon emissions but also for the wider energy system cost. Both centralised storage and stronger inter-connection can play a role in increasing flexibility, but the demand-side also has an important role. Avoiding electricity consumption during peak hours means less congestion in the grid and less need for expensive peaking power plants. In contrast, saving electricity during periods of significant excess generation may not save any carbon emissions and could increase energy system costs as renewable generators might have to be curtailed. As grid decarbonisation proceeds, the carbon saving impacts of peak demand reduction will fall, but the costs and security benefits will increase. The latter effects are critical to future systems, and therefore merit more attention than short term carbon benefits.

What does this mean for energy efficiency? The implications of the much more time-specific nature of environmental and energy system benefits in an electrified world require different approaches to policy design. Most energy efficiency programmes either focus on rolling out particular energy efficiency measures or provide incentives to deliver energy savings. But as explained above, with increasing electrification the benefits of energy efficiency depend on when and not just how many savings are achieved. For example, rolling out commercial lighting efficiency measures in a geography with consistent solar generation during the day such as California "may actually exacerbate the challenges associated with increasing penetration of non-dispatchable renewables" (Martinez and Sullivan 2014).

This is why in some capacity markets energy efficiency together with demand response is allowed to participate aimed at lowering peak load. Capacity markets do not purchase energy, but seek to ensure that adequate capacity – the ability to meet energy demand – will be available to serve expected load (generators actually dispatched in future time periods will also be paid in the energy market for the energy they produce and sell). They pay for the value of a service to the system, i.e. to reduce the cost of capacity for a given reserve margin, as well as lowering wholesale energy prices. The amount of capacity that is estimated to be needed in future is set by the system operator based on projected load and the desired reserve margin; for this reason, a committed reduction in future load lowers the amount of generation capacity needed, and helps meet capacity requirements, just as a power plant does (Rosenow et al. 2017).

When these markets were first introduced in New England (United States) in 2006-08, efficiency and demand response advocates rightly pointed out that actions taken on the demand side to lower demand were just as valuable – and sometimes more valuable – than actions that could be taken on the supply side to add new generation capacity to meet load requirements in peak periods or when reserve margins are tight for other reasons, such as an unplanned generator outage (ibid).

Consequently, some capacity markets have been designed to permit demand response and efficiency assets to compete directly alongside conventional supply-side resources in the auctions set up to procure capacity on a forward-looking basis. The examples in the United States are the ISO-New England, PJM and New York-ISO capacity markets, with ISO-New England and PJM having the most experience authorising end-use energy efficiency to bid into the forward capacity markets (Liu 2016, 2017).

Another example is the potential for using smart meter data to identify homes that are particularly suitable for load shifting and heat pumps through providing a much more accurate and granular assessment of properties (Crawley et al. 2020). Emerging business models such as heat-as-a-service could further benefit from such approaches.

Challenge number five - Hydrogen

Because electricity cannot serve all end-uses other energy carriers will be needed in a net zero economy. It is for this reason that in recent years hydrogen has emerged as a topic of considerable interest on the agenda. Informed analysis focusses on energy uses that will be difficult to electrify, in particular industrial processes in which chemical reduction is needed as well as heating (notably primary steel-making) and long-range transportation where battery weight might be prohibitive (e.g. in aviation, shipping and heavy road freight).

In addition, hydrogen may have a role in energy storage, especially where storage times exceed a few hours and therefore battery storage is uneconomic. Systems with significant space heating loads already experience cold-weather peaks of many days, traditionally addressed by fossil fuel storage. Future systems dependent on wind are likely to experience supply lulls for similar periods. In cool temperate climates, both are likely, and in the worst-case scenarios the effects coincide. Storage needs in a medium sized economy are likely be tens of TWh (Cassarino and Barrett 2022). Only chemical and thermal storage seem likely to be appropriate, implying a potentially large role for hydrogen.

In principle, hydrogen can be used as a like-for-like replacement of fossil fuels in a wider range of applications, reducing the need for electrification. It has even been claimed that this would minimise the need for further energy efficiency improvements. For example, a study commissioned by Eurogas (DNV GL 2020), the European gas sector business association, claims that hydrogen used for heating has an advantage over alternative low or zero carbon heating technologies in that it does not require extensive and potentially disruptive building retrofit measures such as wall insulation and window replacement. Similar claims for hydrogen-powered light vehicles also focus on limited changes to refuelling infrastructure. However, most analysis confirms that electrification is a better option in most low-temperature heating and light vehicle options and that wider claims are part of a hype cycle that has now peaked (Rosenow and Lowes 2021).

The fundamental disadvantage problem for hydrogen is cost. Hydrogen is not a resource and but an energy carrier that needs to be produced. The two most likely production methods of low carbon hydrogen are reformation of natural gas with capture and storage of CO_2 (blue hydrogen) and electrolysis (green hydrogen). Because of the transformation costs and energy losses, hydrogen is more expensive than the fossil fuels or electricity from which it manufactured. Blue hydrogen is expected to cost about three times more than fossil gas (Sunny et al. 2020). Green hydrogen could, in principle, be made using electricity at times or locations with low prices, but currently is currently significantly more expensive than grid electricity.

The implication is that hydrogen is unlikely to be the preferred zero-carbon fuel where electricity is an option. In sectors in which hydrogen is likely to be used, the high unit cost will provide an additional stimulus for efficiency. For example, it will strengthen the case for efficient fuel cells in heavy freight transport. In general, the economic case for energy efficiency in a world with widespread hydrogen use improves rather than diminishes.

Deciding not to deploy cost-effective energy efficiency measures creates an economic liability in the form of higher running costs, unnecessary investment in energy supply infrastructure and fewer of the multiple benefits of energy efficiency.

Policy implications

Energy systems are typically required to deliver on a number of important goals - usually to deliver energy services reliably, within socially acceptable levels of environmental impact and at a reasonable cost. The role of policy intervention in energy systems is to establish framework that ensures the decisions of individual actors in the system deliver such an outcome. The importance of addressing climate change now makes delivering mitigation goals the key overarching policy goal. And the scale of change implied by net zero targets means that policy needs to deliver systemic change. In itself, this has huge implications for policy – the level of ambition needs to match the scale of change needed.

Upstream energy supply change is not enough. Currently, three-quarters of global final energy is by direct use of fossil fuels. To deliver a net-zero compliant energy system, that needs to fall to close to zero within a few decades. It is difficult to envisage a more profound change. Energy efficiency is only part of the changes in energy use needed. Public policies for energy use will also need to address support for switching to decarbonised energy carriers (typically electricity and hydrogen) and more flexible use to match renewable electricity supply. In short, 'energy efficiency policy' needs to be reinvented as 'energy use policy'.

However, not everything changes. The naïve idea, from neo-classical economics, that getting prices right will automatically deliver efficient outcomes was proven wrong with respect to energy use in the 1970s, but has reappeared in the guise of the claim that carbon pricing is the central instrument of 'climate policy'. Carbon prices at any politically feasible level seem unlikely to be sufficient to drive change at the required rate in three critical areas - infrastructure investment, innovation and behavioural change. Effective energy use policy has always required more targeted instruments, including regulatory and information instruments, as well (Stern 2006). Analyses of future policy options show that this will remain true (IPCC, 2014; IEA, 2021).

Based on our analysis, the focus of energy efficiency policy will need to change from a focus on traditional end use technologies using fossil fuels to high efficiency components and systems to a net-zero carbon system. Some priorities, not directly related to energy conversion technologies, will remain robust through the change, for example the need to promote high-efficiency building fabric and mass transit systems. In other cases, policies and programmes will need to migrate, e.g. from supporting efficient boilers to heat pumps, from efficient internal combustion engine vehicles to electric vehicles, and from efficient industrial processes to wholly new processes. And a precondition for all of this is support for zero-carbon energy infrastructure, notably strengthened electricity networks and hydrogen for hard to electrify applications.

Specifically, measures-based energy efficiency programmes such as publicly funded financial support schemes should identify and particularly support those efficiency technologies that deliver the highest system benefits rather than just focusing on those technologies that offer the highest and cheapest short-term energy savings.

The target metric of major energy efficiency programmes such as Energy Efficiency Obligations currently is mainly defined in units of energy savings (e.g. GWh) with only some exceptions (Rosenow et al. 2017). There is potential for modification to account for wider benefits, especially time-varying carbon value of savings, and first initiatives are underway. For example, in California a new metric for measuring the impact of energy efficiency programmes, called Total System Benefit, has been adopted in 2021. It combines and optimises the energy and peak demand savings goals, along with greenhouse gas benefits of energy efficiency, into one metric that can be forecasted and tracked (CPUC 2021).

Conclusions

Net zero and the wider shifts in energy systems pose new challenges to the traditional role of energy efficiency. Our analysis suggests that energy efficiency will become even more, not less important for meeting climate goals and achieving other societal goals. In order for this to happen, the benefits of energy efficiency have to be rethought. The historic focus on user cost reductions is now clearly inadequate. In the short term, the key benefits are likely to be related to carbon reduction, both the direct effects of demand reduction and enabling the speed of transition to renewable energy. In the longer term, as energy system approach zero emissions, the benefits will be seen in system cost reduction, in particular reduction in the cost of electricity and hydrogen capacity. In both cases, a whole system approach is needed. A strong focus on electricity capacity also points to policies increasingly taking into account the time dependence of energy use.

We note a mismatch of existing policies that too often focus on incremental improvements of fossil fuel-based technologies or deliver energy savings without differentiating what kind of savings, when and where they occur. The good news is that technology and a better understanding of the most effective decarbonisation pathways allow us to readjust energy efficiency policies in such a way that they provide a much better fit with the net zero agenda.

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