Technical limits for energy conversion efficiency

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Abstract

To reach climate targets, unprecedented levels of energy efficiency improvements are required. To prioritise investments, it is necessary to know the energy saving potential associated with each action. Understanding the potential of technical improvements, requires knowledge on the highest technically achievable efficiency of a technology – the technical efficiency limit. When focusing on technical efficiency improvements, two distinct types of technical systems are recognised: conversion devices and passive systems. Previous research has analysed the technical efficiency limits of passive systems, in this study, the technical efficiency limits of major conversion devices are quantified using physical models. The resulting limits are used to calculate stochastically the energy saving potential of each device and design parameter for the United Kingdom. The UK's final energy demand could be reduced by 25 % if conversion devices were operated at their technical limit and two thirds of these savings are in transport. The analysis suggests that a) improvements in conversion efficiencies are insufficient to reach energy reduction targets, except in transport and b) that for most technologies it is more important to focus on converging towards the efficiency level of the best available technologies rather than on research pushing the boundaries of conversion efficiency.

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1 Introduction

If governments are to follow through with their decarbonisation pledges, then much effort is likely to be spent on improving of energy efficiency since energy Efficiency measures have repeatedly been hailed as the most cost effective mitigation tool [1]. In fact, the International Energy Agency (IEA) estimates that 40% of the emission reduction in a two degree scenario, in line with the Paris Agreement [2], could be sourced by efficiency improvements [3].

To make the most of the limited resources we can apply to bringing about change, actions must be prioritised in a rational way. The energy saving potential (ESP) metric has been used as a helpful tool to help decision makers prioritise energy efficiency actions. Equation 1 defines the ESP of a policy or technology k in its most general form.

$$\mathrm{ESP}_k = E_k \Delta \eta_k \tag{1}$$

where E_k is the amount of energy consumption of a given technical system while $\Delta\eta_k$ is the efficiency gap that exists between the current state of the energy system and a possible future one due to an improvement k.

Energy saving potential estimates are abundant in the academic and grey literature, however, the vast majority of studies focus on establishing the economic saving potential–where $\Delta\eta_k$ refers to the efficiency gap between current efficiency and best available technology (BAT) [4]. However, such economic analyses are not appropriate for long term investments such as research and development investments, because in the long run, BATs for many devices are expected to be overtaken by further technological development. In contrast, many energy technologies which have been under development for a century [5, 6] and might actually be reaching physical limitations. The solution to this issue is to estimate $\Delta\eta_k$ such that it compares the current efficiency to the technically maximum achievable efficiency for each technical energy system.

Technical energy efficiency measures can be helpfully categorised as either energy conversion efficiency improvements or passive system improvements [7]. Conversion efficiency, refers to the efficiency with which primary energy sources are converted to increasingly more useful energy forms. It concerns the efficiency of machines such as gas turbines, electric motors, internal combustion engines, and is measured as the ratio of useful energy output to source energy input. Passive systems, on the other hand, are those systems that enable the provision of energy services from a given unit of useful energy. This exchange between useful energy and service (e.g. passenger-kilometres or degree days of heating) happens at the end of the energy supply chain and involves technical interventions such as building insulation and vehicle aerodynamics. A further distinction between the two technical systems is their “proximity” to the end-user. Changes in conversion device efficiency do not have a large impact on the way in which an energy service is provided; most home dwellers cannot tell the difference if a house is heated with a conventional or a condensing boiler [8] and use of an ultra-efficient electric motor does not affect the user-experience of the motor-system [9]. On the other hand, passive system changes improvements or changes have a visible impact on the user. For example, to increase passive system efficiency in road transport, cars should be smaller and more streamlined, while to improve the passive system efficiency of buildings, walls should be thicker.

Cullen and Allwood have estimated technical limits for passive systems [10], both at a global level, but have not analysed technical limits for conversion devices. In addition, the wider literature does not provide a comprehensive assessment of the technical efficiency limits across the full range of energy conversion devices. Therefore, this study aims to provide researchers, modelers, and decision makers with consistent estimates of the technical efficiency limit of all major energy conversion devices. Section 2 explores the previous work already done in this field in more detail, section 3 outlines the methodology employed to estimate the efficiency limits, and section 4 provides a summary of the estimates as well as an assessment of the ESP for the UK.

2 Previous Work

2.1 Energy Saving Potential

Scholars from several fields of energy science and economics have contributed to the discussion on efficiency limits, and these studies can be used to estimate ESP for national and regional energy systems. For example, Beaudreau and Lightfoot [11] estimated the physical limits to energy efficiency growth in the next century that can be achieved through R&D. While, Letchert et al. [12] use a bottom-up model to estimate the maximum possible efficiency gains that could be achieved in major global economies if best available technologies were adopted in all end-use sectors. In addition, the grey literature contains several estimates of economy-wide energy saving potentials which been used to inform decision – a list of high profile examples are shown in the "Supplementary Informations".

The main shortcomings of these approaches, is that they use best available technologies as the upper efficiency boundary to calculate ESP, and that they tend to focus on the economic potential of efficiency rather than on the technical. While these studies are useful for short to medium term policy and strategy setting, they can be misleading for long term projections because the upper efficiency boundaries for each technology is likely to increase with time - as it has done throughout the past century [6, 13]. A slightly different approach can be found in the preparatory studies for the European Commission's Ecodesign legislation [14]. In these studies, analysts are asked to also provide efficiency (and cost) estimates for Best Not Available Technology. However, the definition of Best Not Available Technology is loose and often analysts shy away from its characterisation. One the one hand, the use of physics-based efficiency limits overcome the risk of underestimating the role of efficiency improvements by assuming that best-available technologies do not evolve. On the other hand, the entirety of the technical efficiency savings are not achievable in the economy [15] due to economic consideration. One important dynamic that reduces the real world impact of efficiency improvements on energy savings is the direct "rebound effect": as efficiency increases the marginal cost of energy services decreases leading to higher demand for energy services and thus higher energy consumption [16]. There are also indirect rebound effects that are caused by the use of monetary savings from efficiency improvements for the additional demand for other energy intensive goods and services [17]. There is empirical evidence for the existence of this effect [18, 19, 20], however, in most instances the rebound effect only reduces the expected energy savings by less than 30% in developed economies[21].

2.2 Societal Exergy Analysis

The field of Societal Exergy Analysis (SEA) has been involved in providing a physically based framework to estimate economy wide efficiency since the mid 1970s [22]. Instead of using on first law efficiencies and energy accounts, scholars in this field have focused on energy's "ability to perform Work", which is also known as exergy. The framework has had two main outputs. It enabled the understanding of the historical role of energy efficiency improvement in overall economic development firstly proposed by Aryes [5, 6] through and analysis of the US economy. The model was also successfully applied to other developed regions such as the EU and Japan [23, 24] highlighting that Useful exergy should be considered as a factor of production that explains economic growth. Societal exergy analysis has also enabled a framework to prioritise energy efficiency action in different countries and sectors [25]. For example, a 2001 study of the UK energy system identified gains in the commercial and residential sector exceeded those possible in the industrial sector [26]. However, societal exergy analysis still has some shortcomings: analysis is limited to energy and mostly ignores the CO_2 implications of efficiency actions; metrics to quantify the ESP (called Improvement Potential in SEA literature) is purely theoretical as it's calculated comparing present day exergy efficiency with an exergy efficiency of unity, which is unreachable because of thermodynamics and physical constraints. Lack of data of appropriate quality has been identified as a key shortcoming of the field [27], often because of the ambitious scope of the analyses which tend to cover several countries or span several years.

2.3 Conversion Devices and Passive systems

Cullen and Allwood have advanced the field of SEA by building a framework linking CO_2 emissions to exergy efficiency thus enabling the comparison of demand side and supply side measures [7] for climate change mitigation. In addition, they introduced the distinction between Conversion Devices and Passive Systems, enabling an improved characterisation of the different technical efficiency options available. They estimated the practical limits for the energy efficiency of passive systems, providing a more realistic metric for energy saving potential than those used before [10]. Their estimate of ESP for conversion devices uses theoretical limits for the target efficiency, which are unattainable in practice. A cursory attempt was made to estimate technical limits for conversion devices, using a heuristic metric based on Finite Time Thermodynamics [28]. However the resulting energy savings estimate of 85% at the global level does not represent the true technical achievable savings, as it is constrained by unavoidable physical losses which have not been accounted for in the analysis. Ma et al. used this same framework in the analysis of the Chinese economy [29] as a tool to identify the most promising technical actions to increase the efficiency of the Chinese energy system. In more recent work by Paoli et al [30], the framework was applied to the United Kingdom (UK) with a focus on conversion devices: the average efficiency of each device was better characterised by increased data collection and by the use of a stochastic method which showed the uncertainty associated with this method explicitly.

The present study aims extend the analysis by Cullen and Allwood, by creating consistent and representative technical efficiency limits for all major energy conversion routes. The estimated technical efficiency limits are then applied to the UK energy system to estimate the technical energy savings potential from advances in conversion device efficiency. The results are used to provide insights into the best way to prioritise actions and strategies (such as R&D funding) that aim to increase end-use conversion efficiency based on the technical characteristic of each conversion device.

3 Methods

Conversion devices convert energy from one form into another form, to provide more utility for the user. For example, water heaters convert natural gas fuel into heat in water and electric motors convert electrical energy into rotational work – in each case the converted energy form is more useful. Defining technical limits for energy conversion devices allow us to estimate the energy savings potential if all devices were operated at their technical limit. This provides an upper limit for energy savings and helps prioritise specific actions for improving energy efficiency.

3.1 Technical efficiency limit

There are innumerable types of machines that transform energy to more useful forms and there is no unique way to classify and categorise these technologies. In this study, the classification of conversion devices follows previous work by Paoli et al. [30] which classify end-use conversion devices in 8 categories, where each conversion device category represents technologies that follow the same operating principles . For example, the category “Diesel Engines” includes devices that range from engines in small cars all the way to engines used for shipping. Upstream conversion devices such as electricity generation plants and refineries are excluded because the analysis focuses on the end-use conversion efficiency. The categories used in this analysis are described in the *Supporting information.*

In the literature the term “technical efficiency limit” (TEL) is used to to refer to an array of meanings. In economic assessments of energy efficiency, it refers to the efficiency level that would be achieved without market distortions [15], while in techno economic assessments, it often refers to the efficiency of the best available technologies [4]. In this study, the technical efficiency limit of each device is defined as the steady-state conversion efficiency that can be achieved while taking into consideration unavoidable energy losses, but ignoring economic considerations. The estimated TEL considers factors such as the properties of materials, unavoidable friction losses and non-ideal thermodynamic cycles. Economic factors and manufacturing constraints are ignored because these aspects are contingent to the present techno-economic situation and are subject to future changes. For example, specifications such as the minimum feature size that can be economically manufactured [31] and the thermal properties of materials [32] have increased over time. On the other hand, practical considerations related to the delivery of energy services are accounted for, such as the the power density of conversion (kW/m^3 or kW/kg) which should not decrease due to the proposed efficiency improvements.

A summary of the methodology and the steps taken to model each conversion device is shown in the flowchart in Figure 1. The parametric model methodology (Method A) is preferred and whenever possible, this method is used. However, for some devices, physical modelling is prohibitively complex due to a large number of design parameters or due to the presence of important complex interactions that require computationally intensive models (such as CFD or FEA). For these cases, the loss reduction methodology is employed as an alternative physical basis for the technical efficiency limit.

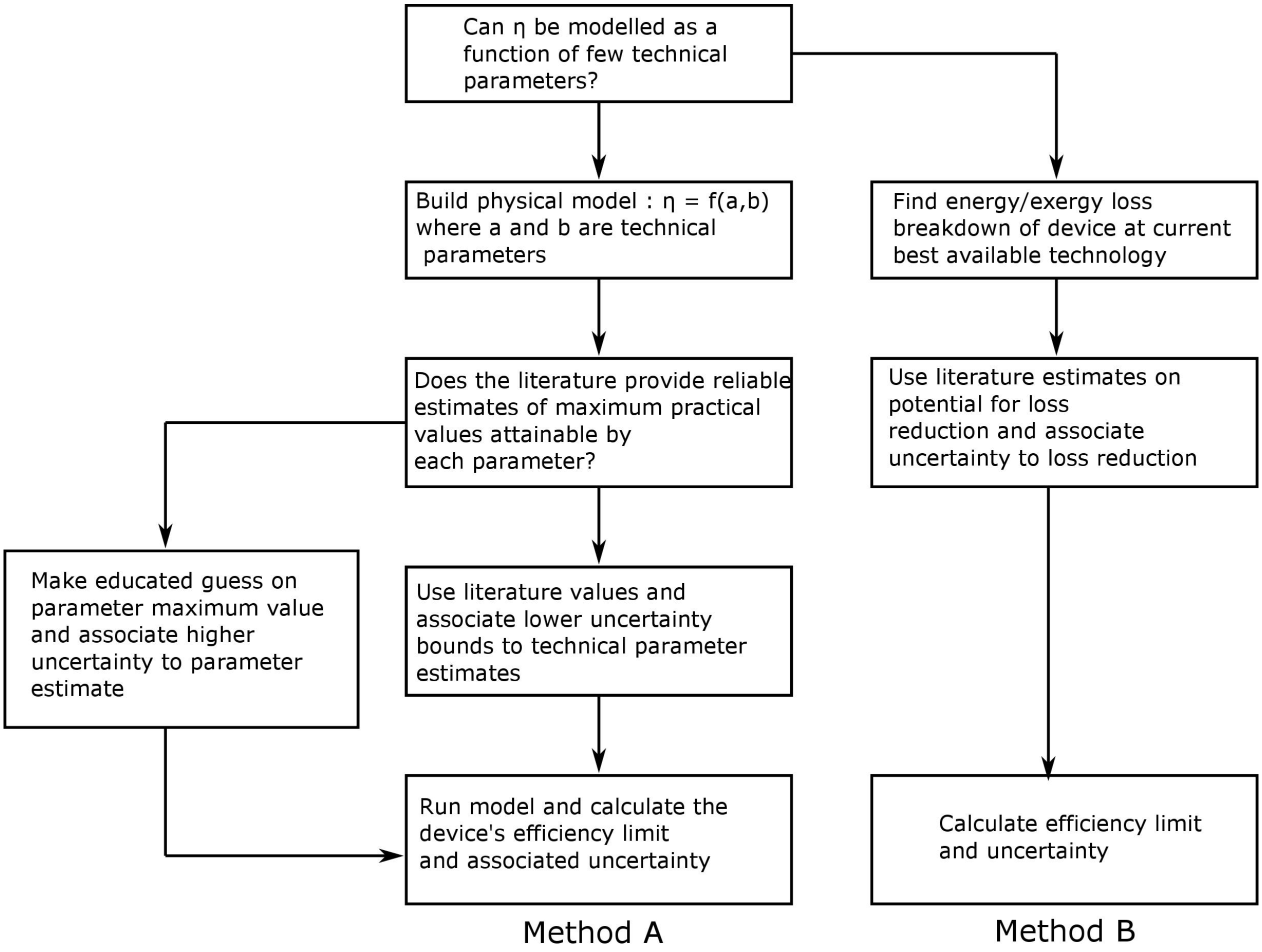


Figure 1: Flow chart showing the decisions and steps taken to determine the technical efficiency limits following both methodologies.

To reduce the number of parameters studied and the complexity of the models, efficiency at steady state and rated power operation is modelled by default. This simplification is acceptable for most conversion devices either because they operate mostly at constant load, or because their performance degrades only marginally for variable load. One important exception is for internal combustion engine used in light duty vehicles, where the highly variable load and the strong correlation of efficiency with load conditions, means that the average efficiency varies significantly from the constant load efficiency [33]. Therefore, for road transport, both the current efficiencies and the TEL are estimated for engines operating over a typical drive cycle. Gas turbines (including Jet Engines), boilers, and coolers were analysed using method A; reciprocating engines, electric motors, and light devices were analysed with method B. The methodologies and models used to model each of the conversion devices, including all relevant sources and published expert opinions, are presented in the *Supporting Information* document.

3.2 Current efficiency

To operationalise the TEL (η_{TEL}), it is necessary to know what is the current status of conversion efficiencies for each device categories. The current status of efficiency is defined using two values, the average efficiency (η_{avg}) and the best available efficiency (η_{BAT}) for each sector:

- *Average efficiency* represents the typical value of conversion efficiency for a given device. Data on average conversion efficiencies is difficult to obtain and official statistics do not track their trends. Therefore, average efficiency is estimated for each conversion device using a variety of methods which depend on the device specific data availability. Key sources include: product catalogues (such as Eurovent product database [34] and the Product Characteristic Database [35]), end-use energy statistics for the UK [36], and Ecodesign preliminary studies [37, 38]. The collected data is used to estimate a probability distribution which represents the confidence of the average efficiency estimate. The probability distribution is defined as a Normal distribution which has the same mean and standard deviation as the data.
- *BAT efficiency* represents the highest efficiency of each device that is available in the market. The BAT is established through desk research focused on searching product catalogues. The BAT is is modelled as a deterministic value rather than as a probability density because its value is well defined. η_{BAT} is always higher than η_{ave} but it can be either equal or slightly higher than the upper bound of the range current efficiency range. That is because the range of current efficiencies should represent the 90th percentile range, while η_{BAT} might represent a niche technology.

Figure 2 depicts the relationship between the three efficiencies that are defined for each device. As explained in the above section, η_{TEL} and η_{avg} are defined as a probability distributions, while the η_{BAT} is a deterministic value.

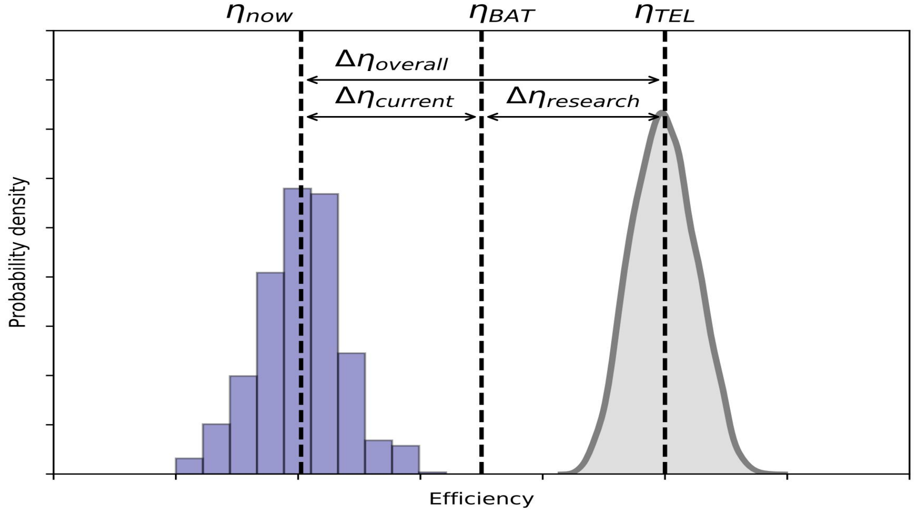


Figure 2: Diagram showing the conceptual difference between current efficiency (η_{now}), best available efficiency (η_{BAT}), and the technical efficiency limit (η_{TEL}). Current efficiency is understood as a probability density function based on data. The TEL is understood as a probability density function representing the uncertainty of the models and parameters used in its estimation.

The analysis uses first law efficiencies, rather than second law efficiencies as done in the SEA literature, because energy efficiency better captures useful energy defined as the last stage of quantifiable energy before the delivery of an energy service. This is best exemplified by the case of the residential boiler, where the first law efficiency is around unity, while the second law efficiency is around 15%. The lower value of the second law efficiency reflects the use of that high quality energy to deliver low temperature heat, however, for space heating it is this low temperature (30-80 C°) heat that is required, rather than work. The energy balance is built using the lower heating value (also known as the net calorific value) of fuels so all efficiencies are calculated on this basis.

3.3 Energy saving potential estimation

The Energy Saving Potential (ESP) is a measure of the energy associated with the quantity of Final energy that would be saved if each conversion device was operated at a target efficiency. The computation of ESP requires knowledge on the energy throughput (E_d) of each conversion device (d) as well as the current (η_d^1) and target efficiency (η_d^2). The throughput of each conversion device in the UK was already estimated for the 2013 UK energy system in a stochastic manner in previous work by Paoli et. al [30]. This means that the quantity of final energy input in each device is defined as probability distribution which represents the uncertainty of the estimate. Equation 2 shows the formula used for the calculation of the ESP in its general form

$$\mathrm{ESP}_d = E_d \left(1 - \frac{\eta_d^1}{\eta_d^2}\right) \tag{2}$$

With the information on energy efficiency available, three ESPs can be defined. First, the overall ESP (ESP_o), represents the savings associated with moving from current efficiency to the TEL ($\eta_d^1 = \eta_{avg}; \eta_d^2 = \eta_{TEL}$). Second, the current ESP (ESP_c) which represents the savings associated with moving current efficiency to BAT efficiency ($\eta_d^1 = \eta_{avg}; \eta_d^2 = \eta_{BAT}$). Third, the research ESP (ESP_r) which represents the savings associated with moving from BAT efficiency to TEL ($\eta_d^1 = \eta_{BAT}; \eta_d^2 = \eta_{TEL}$). All of these saving potentials are calculated at the most granular level (for each combination of fuel, sector, end-use and device) and then aggregated to present the savings at a sectoral, device, and country level.

The ESP_r is broken down for each technical parameter and loss reduction mechanism identified. In this case the ESP_{rp} measures the potential savings associated with the improvement of a given parameter p from its BAT level to the level identified for the calculation of the TEL. The potential is calculated by first estimating the efficiency associated with a given parameter (η_p), assuming that all other parameters remain equal. The saving potential is calculated following equation 4

$$\Delta\eta_p = \eta_{BAT} - \eta_p \tag{3}$$

$$\mathrm{ESP}_{rp} = E_d \left(1 - \frac{\eta_{BAT}}{\eta_{BAT} + \Delta\eta_p}\right) \tag{4}$$

For all the above mentioned measures, a Carbon Saving Potential (CSP) is calculated for each device (d) and fuel (f) combination using equation 5

$$\mathrm{CSP}_d = c_f \; E_{df} \left(1 - \frac{\eta_{df}^1}{\eta_{df}^2}\right) \tag{5}$$

where c_f is the carbon emission per unit energy ($\mathrm{gCO_2/MJ}$) associated with each fuel. Carbon emission factors are taken from the UK government official emission factors for the year 2013 [39]. All the saving potentials are calculated using a Monte Carlo method taking 5000 random samples from each distribution using the NumPy package [40] in Python.

4 Results

4.1 Technical parameters and loss mechanisms

In order to establish the technical efficiency limits of each conversion device, it is first necessary to identify the key design parameters and loss mechanisms affecting efficiency. For each parameter and loss mechanisms, the maximum range of values to which it can be stretched through technical improvements is identified. The full analysis of each conversion device which includes a) with the rationale for the choice of each parameter and its relation to efficiency, and b) the sources and expert opinions used to determine the maximum reachable value of each parameter; is presented in the *Supporting Information.* Table 1 summarises and describes each of the technical parameters and loss mechanisms that have been used to estimate the efficiency limit of each conversion device.

Table 1: List and description of the technical parameters and loss mechanisms used to characterise the efficiency limit of each device. The optimal value of a parameter represents either the highest or lowest achievable value of the parameter depending on whether it is proportional or inversely proportional to efficiency.

Device	Parameters	Optimal value		Description
Chemical to Work				
Jet Engine	Pressure Ratio	90–100	–	Ratio of pressures at the entry of the turbine and the one at the exit of the compressor.
	Turbine Inlet Temperature	1900–2100	K	Temperature at the exit of the combustion chamber, highest temperature experienced in the cycle
	Polytropic efficiency	92–95	%	Indicator of the compressor and turbine quality
	Propulsive efficiency	85–90	%	Indicator of the efficiency with which the jet's momentum is converted in useful kinetic energy
RE Engine	Compression Ratio	35–40	–	Ratio of top dead center volume to bottom dead center volumes
	Heat Loss Reduction	40–50	%	Reduction of heat transfer through cylinder walls
	Exhaust Loss Reduction	15–20	%	Reduction of losses in exhaust gasses by means of work recuperation
	Friction Loss Reduction	80–90	%	Reduction of friction in piston–wall assembly, cam–valve assembly and crank assembly
Electrical to Work				
Electric Motor	Rotor copper loss reduction	100	%	Avoidance of rotor copper losses by use of synchronous machines
	Stator copper loss reduction	15–25	%	Reduction of current induced losses in the stator windings
	Stray loss reduction	25–30	%	Reduction of losses occurring at stator–rotor interface
	Iron loss reduction	60–75	%	Reduction of losses induced by the magnetic flux
	Friction loss reduction	25–30	%	Reduction of losses in bearings and ventilation system
Chemical to Thermal				
Boiler	Equivalence ratio	1.01–1.1	–	Ratio of the actual air flow compared to the airflow required for stoichiometric combustion
	Minimum temperature difference	6–9	K	Temperature difference between flue gas exit temperature and inlet water temperature
	Heat Loss	0.5–1	%	Share of output lost to the environment rather than transferred to water
Electrical to Thermal				
Cooler	Compressor isentropic efficiency	80–85	%	Measure of compressor quality and efficiency
	Evaporator delta temperature	3–6	K	Temperature difference between evaporator temperature and required internal temperature, mesure of internal heat exchanger effectivness
Electrical to Illumination				
LED	Driver efficiency	92–97	%	Efficiency of AC to DC conversion
	Optical efficiency	90–95	%	Ratio of photons exiting the lightbulb over photons being generated by the device
	Wall plug efficiency	90–100	%	Ratio of radiative flux (photon generated) over DC electricl power input
	Spectral efficacy	348–414	lm/W	Convolution of produced radiative flux spectrum and the human's luminous spectrum

For jet engines, the TEL is defined by the propulsive efficiency and by operating parameters of turbomachiery, the pressure ratio, the turbine inlet temperature, and the the polytropic efficiency of compression and expansion. To achieve the maximum values of turbomachinery parameters, materials able to sustain higher temperatures such as ceramics or ceramic composites, are required. While improvements in polytropic efficiency and pressure ratio can be achieved by optimised design and ever smaller tolerances in blade manufacturing. Propulsive efficiency can be improved by switching to open rotor architectures. All these solutions require further R&D since solutions are not yet available.

For reciprocating engines the technical advances associated with the TEL are: reduction of the in-cylinder heat losses by the use of thermal barriers and higher temperature materials for the engine block; recovery of exhaust gas losses by means of an Organic Rankine Cycle, reduction of whole engine friction losses by use of advanced lubricants. The compression ratio (CR) increases to around 30, therefore stronger materials are required in the engine block. All these advances have important technical challenges and require R&D advances.

For electric motors, the most important design changes required to achieve the TEL (without modifying majorly the energy density of the motors) are: a shift to synchronous technology, thus removing rotor copper losses, and the use of amorphous metals in the core, thus halving the iron losses in the rotor. Synchronous motors built using permanent magnet or synchronous reluctance technology are already available for specialised applications while amorphous metals are commonly used in transformers. Other improvements which require further research include design optimisation to reduce stray losses and stator copper losses as well as the use of advanced lubricants to reduce friction losses.

For boilers, the equivalence ratio, the condenser pinch point temperature difference, and the ambient heat losses define the TEL. The optimal values can be reached by further increasing the effectiveness or the area of the heat exchangers and by developing burner designs that enable efficient combustion near stoichiometric conditions. Heat losses can be avoided by better heat exchanger design and larger insulation. The greatest technical challenge for boilers is the improved equivalence ratio, since flame stability and emission control become more difficult at near stoichiometric conditions. The other options require mostly design changes rather than technological improvements.

For coolers, the TEL represents a vapour compression cycle with a much lower temperature difference between the evaporation temperature and the desired room temperature and by improving compressor efficiency. Smaller temperature differences are achievable by designing larger heat exchangers and improved heat transfer coefficients. The compressor efficiency can be improved by a shift towards radial compressors and enhancements in their design. The lower temperature difference in the evaporator can be achieved mostly by design changes, while the improved compressor efficiency required further research.

The TEL of light devices is estimated by focusing on LED technology because of its combination of high efficiency potential and high quality light output. The TEL is estimated taking in consideration marginal improvements in driver (AC/DC inverter) efficiency and in optical efficiency of light bulbs. The largest efficiency improvement contribution is made by important advances in the wall plug efficiency which is estimated to be able to reach values just under unity. This value is limited by the practical power density requirements of (1-5 W/cm^2) and manufacturing considerations since values above unity have been measured in laboratory scale devices. While R&D is required to improve wall-plug efficiency and spectral efficiency, the other parameters could mostly be improved by design changes.

Table 2: Current efficiency and efficiency limit of conversion devices used in various sectors. Quantities provided as ranges represent the range between the 10th and 90th percentile of the values shown.

Device	Sector/End-use	Power Rating		Current Efficiency	BAT	TEL
Chemical to Work						
Gas Turbine	Industry	5-50	MW	30-42%	43%	59-62%
	Aviation	10-30	MW	30-40%	41%	54-58%
SI Engine	Road Transport	50-200	kW	15-23%	36.5%	56-62%
	Other	<10	kW	15-30%	30%	56-62%
CI Engine	Road Transport	80-400	kW	21-35%	36.5%	56-62%
	Rail Transport	2-5	MW	30-45%	43%	60-66%
	Navigation	1-30	MW	40-46%	55%	60-66%
	Industry	0.5-5	MW	40-46%	55%	60-66%
Electrical to Work						
Electric Motor	Residential	<5	kW	79-88%	90.5%	91.6-92.8%
	Services	5-20	kW	93-95%	96.5%	94.7-95.4%
	Industry	10-200	kW	81-96%	96.8%	97.8-98.2%
	Road Transport	50-150	kW	86-96%	96.5%	97.8-98.2%
	Rail Transport	2-10	MW	93-95%	96.8%	97.8-98.2%
Chemical to Thermal						
Boiler	Buildings	8-50	kW	80-93%	93%	93-101%
	Industry	50-5000	kW	70%-90%	90%	82-101%
Electrical to thermal						
Cooler	Space Cooling	5-50	kW	550-850%	850%	900%-1100%
Cooler	Process Cooling	0.5-500	kW	100-300%	300%	320%-380%
Electrical to Illumination						
LED	Residential	-		50-80 lm/W	107lm/W	284-350 lm/W
	Services and Street lighting			80-100 lm/W	107lm/W	284-350 lm/W
	Industry			90-110 lm/W	107lm/W	284-350 lm/W

4.2 Technical efficiency limits

Having quantified the key design parameters and loss reduction potentials, the technical efficiency limits are calculated for each device and shown in Table 2.

For jet engines and reciprocating engines used in road transport, the efficiency measures the work delivered to the aircraft and to the wheels respectively. Therefore, the Jet Engine efficiency includes both losses associated from work extraction in the engines core (thermal efficiency ≈ 0.6) and with the transfer of momentum (propulsive efficiency ≈ 0.9). For road transport engines, the efficiency includes the losses in the engine as well as in the transmission system. For the technical limit, the maximum engine efficiency is compounded with the efficiency associated with a hybrid propulsion of 85%. Higher efficiency limits are found for large reciprocating engines (for industrial, rail, and marine applications) and for stationary gas turbines. Large reciprocating engines have a higher TEL than those used for road transport because they mostly work at constant load and because their larger size makes them inherently more efficient (lower RPM, higher volume to area ratio). Higher uncertainties are associated with RE engine estimates that jet engines because the latter are estimated with method A while the former with method B.

The BAT for jet engines equals the maximum efficiency and is representative of the GE9X engine [41]. The BAT of road transport engines is representative of a 1.9l General Motor diesel (combined with a hybrid powertrain with 85% efficiency) studied by the DOE to determine the efficiency limits of engines [42], while for large engines the efficiency is representative of the Wärtsilä 31 engine [43]–currently recognised as the most efficient engine in use.

The efficiency of electric motors only takes into consideration the losses associated with electrical to shaft work conversion and excludes the wider motor system (fans, pumps, etc.). The current efficiency and TEL are both highly proportional to the power rating of the motor. Therefore, motors in different sectors are given a different efficiency range which is a function of the power rating distribution in each sector. TELs range between the high values of 92% to 98%. The uncertainty in the TEL estimation for electric motors is comparatively small, despite being estimated with the loss reduction method, because high quality loss reduction estimates are present in the literature and because the loss mechanisms are mostly independent of each other. The BAT assumed for electric motors are devices with the IE4 efficiency classification [44].

For boilers, the efficiency is a measure of the chemical energy transfered to the hot water flow exiting the boiler. Efficiency can be greater than unity because energy statistics are compiled using the lower heating value, while condensing boilers are able to recover the latent heat of vaporisation. The boiler efficiency is strongly dependent on the temperature of the return water temperature because this determines the maximum amount of heat that can be extracted from the flue gasses. In buildings, the efficiency is computed as the average efficiency between return water temperatures of 60 C° and 30 C°, as prescribed by European standards [45]. The resulting variation of values in TEL is caused by different fuels having varying net efficiency values because of different HHV to LHV ratios. The TEL of boilers reaches 101% for gas and 93% for coal, however within the same fuel the uncertainty range is small ($\leq$1%). There is high variability of operating conditions of industrial boilers due to varying steam temperature, pressure, condensate return temperature, make up water share, therefore it is not possible to estimate their average TEL with any precision. For boilers BAT is equivalent to the highest efficiency found in the UK's product characteristics database [35].

For light devices, the efficiency is defined as the lumens at the outlet of the light bulb over the input electrical power (in alternating current). The TEL of LEDs is estimated to range between 284 and 350 lm/W. The large uncertainty is associated with the maximum achievable spectral efficiency, which is difficult to define. The BAT represents the 2015 benchmark technology identified by the US Department of Energy solid state lighting report [46]. In industry and services (which includes street lighting), the current efficiency is higher than the BAT because of widespread use of sodium-lamps which have efficacies around 200 lm/W but low colour quality (CRI $\approx$50).

For coolers used for space cooling, the efficiency is defined as the Seasonal Efficiency (defined by European standards) which reflects the average efficiency of a cooler to maintain a room at a constant 20 C° throughout the year in an average European climate. The BAT for coolers in space heating is taken as the air conditioning with the highest SEER in the Eurovent database [34]. Coolers used for process cooling have varied use cases meaning that it is difficult to characterise their average efficiency. Therefore a wide range of efficiencies is assumed, the gap between BAT and TEL for process cooling is assumed to be equivalent to the one for space cooling.

4.3 UK Energy Saving Potential

The above calculations of TELs for each device in each sector enables a more reliable estimate of the energy saving potential (ESP) and the carbon saving potential (CSP) associated with each conversion technology. The methodology is applied to end-use energy consumption data in the UK in 2013.

The average Final to Useful energy efficiency in the UK in 2013 is estimated to be 69% ± 3%, while if all devices operated at their TEL, the average efficiency would be 88% ± 2%. If efficiency was to reach this level, 1460 PJ of Final energy and 110 $MtCO_2$ of emissions could be avoided. These savings represent one quarter (25%) of both total Final energy demand and of CO_2 emissions from the energy sector. If conversion devices operated at their BAT levels of efficiency, the average efficiency would be 79 % ± 2% and 920 PJ of Final energy could be avoided, equating to 16% of total demand. Table 3 shows the breakdown of the Final and Useful energy consumption in the UK as well as the Final energy demand that would result if all devices were operating at their TEL, and the associated percentage savings.

Table 3: Breakdown of the Final and Useful energy consumption of the UK by sector. The Final energy consumption that would be obtained if all devices were operating at their TEL or at BAT, and the associated savings are also displayed. Energy consumption values are in PJ, values in brackets represent the percentage savings.

Sector	2013 Final energy consumption	2013 Useful energy consumption	Final energy consumption if CD operate at TEL	Final energy consumption if CD operate at BAT
Transport	**2229**	**634**	**1189 [46%]**	**1591 [28%]**
Road	1550	375	752 [51%]	1023 [34%]
Aviation	495	173	309 [37%]	420 [15%]
Navigation	142	61	97 [32%]	111 [21%]
Rail	42	25	31 [27%]	38 [11%]
Buildings	**2461**	**2371**	**2127 [14%]**	**2227 [10%]**
Residential	1729	1662	1507 [13%]	1560 [10%]
Services	733	709	619 [16%]	666 [9%]
Industy	**1103**	**1004**	**1019 [8%]**	**1056 [4%]**
Industry	1015	933	943 [7%]	973 [4%]
Primary	89	71	76 [14%]	83 [6%]
Total	**5793**	**4010**	**4334 [25%]**	**4874 [15%]**

As shown in Figure 3 the largest ESP and CSP is associated with diesel engines and spark ignition engines which account for 683 and 333 PJ of savings respectively, followed closely by boilers and gas turbines. Devices powered by electricity show the lowest saving potentials with overall savings of 250 PJ with most of the saving coming from light devices which have the highest overall efficiency gap.

In Figure 4, the ESP and CSP are grouped and ordered by sector. The highest impact can be seen in the transport sector, with an ESP of 1186 PJ and a CSP of 85 t CO2; this is equivalent to 75% of the overall ESP. Road transport ESP alone accounts accounts for more savings that all other sectors, with 61% of total savings.

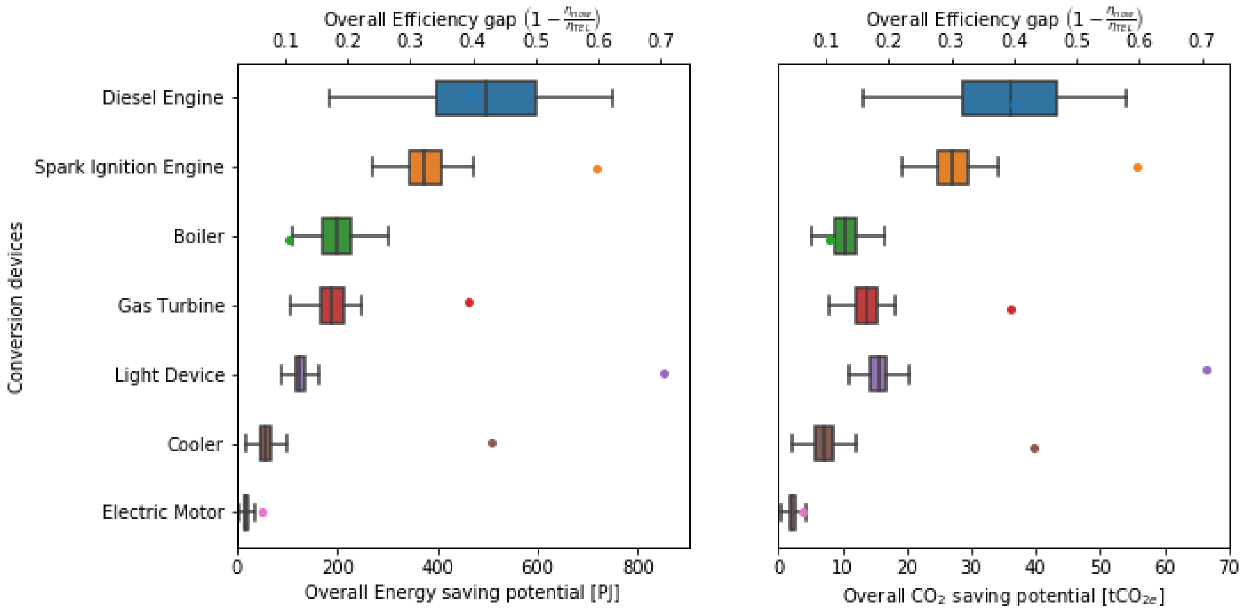


Figure 3: Boxplot showing the ESP and CSP associated with each conversion device (bottom horizontal axis), the points refer to the efficiency gap of each device (top horizontal axis)

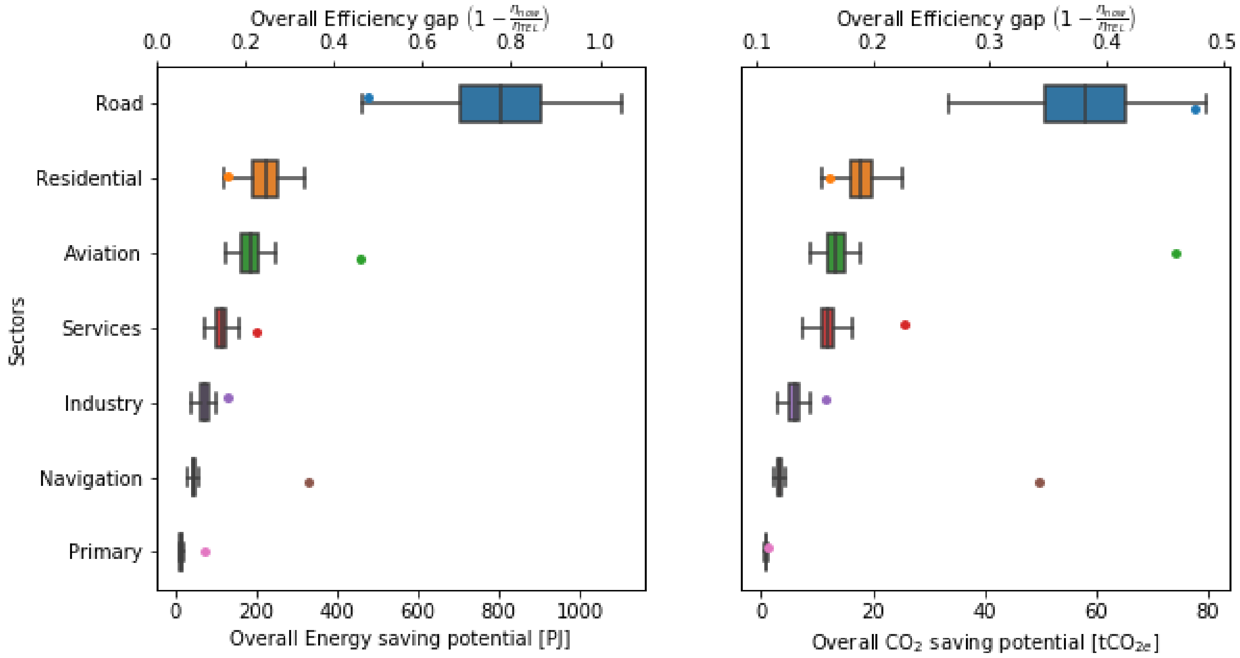


Figure 4: Boxplot showing the ESP and CSP associated with each sector (bottom horizontal axis), the points refer to the efficiency gap of each device (top horizontal axis)

In Figure 5 each device-sector combination is plotted with the scale of energy conversion on the x-axis and the efficiency gap on the y-axis. The figure shows that similar saving potentials can be of different nature: for some devices there is a large efficiency gap and a low energy conversion, such as lights; while others have low efficiency gaps but a high energy throughput, such as residential boilers. Devices with the highest ESP

(Diesel and Spark Ignition engines) have both a high technical efficiency gap and a high throughput.

Figure 6 shows another characteristic of each conversion device: the difference between the current efficiency gap and the technical efficiency gap. Devices with a high technical efficiency gap have a TEL that is is much larger than the current BAT levels. Devices with a large current efficiency gap have a current average efficiency that is much lower than the BAT. Only light devices and gas turbines have a technical efficiency gap that is higher than the current efficiency gap. For devices with the highest ESP, the current efficiency gap is around 2.5 times larger than the technical efficiency gap.

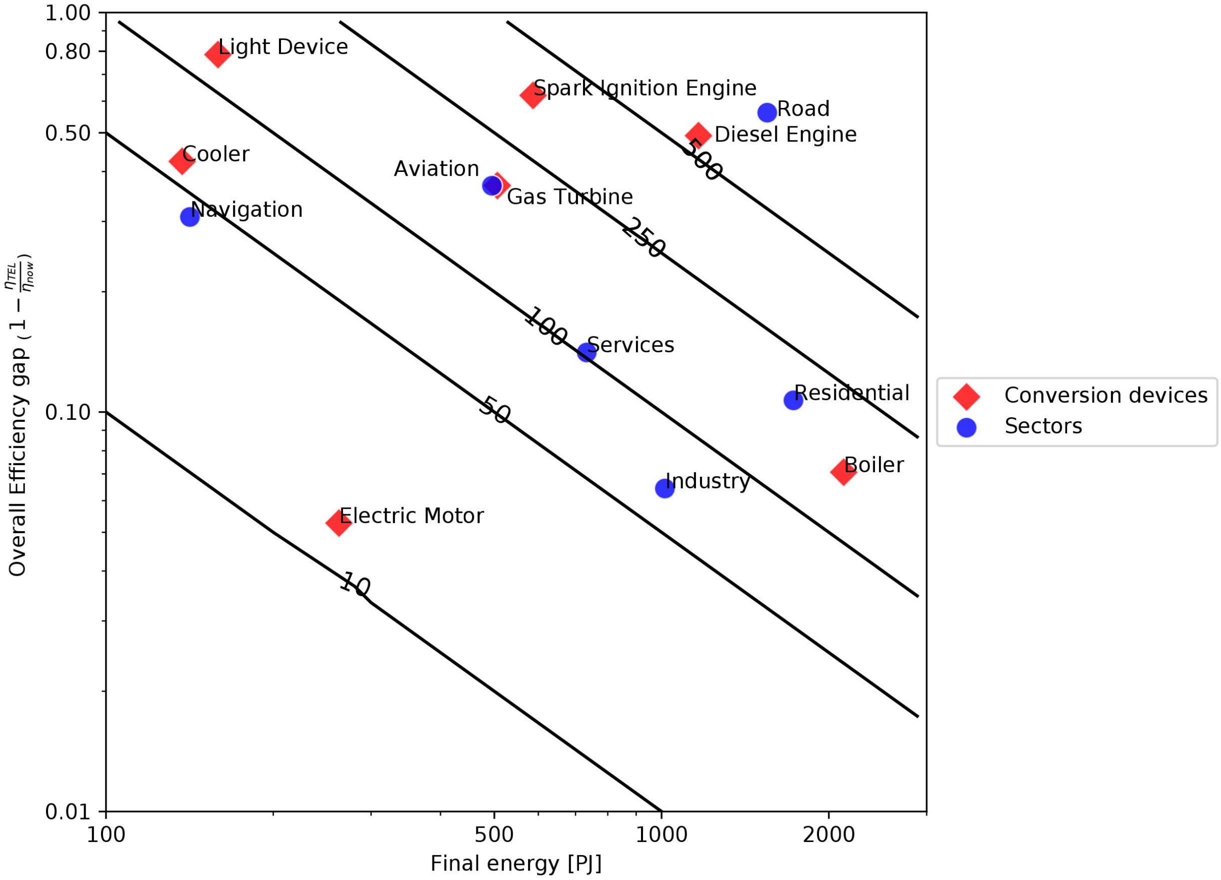


Figure 5: Log-log plot showing combinations of sector and conversion device where the x-axis represents the final energy throughput of each sector-device combination, while the y axis represents the gap between the current efficiency and the TEL. The contours represent lines of constant energy saving potential.

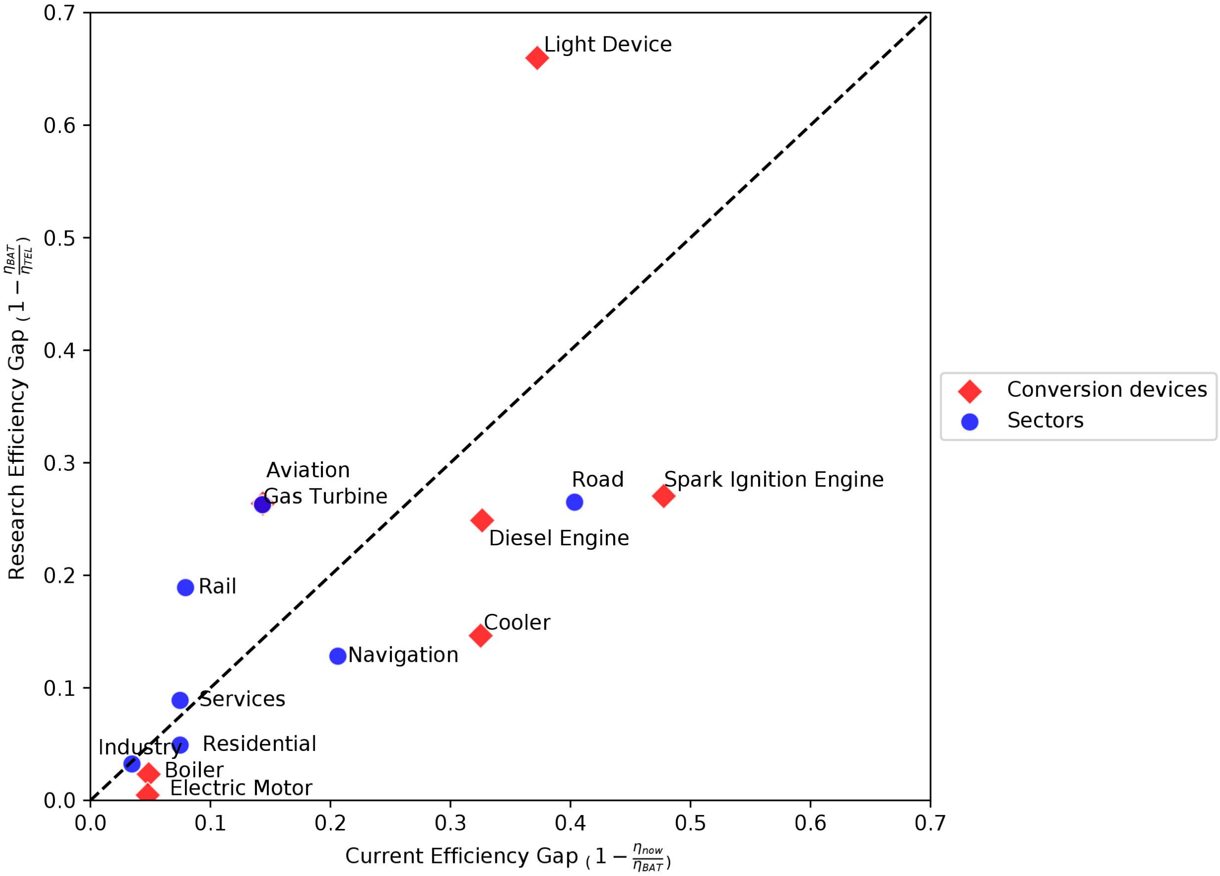
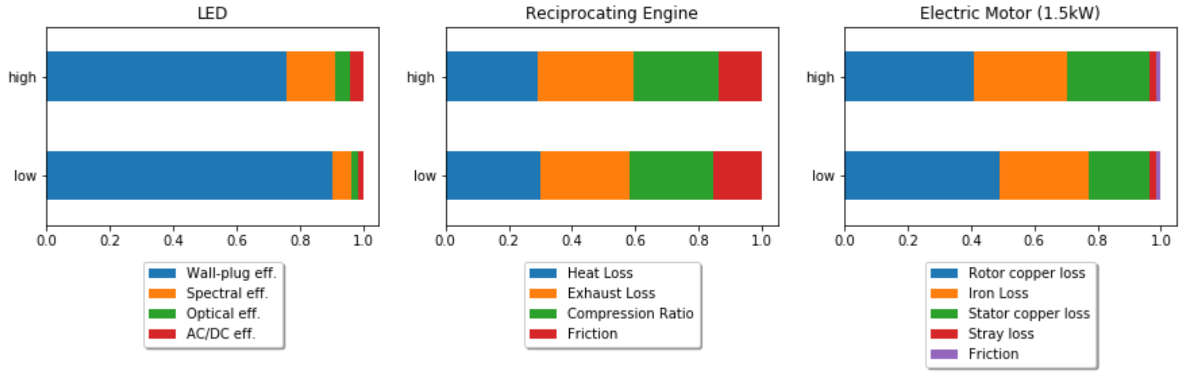


Figure 6: Plot showing sectors and conversion devices where the x-axis represents the efficiency gap between current median efficiency and the best available technology, the y-axis represents the technical improvement gap between the best available technology and the technical efficiency limit.

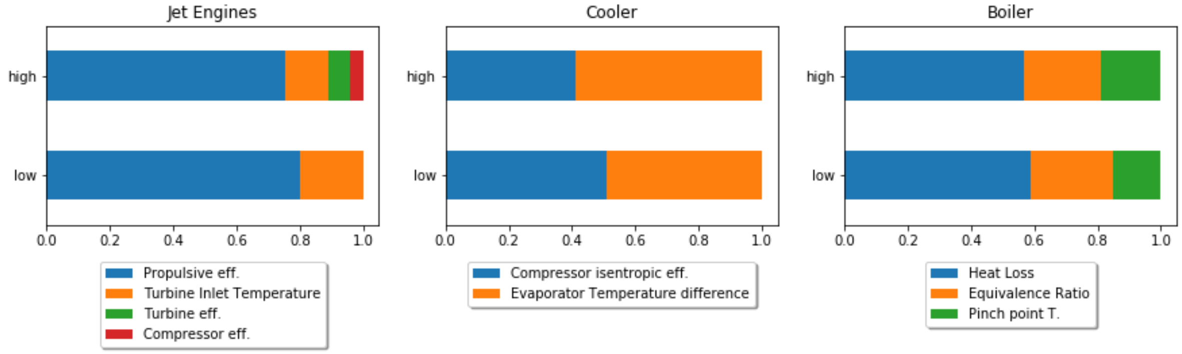
4.4 Technical parameter contribution

Figure 7 shows the relative importance of each parameter on the technical efficiency limit, including the share of efficiency improvement attributed to each parameter. Two bars are shown for each device which represent the lower and upper bounds of possible parameter improvement. A single parameter dominates the saving potential in three of the devices: wall-plug efficiency (0.7-0.8) for LEDs; propulsive efficiency (0.7-0.8) for Jet engines; heat loss (0.5-0.6) for Boilers. In contrast, the loss mechanisms are distributed more widely for reciprocating engines, electric motors, and coolers.

Knowing the relative importance of each parameter to move from BAT efficiency to the TEL, it is possible to estimate a saving potential for each technical improvement. Figure 8 shows the energy saving potentials grouped into broad engineering research areas: “Turbomachinery” (which includes improvements in compressors and turbines across all devices), dominates the ESP at 260 PJ for the UK. This is closely followed by “Heat Transfer” (which includes savings from both heat transfer reduction and improvements across devices) and “Material Science” (which includes parameters that are mostly driven by improvements in material properties). “Semiconductor design” also plays an important role, as increases in LED wall plug efficiencies have a large ESP. Electrical engineering (related to electric motor improvements) and “Tribology” (related to reduction of friction losses across all devices) have lower ESPs. Viewing the ESP through the lens of engineering disciplines can help indicate priorities for energy efficiency research agenda setting and investment. Detailed assumption behind the association of technical parameters to research areas is found in the *supporting information.*



(a) TEL estimated using method B



(b) TEL estimated using method A

Figure 7: Relative contribution of each parameter to the TEL. The lower and high column represent the lower and upper bound of the probability distribution for each parameter.

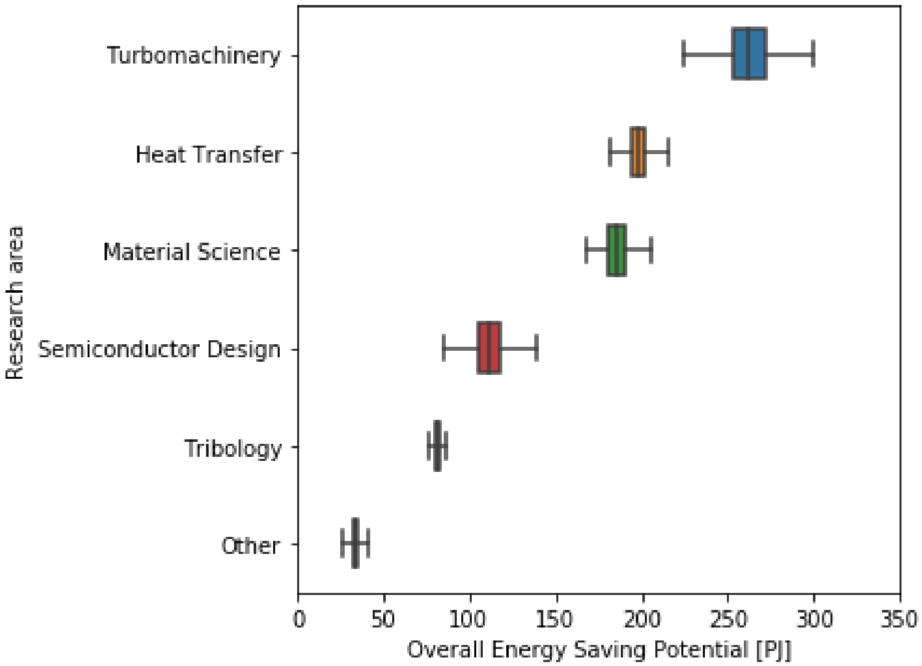


Figure 8: Energy saving potential of each technical parameter grouped into major engineering research areas. The boxplot represents the uncertainty associated with the estimate of saving potential.

5 Discussion

5.1 Insights from conversion efficiency limit study

For all conversion devices there is a trade off between power density and efficiency, since most loss mechanisms are proportional to the intensity with which energy is converted. For example, copper and iron losses in electric motors are proportional to the current and flux density; the energy losses from boilers and coolers are proportional to the heat exchanger surface area per unit of power output. However, not all key performance parameters are subject to this trade off: Increasing the compression ratio in reciprocating engines, the turbine inlet temperature is gas turbines or the equivalence ratio in boilers, benefits both power density and efficiency. For these devices, it is easier to establish objective limits for a parameter, because only the physical limitations need to be considered. On the other hand, parameters that are subject to the efficiency/power density trade-off require further assumptions about the effect of a given parameter on power density.

The results from this study show that the largest potential improvements in conversion efficiency are found in devices that convert chemical energy to work despite decades of engine's and turbine's efficiency improvements. There are two reasons that can explain this observation. First, the conversion of chemical energy to work is concentrated in the transport sector where high power density is required. It is plausible that designers have historically favoured improvements in power density over efficiency gains. This idea is supported by studies investigating the improvement rates of vehicle performance in the USA [47]. Second, in chemical energy to work conversions, increased efficiency is related to parameters which depend on technological development and material science, such as maximum temperatures and pressure. Whereas for most other conversion routes improved efficiency can be achieved more easily by sacrificing power density. For example, over-sizing the heat exchange surface area in a boiler or the windings in an electric motor results in higher efficiency levels and these design changes can be implemented readily.

This novel definition of technical efficiency limits should be considered by scholars studying the links between energy efficiency and economic growth, since the technical limits are considerably lower than the theoretical limits, often used in studies using the exergy metric. In particular, authors claiming the important role of thermodynamic efficiency improvements in economic growth [48, 49] can now explore the impact of technical limits to efficiency growth on their economic models.

5.2 Prioritisation of actions

The total estimated ESP (energy saving potential) for conversion derives in the UK equates to 25% of the country's final energy in 2013. This compares to the 89% reduction in global energy demand that was estimated by Cullen and Allwood [10] using theoretical efficiency limits to conversion devices, demonstrating that many of the identified energy losses cannot be resolved in practice. The 25% ESP for UK conversion devices is not sufficient to reach climate goals, and this does not take into account further limitations related to the economic viability of implementing these efficiency options. When calculating the ESP associated with bringing the average efficiency up to current BAT levels, the estimated saving potential is 16%.

The main message to draw from this result is that improvements in energy conversion efficiency alone are insufficient to meet the energy demand and CO_2 emission reductions targeted and that the improvement potential of passive systems is much higher than for conversion devices. However, there are sectoral variations. For example, in the transport sector conversion efficiency improvement still plays an important role, with up to 50% reductions in energy demand possible. This is particularly important for aviation, where the conversion of energy could be improved by 37% and where passive system improvements are more difficult to obtain. Conversely, in the residential and industrial sectors, reaching the TEL for conversion efficiency has a relatively limited impact on the saving potentials. For the residential sector, this is because boilers, which consume the majority of energy, have only a limited efficiency improvement gap. While in the industrial sector, a significant share of energy demand is used directly for chemical reactions, without undergoing an energy conversion. On the other hand, large passive system improvements are readily available in these sectors, mostly in the form of better heat insulation. Passive systems have larger technical saving potentials since et al. [28] found that their technical ESP is equivalent to 73% of global energy demand.

Having taken a probabilistic approach to the estimation of the ESP, it is possible to compare the uncertainty associated with each estimate. This makes the prioritisation and comparison of efficiency options more robust. For example, Figures 3, 4, and 8 show clear overlaps of ESP for devices, sectors and engineering research areas, meaning a more simplistic prioritisation based on averages could be misleading. Table 2 shows there is considerable spread in the efficiency ranges, however, the majority of the uncertainty is associated with the estimates of current average efficiency rather than for the TELs.

The results shed light on the type of actions required to fully leverage the capabilities of energy conversion improvements for each technology. While a push towards BAT efficiency would yield biggest savings, there situation is different across technologies. In devices such as boilers and electric motors, the difference between the current BAT and the TEL is small, while the gap between current average efficiency and BAT is much larger. These technologies have been under development for over a century, leading to known cases with high efficiencies. For these devices, efforts should concentrate on moving the average conversion efficiency towards the BAT, by forcing the market uptake of more efficient devices. Options include driving policy towards more stringent minimum performance standards or employing scrappage schemes, such as those sporadically implemented for road vehicles. In contrast, technologies such as light bulbs and reciprocating engines display similar gaps between average efficiency, BAT, and TEL. For such devices, research and technology development should be pursued in addition to efforts to increase market penetration of efficient devices.

There are two reasons why the identified technical saving potentials could not be realised in full, even assuming that that all energy conversion could operate at its TEL. First, efficiency improvements caused by technological innovation could lead to increased energy service demand. In developed countries, this would be detrimental for the achievement of climate goals, especially if the saved monetary resources are used to increase demand for highly carbon intensive activities such as air travel. It is therefore advisable that, in addition to policies fostering efficiency improvement, governments put in place economic policies aimed at limiting the extent of energy demand rebound, both direct and indirect [50]. Second, the present analysis assumes a static energy system, that is, static energy conversion chains that deliver Useful energy. However, the energy system is undergoing a transition with the aim of reducing carbon emissions. This transition implies profound changes in the way in which energy is transformed to deliver energy services, mostly by increasing the share of electricity as an energy vector. Increased electrification across sectors would have a sizeable impact on the relative importance of the savings from each conversion device.

The use of technical parameters in the assessment of ESPs for conversion devices has enabled the links to engineering research areas to be made. Turbomachinery, which enables improvements in both axial and radial turbines and compressors is shown to have the highest energy conversion saving potential. This is followed by material science and heat transfer improvements, with similar potentials, while tribology (the study of friction reduction) has a smaller impact. While these results are only a first order analysis, and only apply to energy conversion devices, this study provides example of how a granular and technically consistent models of the energy system can be used in the setting appropriate research agendas.

While efficiency improvements alone cannot bring the energy system to complete decarbonisation, it is a key enabler other measures such as renewable electricity and heat deployment since it reduces the overall quantity of energy that needs decarbonising. The results of this study confirm the substantial savings that can be brought about with already known technology even in a developed country such as the UK. Even though further efforts are needed to reap efficiency's full benefits, it is promising that most policy documents – for instance the latest UK Net-Zero advice report [51] and the EU's long-term decarbonisation strategy [52] – recognise the importance of efficiency improvements in all sectors and make it a key part of the technology roadmap to a zero-carbon society.

6 Conclusion

This study has presented a physics based analysis of the technical efficiency limits across the energy system and used them to calculate the saving potentials (ESP and CSP) associated with conversion efficiency improvements.

While the literature has many examples of economic energy saving potential studies of technology options, this is the first attempt in the literature to consistently quantify the technical efficiency limits of energy conversion devices. The efficiency limits are estimated based on extensive physical modelling and literature review. A stochastic approach has been used throughout the analysis to be open about the considerable uncertainties associated with this research area.

Three main conclusions can be drawn from this study. First, in order to increase end-use conversion efficiencies, it is best to focus on convergence towards BAT levels rather than on R&D projects aimed at increasing the performance conversion devices. Second, conversion efficiency alone is not sufficient to meet the UK's climate and energy reduction targets, since even at the technical limit, only 25% of energy demand could be reduced. Third, conversion efficiency improvements can have the most impact in the transport sector, particularly for the road transport sector, accounting for half the total ESP.

The ESP metric, provides an estimate of the potential savings from efficiency improvements for a given technology or sector, with all else being equal. However, it does not account for future changes in energy flows, technology choices, and energy transition pathways. Given the energy system is in constant change, the technical efficiency limits should be applied in context of possible long-term energy transitions. Future work should combine the efficiency limits from this study with long term energy projections to explore how different energy system configurations affect the potential savings from each technology.

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