Energy productivity:

Increasing efficiency in an expanded, electrified energy system

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Energy
Transitions
Commission

Insights Briefing

The Energy Transitions Commission (ETC) is a global coalition of leaders from across the energy landscape committed to achieving net-zero emissions by mid-century, in line with the Paris climate objective of limiting global warming to well below 2°C and ideally to 1.5°C.

Our Commissioners come from a range of organisations – energy producers, energy-intensive industries, technology providers, finance players and environmental NGOs – which operate across developed and developing countries and play different roles in the energy transition. This diversity of viewpoints informs our work: our analyses are developed with a systems perspective through extensive exchanges with experts and practitioners. The ETC is chaired by Lord Adair Turner who works with the ETC team, led by Ita Kettleborough (Director), and Mike Hemsley (Deputy Director). The lead authors of this insights briefing are Stephannie Dittmar Lins and Elena Pravettoni.

Energy productivity: Increasing efficiency in an expanded, electrified energy system briefing was developed in consultation with ETC Members, but it should not be taken as members agreeing with every finding or recommendation. The ETC team would like to thank the ETC members, member experts and the ETC's broader network of external experts for their active participation in the development of this insights briefing.

The ETC Commissioners not only agree on the importance of reaching net-zero carbon emissions from the energy and industrial systems by mid-century but also share a broad vision of how the transition can be achieved. The fact that this agreement is possible between leaders from companies and organisations with different perspectives on and interests in the energy system should give decision-makers across the world confidence that it is possible simultaneously to grow the global economy and to limit global warming to well below 2°C. Many of the key actions to achieve these goals are clear and can be pursued without delay.

This report should be cited as: *Energy productivity: Increasing efficiency in an expanded, electrified energy system.*

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Introduction

The growth of energy supply has been essential to the growth in human welfare. Since 1900, total global primary energy demand has increased 15 times, enabling a 34 times increase in global gross domestic product (GDP) and a seven-fold increase in GDP per capita.[1] Humanity's increasing ability to produce and use fossil fuels has driven this increase. Today, 80% of primary energy demand comes from coal, oil or gas.[2] But the inevitable consequence has been rising CO_2 emissions and global warming which poses a huge threat to human welfare.

It is therefore essential to shift the vast majority of humanity's energy sources from fossil fuels to various forms of zero-emissions technology. This will primarily be driven through massive clean electrification – electrifying as much of the economy as possible and decarbonising sources of electricity supply. In addition, bioenergy and the use of carbon capture and storage (CCS) must be used to eliminate emissions in those sectors where carbon-based molecules will continue to be needed to provide energy, or as a feedstock in material production.[3] Much of the Energy Transitions Commission (ETC)'s work has been focused on how to achieve these different forms of decarbonisation and on the optimal balance between them.

But there is also a huge opportunity to improve "energy productivity" – using less energy inputs to achieve any given level of human welfare. Energy productivity improvements can be achieved through several measures - technical energy efficiency, service efficiency, and materials efficiency.[4] Achieving that improvement can accelerate the pace of emissions reductions in the period before decarbonisation of energy supply has been achieved; and even if we could ultimately derive all energy from zero-emissions sources, maximising energy productivity should be a priority since it will reduce the costs of the energy system, reduce the need to devote land, water and other materials to producing energy, and increase countries' energy security by reducing the need for fossil fuel imports.

The potential for and importance of energy productivity improvement has therefore been noted for several decades, for instance in reports by the International Energy Agency (IEA). These reports have also highlighted the slow pace of energy productivity improvement relative to potential. At COP28 in Dubai, 133 countries therefore committed to doubling the pace of energy efficiency improvement from around 2% per annum in recent years to 4% by 2030.[5]

However, the precise meaning of that commitment is in some respects unclear; for instance, whether it relates to primary energy or final energy.[6] Many countries, however, do not have clear policies to deliver this commitment, or a clear understanding of the highest potential sectors and technologies, both in the short- and long-term. Meanwhile, the growth of artificial intelligence (AI) based demand for electricity, which challenges past assumptions that service-based economies are likely to use less energy, may make the agreed target more difficult to achieve.

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[1] Our World in Data, *Global GDP over the long run*. Available at: *https://ourworldindata.org/grapher/global-gdp-over-the-long-run*. [Accessed June 2025]; World Bank.

[2] IEA (2025), *Global Energy Review 2025*.

[3] ETC (2021), *Making Clean Electrification Possible.*

[4] Technical energy efficiency measures the input of energy required to deliver a desired energy service; service efficiency measures the potential for people to enjoy the same standard of living while using less energy-intensive services (e.g., using public transport rather than private cars), or products (e.g., increasing utilisation of existing buildings rather than building new ones); and material efficiency refers to that which can be improved by delivering a given quantity of products with reduced material inputs (e.g., fewer kg of steel or cement used to construct a building).

[5] COP28, *Global Renewables and Energy Efficiency Pledge*. Available at *https://www.cop28.com/en/global-renewables-and-energy-efficiency-pledge*.

[6] Although the target does not specify if the improvements are in primary or final energy, it builds from IEA analysis that point to an improvement in primary energy – see Box B of ETC (2024), *Credible Contributions: Bolder Plans for Higher Climate Ambition in the Next Round of NDCs.*

In this report, *Energy Productivity: Increasing efficiency in an expanded, electrified energy system* and an accompanying report, *The Road Ahead: Electrification, design and mobility choices for efficient transport*, we identify the scale of energy productivity improvement that could be achieved over the next 25 years, the sectors and technologies which have the highest potential, and the policies required to drive both short and long term progress.

We cover in turn:

1. Definitions: Energy productivity, primary energy, final energy, useful energy and energy services.
2. Historic and recent trends: Gradual improvement in energy productivity but well below the COP28 target.
3. Potential improvements in energy productivity:
    - Reducing the final energy needed to support rapid growth in useful energy and human welfare.
    - Reducing the primary energy required to deliver final energy supply.
    - Annual improvement rates and implications for the COP28 target.
    - The opportunities of energy productivity improvement: Potential reductions in required investment and resource input.
4. Fundamental drivers of long term energy demand growth: Rebound effects, artificial Intelligence, and future new energy uses.
5. Actions to drive cost-effective energy productivity improvement.

Box A lays out the report's key messages, and additional detail is provided in the following sectoral reports, briefs and appendices which cover:

- *Achieving Zero-Carbon Buildings: Electric, Efficient and Flexible* (2025) illustrates the large opportunities to operate buildings more efficiently and to reduce the amount of materials used in construction.
- *The Road Ahead: Electrification, Design and Mobility Choices for Efficient Transport* (forthcoming 2025) analyses the potential for a dramatic improvement in the energy efficiency of road transport, primarily through electrification.
- *Energy Productivity Improvement Potential in the Hard to Abate Sectors* (forthcoming early 2026) sets out the potential to improve energy efficiency in heavy industry (e.g., steel, cement and petro-chemicals) and long distance transport (shipping and aviation).

Box A

Key messages on energy productivity

Increasing output while reducing energy input:

- Between now and 2050, the world could expand energy services and enable a doubling of global GDP while reducing final energy use by 24% and primary energy use by 36% versus today's levels. Energy services will grow rapidly to meet the demands of increasingly prosperous societies, with passenger road transport growing 70% and both cooling and aviation demand by 150%. However, energy inputs to the economy can be significantly reduced through renewables reducing energy losses in the power system, and electric vehicles and appliances reducing losses from today's fossil fuel equivalents, alongside other efficiency actions.

Electrification and electrical equipment efficiency are the biggest drivers:

- Electrification – electrifying building heating and cooking, road transport and parts of industry – could cut final energy demand by 24% vs. a business as usual (BAU) scenario, with electricity growing from 21% to 63% of total final energy use.
- Improvements in the efficiency of electrical equipment and vehicles could deliver a further 10% reduction.
- Reduced demand for energy services could contribute a further 11% cut. Around two-thirds of this reflects improved operational efficiency in buildings, logistics systems, as well material recycling, with only a third (i.e. a 4% total reduction of final energy demand) depending on changes in consumer behaviour.

The greatest opportunities are in building and road transport:

- Around two-thirds of the total opportunity to reduce final energy demand by 2050 lies in buildings and road transport, reflecting the huge potential of electrification to increase the efficiency of building heating, cooking and road vehicles. Final energy use could be reduced by 60% and 80% respectively versus BAU even while energy services rise rapidly.
- In addition, there are major opportunities to reduce energy demand, and in particular peak energy demand, via better appliances and building design, construction and management.

Country-level priorities for delivering energy productivity will differ:

- In all regions, electrifying road transport offers the largest and most consistent opportunity to reduce energy use and lower fuel imports.
- In high-latitude countries (e.g. Europe, Canada, Northern China), electrifying building heating by replacing gas boilers with heat pumps should be a central focus, given the scale of heating demand.
- In developing and tropical countries, cooling demand is rising rapidly. Policies must ensure high-efficiency air conditioning (AC) becomes the norm, by accelerating the turnover of existing stock and mandating efficient new systems and building envelopes to manage peak demand.
- In South and Southeast Asia and parts of Africa, transitioning away from the use of traditional biomass for cooking to cleaner cooking fuels (e.g., LPG) or electric stoves offers major health and efficiency gains.

COP28 4% per annum target - feasible for two decades:

- Electrification and further actions for higher productivity makes it possible to grow final energy productivity by 3.4% per annum, and primary energy productivity by 4.2%, for the next two decades.[7] This is in line with the COP28 commitment to double the pace of energy productivity improvement. But this increase will only occur if countries enact policies and other actions to achieve the highest potential improvements.

Improved energy productivity reduces investment and resource needs:

- Improved energy productivity could reduce the total investment required to build a zero-carbon economy by around \$0.6 trillion per annum, and reduce the land requirements for solar PV by around 0.2 million km^2, which is equivalent to the land size of Ecuador.

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[7] Our World in Data, *Global GDP over the long run.* Available at: https://ourworldindata.org/grapher/global-gdp-over-the-long-run accessed on June, 2025.

Long-run energy demand depends on rebound effects, AI electricity demand and future energy applications:

- Beyond the next 25 years of widespread electrification, energy demands will likely return to strong growth; this reflects the huge potential for energy use to increase human welfare. During the next 25 years, energy use could also be higher than our projections as a result of rebound effects and growing AI needs.
- This reinforces the need to pursue energy productivity improvements wherever possible, while planning for growing energy supply systems over the long-term.

Actions required to seize the energy productivity opportunity:

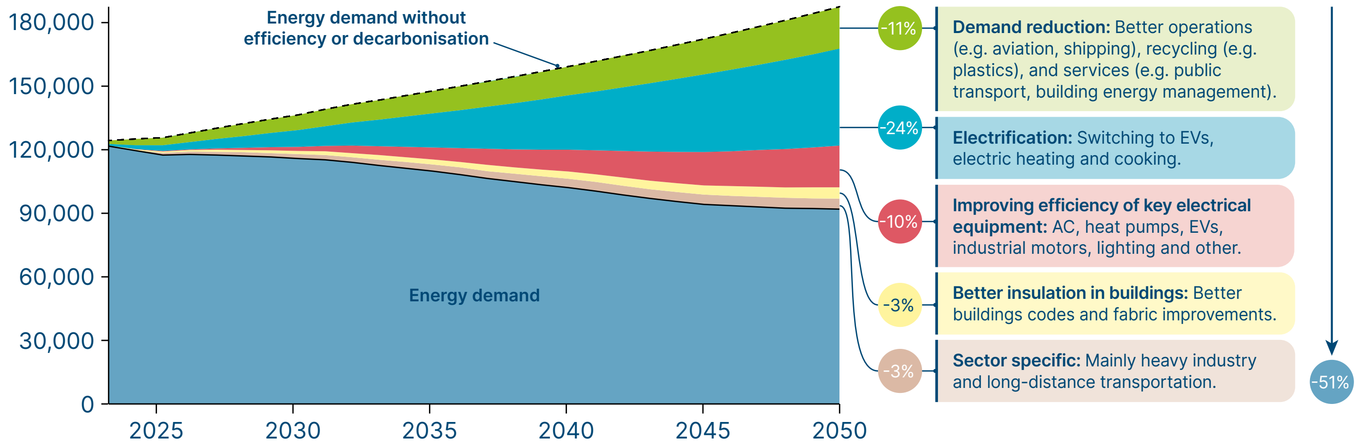
- Countries should develop national policy frameworks which identify opportunities by sector.
- Implement policies to improve final energy productivity, with strong focus on electrification alongside equipment and vehicle efficiency.
- Set clear plans for power sector decarbonisation to replace energy inefficient fossil fuels with low-carbon energy, as the backbone of a low-carbon economy.

Exhibit 0.0

Productivity actions can reduce final energy demand 25% from today; 50% compared to business as usual

Final energy demand
TWh

Key actions
% reduction potential compared to 2050 energy use without efficiency or decarbonisation



Demand reduction: Better operations (e.g. aviation, shipping), recycling (e.g. plastics), and services (e.g. public transport, building energy management).

Electrification: Switching to EVs, electric heating and cooking.

Improving efficiency of key electrical equipment: AC, heat pumps, EVs, industrial motors, lighting and other.

Better insulation in buildings: Better buildings codes and fabric improvements.

Sector specific: Mainly heavy industry and long-distance transportation.

SOURCE: Systemiq analysis for the ETC; IEA (2025), *World Energy Outlook*; MPP (2023), *Hard-to-Abate Sector Transition Strategies*; ETC (2025), *Achieving Zero-Carbon Buildings*; ETC (2023), *Fossil Fuels in Transition*; BNEF (2023), *Electric Vehicle Outlook*.

Definitions: Energy productivity, primary energy, final energy, useful energy and energy services

1

To think clearly about the potential for energy productivity improvements, it is essential to start with a clear conceptual framework and definition of terms.

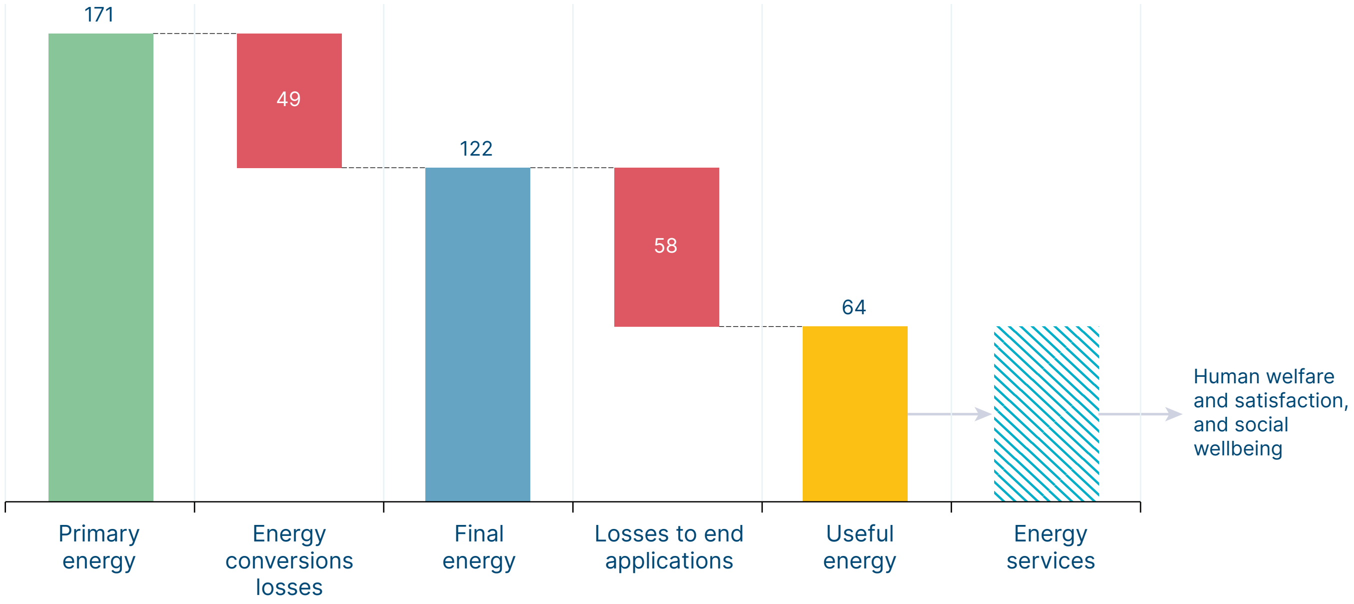
The overarching concept is “energy productivity“ - how much energy input is required to deliver a given level of human welfare. This is conventionally measured as $ of GDP per energy input (in kWh).[8] The rate of improvement in energy productivity is therefore the change in energy productivity from year to year, with a rise in GDP per unit of energy input delivering an improvement in energy productivity.

Exhibit 1.1

Global energy flows can be measured in primary, final, and useful energy

Global energy flows

‘000 TWh, 2023



Examples:

• Crude Oil • Coal • Wind and sunlight	• Refining losses • Heat losses in generation	• Electricity • Diesel	• Appliances internal heat • Energy to wheel losses	• Joules of heat to spaces • Kinetic energy to car wheels	• Warm and cooled spaces • km travelled

What people need

SOURCE: Systemiq analysis for the ETC; IEA, (2025) *World Energy Review;* IEA (2024), World Energy Outlook; International Institute for Applied Systems Analysis, *IIASA PFU Dataset.* Available at https://tntcat.iiasa.ac.at/PFUDB/dsd?Action=htmlpage&page=about. [Accessed May 2025].

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[8] An alternative measure sometimes used is the “energy intensity” of GDP, given by kWh of energy use per $ of GDP: This is the inverse of energy productivity. We use this measure for the sectoral analysis of past trends presented in Section 2, in Exhibit 2.4.

While the COP28 commitment to double the rate of energy efficiency improvement did not precisely specify the measure, a reasonable interpretation is that the commitment was to double the pace of improvement of energy productivity as measured by $ of GDP per kWh.

Energy productivity could however be measured at the "primary energy" level or the "final energy" level – and it is important also to recognise that what ultimately matters to human welfare is "useful energy" or "energy services" [Exhibit 1.1].

- **Primary energy supply/demand:** It is a measure of how much energy has to be put into the energy system at the upstream level before any conversion processes. In 2023, this primary energy supply/demand was 171,000 TWh (615 EJ) of which 80% derived from coal, oil and gas, 10% from bio energy (including traditional use of biomass), 5% from nuclear heat generation, and 5% from hydro and renewable sources of electricity which do not involve conversion losses between primary and final energy measurements.[9]
- **Final energy supply/demand:** It measures the amount of energy used at the point of application, e.g., the amount of electricity used in electrical appliances, gasoline put into an ICE fuel tank, or gas burned in a residential or an industrial boiler. In 2023, global final energy demand amount to 122,000 TWh (440 EJ) of which 67% was fossil fuels used directly, 20% was electricity, and 13% of bio energy used directly. Final energy is less than primary energy because of conversion losses in power generation, fuel refining, electricity transmission and other conversion processes. For instance, 1,000 TWh of fossil fuel primary energy input to power generation produced 300 to 600 TWh of electricity, with conversion losses averaging about 40% percent for gas, if using a combined cycle,[10] and 70% for coal. In the case of nuclear power also, primary energy is about 2.5 to 3 times final energy as a result of the energy losses in the conversion of heat to electricity. For renewable electricity generation by contrast, primary and final energy figures are identical [Exhibit 1.2].
- **Useful energy:** However "final energy" as conventionally defined, does not reflect the fact that a considerable share of final energy input is lost through inefficiencies in some end use applications. For instance, in internal combustion engine (ICE) vehicles the "useful energy" delivered to the wheels is typically only about 25 to 30% of the "final energy" input into the fuel tank, with the other 70 to 75% accounted for by heat losses. Conversely, heat pumps can deliver about 3.5 kWh of "useful energy" into a building for every kWh hour of final energy electricity input. In Chapter 2, we therefore draw on estimates made by the International Institute for Applied Systems Analysis (IIASA) for an estimate of useful energy from 1900 to 2014; and in Chapter 3 we develop an illustrative estimate of how useful energy might evolve between now and 2050.
- **Energy services:** Trends in "useful energy" are in most sectors similar to trends in the "energy services" from which consumers derive value. For instance, trends in passenger road transport km travelled relate closely to trends in kWhs of "useful energy" delivered to the vehicle wheels. But in some cases "energy services" could be increased even if "useful energy" inputs were reduced. For instance:

    - In residential heating, the temperature in the home, which could be maintained via better insulation even if the kWh of useful energy delivered were reduced, is more important than the kWhs of heat delivered into the home.
    - In freight transport (whether road or shipping), the end value of products delivered could be maintained even if improvements in logistics efficiency resulted in a reduction in freight tonne km travelled.
- Finally it is important to note that it would be possible for human welfare to be increased while reducing energy services, if there were changes in consumer preference and behaviour. Thus for instance, if people chose to travel by bicycle or train rather than automobile or plane, and considered this a more enjoyable experience, human welfare could increase even if measures of "energy services" and of "useful energy" supply both fell.

Given these definitions, improvements in energy productivity could result from either:

- Reduced energy demand for energy services, or in the ratio of useful energy demand to energy services, arising from improvements in operational efficiency or changed consumer behaviour. Section 3.1 assesses these opportunities.
- Improvements in the ratio of useful energy services to final energy demand. The very large potential for this is also considered in Section 3.1, with electrification as the biggest driver of efficiency improvement. This reflects the fact that in three sectors in particular – heating, cooking, and road transport – electrification can enable useful energy to be delivered with much reduced energy input [Exhibit 1.3].
- Improvements in the ratio of final energy to primary energy, as a result of reduced energy conversion losses, particularly in electricity generation. This potential is considered in Section 2.2.

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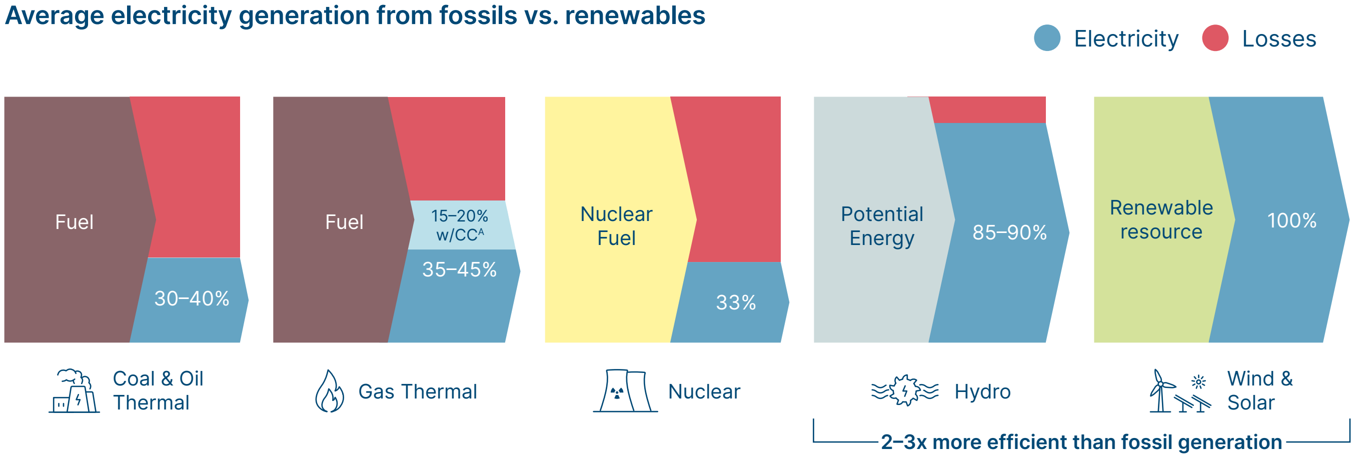
[9] IEA (2024), *Global Energy Outlook.*

[10] Combined cycle uses two interconnected thermodynamic cycles to maximise efficiency in the generation of electricity: the gas cycle and a steam cycle from recovered heat. Boston University (2023), *Power plant efficiency since 1900.*

Exhibit 1.2

Generating electricity with renewables is 2–3 times more efficient than fossil fuels

Average electricity generation from fossils vs. renewables

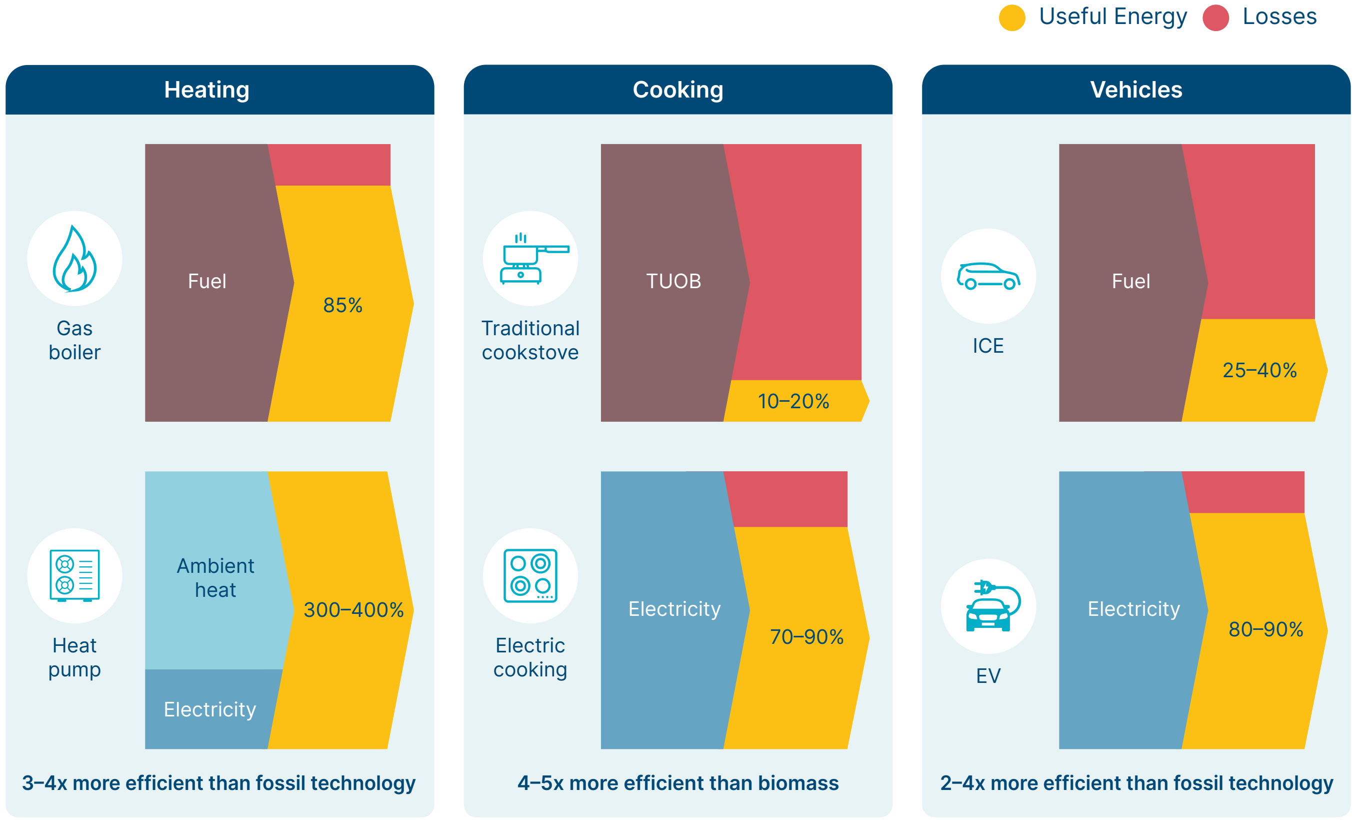


SOURCE: RMI (2024), *Clean Tech Revolution;* Buck Feng (2023), *Power Plant Efficiency: Coal, Natural Gas, Nuclear, and More;* IEA (2008), *Energy Efficiency Indicators for Public Electricity Production from Fossil Fuels.*

Exhibit 1.3

Heat pumps, electric cooking and EVs use 2–5 times less energy than alternative technologies

Average efficiency from appliances and vehicles incumbent fuel vs. electric



NOTE: Biomass here refers to Traditional Use of biomass (TUOB), predominantly wood; ICE = Internal combustion engine.

SOURCE: RMI (2024), *Clean Tech Revolution;* ETC (2025), *Achieving Zero-Carbon Buildings.*

Historic and recent trends in energy productivity

2

Before assessing the potential for energy productivity improvements looking forward, it is useful to understand the factors which have driven both long-term historic trends in energy productivity and more recent developments over the last 10 years.

2.1 Historic trends

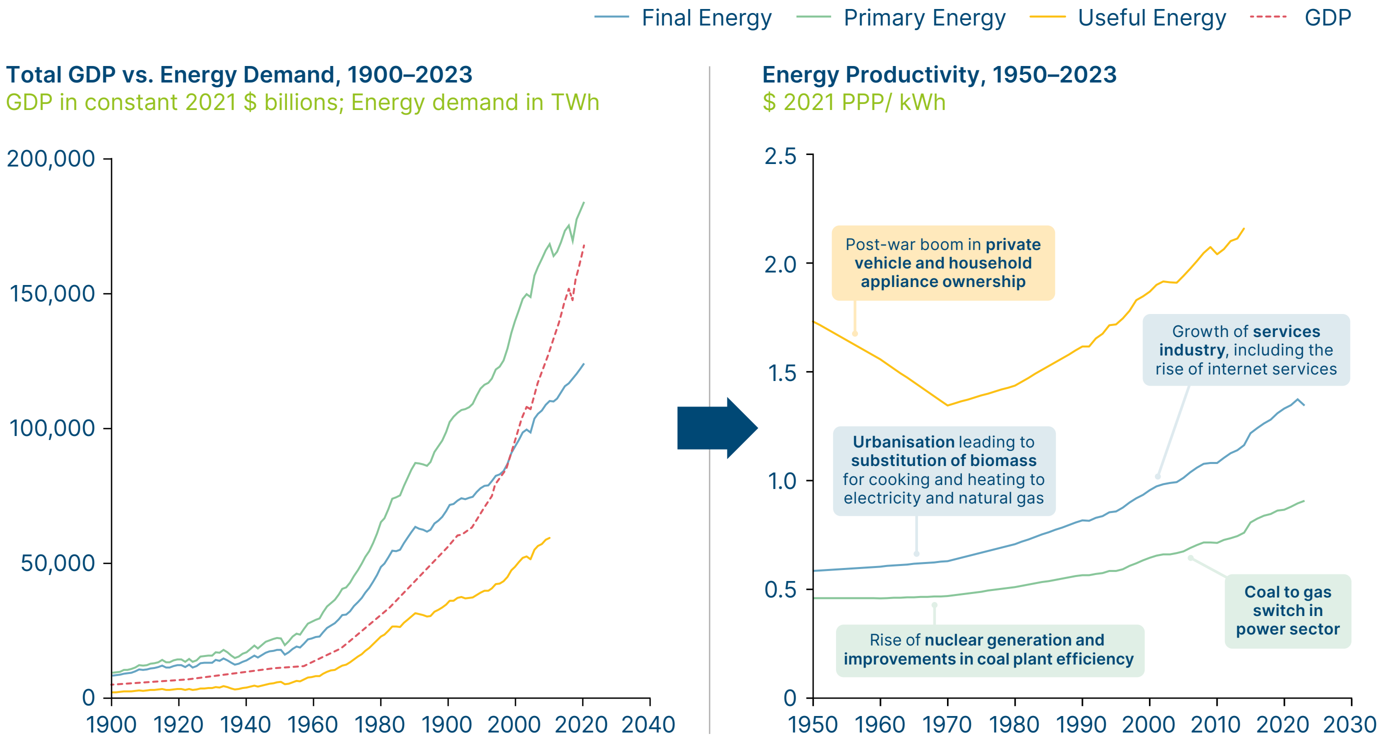
Since 1900 global GDP has grown 330% in real terms, primary energy demand 200% percent, final energy 140%, while estimates suggest that useful energy has grown by about 300%, reflecting greater access to energy services [Exhibit 2.1].

Exhibit 2.1 also shows that from 1950–2023 primary energy productivity has improved by 97% and final energy productivity by 130%, while estimated useful energy productivity declined from 1950 to 1970 (i.e. useful energy supply increased faster than GDP) but rose gradually thereafter, to achieve a 60% improvement between 1970 and 2014.

Exhibit 2.2 shows the implications for both (i) the ratio of final energy demand to useful energy which has fallen from 3.0 in 1950 to about 2.0 today (ii) the ratio of primary to final energy supply which grew slowly from 1950 to 2015 but has begun to decline over the last 10 years.

Exhibit 2.1

Despite improvements in energy productivity, primary and final energy demand still grows with GDP



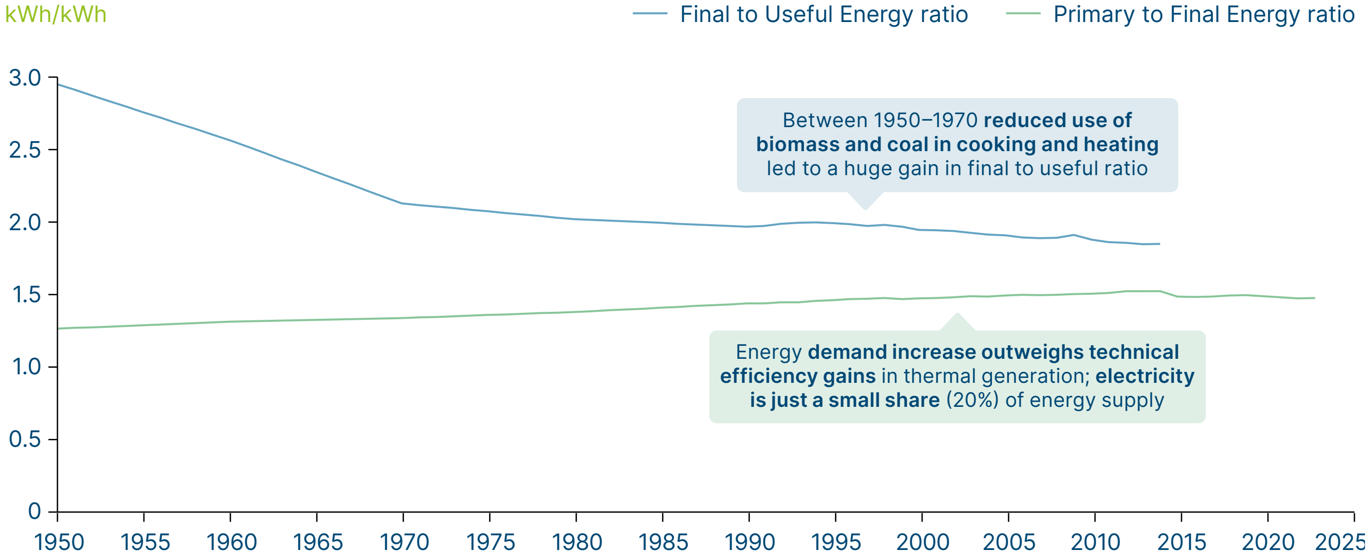
SOURCE: Systemiq analysis for the ETC; World Bank, GDP, PPP (constant 2021 international $). Available at: https://data.worldbank.org/indicator/NY.GDP.MKTP.PP.KD. [Accessed August 2025]; Our World in Data, Global GDP over the long run. Available at: https://ourworldindata.org/grapher/global-gdp-over-the-long-run. [Accessed August, 2025]; IEA (2024), *World Energy Outlook 2024*; International Institute for Applied Systems Analysis, *IIASA PFU Dataset*. Available at https://tntcat.iiasa.ac.at/PFUDB/dsd?Action=htmlpage&page=about. [Accessed May 2025].

Exhibit 2.2

The ratio of final to useful energy improved dramatically, while the ratio of primary to final energy only began to come down in 2015

Energy ratios, 1950–2023

kWh/kWh



Between 1950–1970 **reduced use of biomass and coal in cooking and heating** led to a huge gain in final to useful ratio

Energy **demand increase outweighs technical efficiency gains** in thermal generation; **electricity is just a small share** (20%) of energy supply

SOURCE: Systemiq analysis for the ETC; World Bank Group, GDP, PPP (constant 2021 international $). Available at: https://data.worldbank.org/indicator/NY.GDP.MKTP.PP.KD. [Accessed August 2025]. Our World in Data, Global GDP over the long run. Available at: https://ourworldindata.org/grapher/global-gdp-over-the-long-run. [Accessed August, 2025]; IEA (2024), *World Energy Outlook 2024*; International Institute for Applied Systems Analysis, IIASA PFU Dataset. Available at https://tntcat.iiasa.ac.at/PFUDB/dsd?Action=htmlpage&page=about. [Accessed May 2025].

Key factors driving these developments were:

- Rapid growth in useful energy has reflected growing prosperity and increasing access to energy intensive products and services for more people. Global car ownership grew from approximately 50 million vehicles in 1950 to 1.4 billion today.[11] Aviation has grown from 100 million passengers in 1950 to about 4 billion today. There are more than 1 billion AC units in use by households today vs. a negligible amount in 1950.[12] International shipping has expanded by more than four times in volume since 1970.
- But relative to GDP, useful energy has actually fallen slightly since around 1970: this partly reflects the fact that some (though not all) services are less energy intensive than goods production and that services have grown as a percentage of GDP. Chapter 4 considers whether increasing service intensity will continue to imply reducing energy intensity in the face of AI-related electricity demands.
- The ratio of final energy to useful energy services has fallen due to efficiency improvements in many end-use applications.
    - Between 1950 to 1980, reduced use of biomass and coal in heating and cooking contributed to a rapid improvement in this ratio.
    - Technological progress and regulation has driven a 20–30% reduction in the average fuel efficiency of new cars since 1970s, though progress has slowed recently as a result of a significant increase in average vehicle weight.
    - Refrigerators today use four times less electricity than those in the 1970s[13], modern televisions use 80% less energy than their 1950s equivalent, washing machines dropped from a 0.51 kWh/kg of laundry to 0.14 kWh/kg of laundry in 30 years and 20 years old boilers can be 30% less efficient,[14]
    - and the significant (though still incomplete) shift from incandescent to LED lightbulbs has driven dramatic improvement in the ratio between lumens of light delivered and watts of electricity input.

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[11] IEA (2023), *Global EV Outlook 2023*; UN DESA Transport Statistics.

[12] IEA (2024), *The future of cooling.*

[13] IEA (2022), *Energy Efficiency Indicators 2022.*

[14] CLASP & ACEEE (2021), *Energy Efficiency Appliance Data*; IEA (2022), *The Future of Heat in Buildings;* European Commission, *Household Washing Machines*. Available at *https://energy-efficient-products.ec.europa.eu/product-list/household-washing-machines_en#:~:text=In%201990%2C%20the%20average%20electricity,40%C2%B0C%20in%202020.* [Accessed June 2025]; Rowlen, *How Efficient Is A 20-Year-Old Boiler?*. Available at *https://www.rowlen.co.uk/boiler-advice/how-efficient-is-a-20-year-old-boiler/#:~:text=What%20is%20Boiler%20Efficiency?,was%20pleased%20with%20the%20service.&text=Great%20job%20by%20Rowlen.,Recommended.* [Accessed June 2025].

- Primary energy productivity has improved mostly due to trends in final energy productivity. But there have also been significant improvements in the efficiency of both coal and gas power generation; in some countries, a shift from coal to gas generation has improved average power plant efficiency. At the level of the overall primary to final ratio, however, these favourable factors were until 2015 offset by the fact that a slowly rising electricity share within final energy demand was still overwhelmingly delivered by thermal plant (whether fossil fuel or nuclear) and that electricity growth was fastest in China, where coal generation accounted for over 75% of power supply until 2010.[15] Only over the last 15 years has the rising share of renewable electricity begun to contribute to a fall in the primary to final ratio.

2.2 Recent trends in annual energy productivity improvement

Exhibit 2.3 shows the annual rate of improvement of primary and final energy productivity over the last 70 years and in more detail for the last eight. Key features are:

- Very slow improvement in the 1950s and 60s was followed by a significant acceleration in subsequent decades. This reflected in part:
    - The low and falling cost of new energy sources – in particular oil – during the initial decades and the dramatic increases in price which occurred after 1973.
    - The introduction after 1973 of policies explicitly focused on energy efficiency improvement including in response to concerns about energy supply security. These included the introduction of automobile fuel efficiency standards and the gradual introduction of numerous forms of appliance efficiency labelling and regulation.
- Across the whole of the period 1950–2015 the improvement in primary energy productivity was slower than for final energy productivity. This reflected the increasing role of electricity still primarily produced from fossil fuels and in particular coal.
- Over the period 2016 to 2023 , the annual pattern of improvement has been heavily influenced by the Covid-19 pandemic (which reduced GDP more than it cut energy consumption) but over the whole period 2016–2023 final energy productivity has increased at an average rate of 1.2% while primary energy productivity has increased at 1.4%. This change in relative growth rates – with primary energy productivity now growing faster than final – reflects improvements in the average efficiency of power generation resulting from both a shift from coal to gas and increasing renewables penetration.

Past trends in annual achieved productivity improvement thus fall far short of the 4% per annum target for 2030 agreed at COP28. Exhibit 2.4 shows the pattern by sector, with particularly slow progress in road transport and industry, but somewhat faster progress in buildings; This exhibit shows the sectoral energy intensity, measured as sectoral energy use divided by total GDP.

- In road transport, which saw an average annual improvement of 1.1% between 1990 to 2019, improvements in technical efficiency, especially growing electrification, have been partially offset by increasing vehicle size as discussed in the ETC's analysis of road transport: *The Road ahead: Electrification, Design and Mobility choices for Efficient Transport*.
- In industry, an annual rate of 1.6% has been achieved, but with a significant slowdown in the period 2000–2005. This reflects the rapid growth of energy intensive Chinese industrial production, with more rapid falls after 2010 reflecting China's increasing focus on energy efficiency through the Energy Saving Action Plan.[16]
- Buildings (residential and commercial combined) saw a faster 2.1% improvement from 1990–2019. This reflected the multiple forms of energy efficiency improvement described in the ETC's report on *Achieving Zero-Carbon Buildings;*[17] these include efficiency improvements in multiple forms of electrical equipment (HVAC, lighting, wet appliances TVs, etc.) together with improved insulation efficiency in new buildings in some countries, and steps towards increasing penetration of heat pumps in building heating. In addition, a warming climate has tended to slightly reduce demand, with warmer winters in high latitude countries reducing heating energy demand more than hotter weather in low latitude developing countries increased energy demand for AC.

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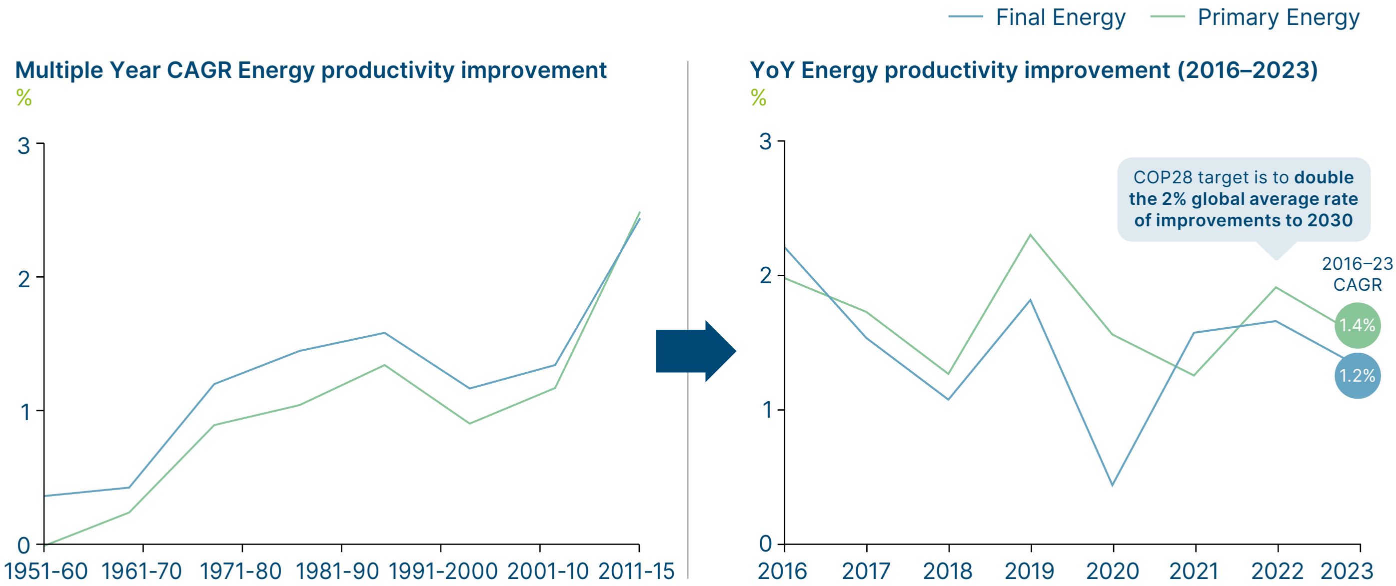
[15] Ember (2025), *Countries and regions: China.* Available at *https://ember-energy.org/countries-and-regions/china/*. [Accessed April 2025].

[16] Yang, M., Patiño-Echeverri, D., Yang, F., and Williams, E. (2015), *Industrial energy efficiency in China: Achievements, challenges and opportunities.*

[17] ETC (2024), *Achieving Zero-Carbon Buildings.*

Exhibit 2.3

Steady progress in energy intensity over the long-run, however recent progress has not entirely recovered from the effects of the pandemic



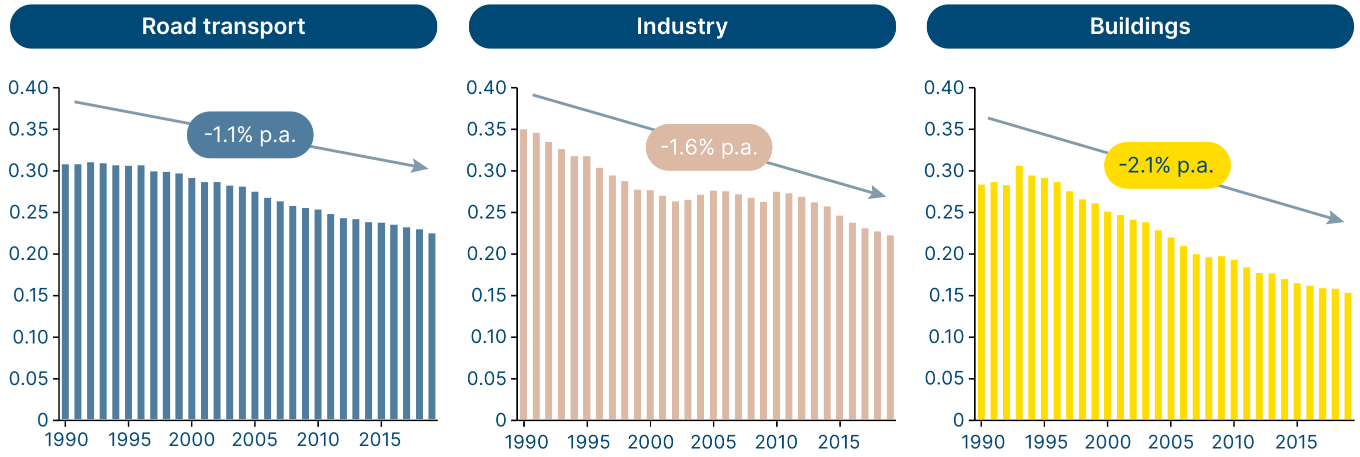
NOTE: CAGR = Compound Annual Growth Rate; YoY = Year-Over-Year.

SOURCE: Systemiq analysis for the ETC; World Bank Group, GDP, PPP (constant 2021 international $). Available at: https://data.worldbank.org/indicator/NY.GDP.MKTP.PP.KD. [Accessed August 2025]. Our World in Data, Global GDP over the long run. Available at: https://ourworldindata.org/grapher/global-gdp-over-the-long-run. [Accessed August, 2025]; IEA (2024), *World Energy Balance 2024*; International Institute for Applied Systems Analysis, *IIASA PFU Dataset*. Available at https://tntcat.iiasa.ac.at/PFUDB/dsd?Action=htmlpage&page=about. [Accessed May 2025].

Exhibit 2.4

Final energy demand intensity has gradually improved across all sectors

Global final energy demand intensity, 1990–2019
kWh/GDP $ 2021 PPP



Improved efficiency in ICE engines and most recently electrification, mainly in China – even if partially offset by larger, heavier SUV models

Technical improvements in manufacturing processes (e.g., lean manufacturing cutting on waste)

Increase in **service economic activity** over industry

Appliance improvements despite rises in use

Warmer winters decreasing heating demand in developing economies

SOURCE: Systemiq analysis for the ETC; World Bank Group, GDP, PPP (constant 2021 international $). Available at: https://data.worldbank.org/indicator/NY.GDP.MKTP.PP.KD. [Accessed August 2025]. Our World in Data, Global GDP over the long run. Available at: https://ourworldindata.org/grapher/global-gdp-over-the-long-run. [Accessed August, 2025]; IEA (2024), *World Energy Balance;* IEA (2022), *Energy Efficiency;* IEA (2023), *Energy Efficiency;* IEA (2024), *Energy Efficiency;* IEA (2023), *Energy End-uses and Efficiency Indicators Highlights;* Finecut Group.

Potential improvements in energy productivity

3

Between now and 2050, the world could expand energy services and enable a doubling of global GDP while reducing final energy use by 24% and primary energy use by 36% versus today's levels. [Exhibit 3.1]. Heated and cooled floor areas could rise by 25% and 150%, passenger road km increase by 70%, and aviation revenue passenger km increase by 150% despite significantly reduced energy inputs [Exhibit 3.2].

This opportunity reflects:

- Huge potential to increase final energy productivity, reducing the amount of final energy needed to deliver useful energy services and rising living standards. Electrification and improved appliance and vehicle efficiency account for a more than third of this opportunity, but there is also potential to reduce demand for energy services by 11% at no cost to consumer living standards.
- Major potential also to reduce the ratio of primary energy inputs to final energy demand: this will be primarily achieved by a shift from thermal power generation to renewables, plus reduced conversion losses in fossil fuel production, though partly offset by increased conversion losses in biofuel and fuel production.

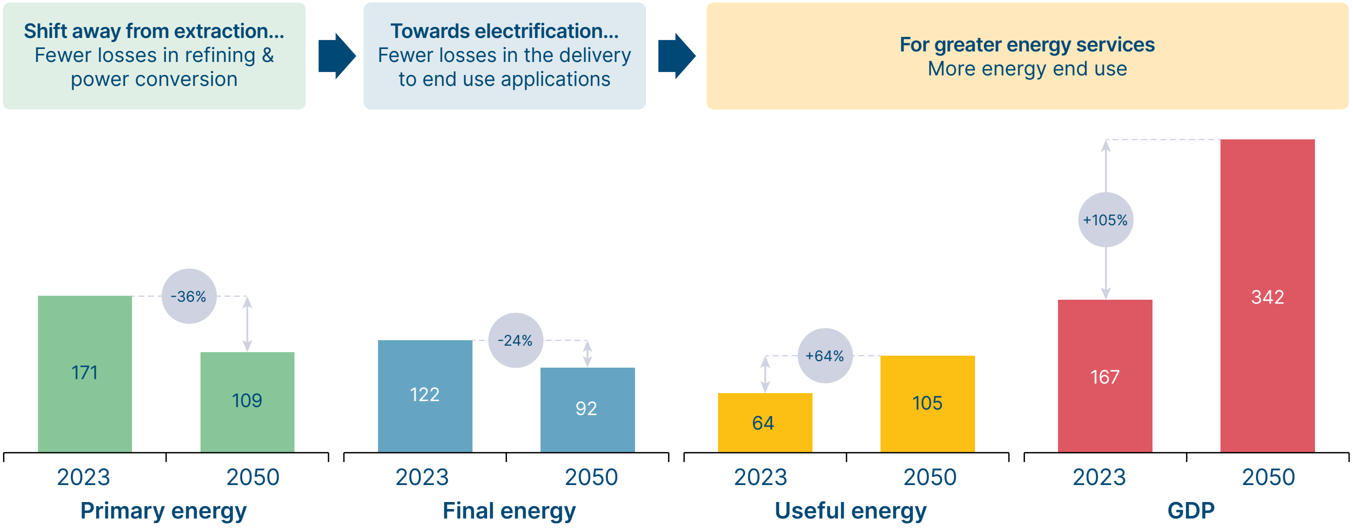
Sections 3.1 and 3.2 describe how these significant improvements can be achieved. Section 3.3 assesses the implications for the rate of annual improvement and for the achievability of the COP28 target. Section 3.4 considers the potential for improved energy productivity to reduce both required energy transition investment and future energy system demands for land and other resources.

Exhibit 3.1

Clean electrification and efficiency lead to a 25-35% reduction in primary and final energy, a 65% increase in useful energy, and a doubling of GDP

Net-zero energy demand with energy productivity levers

Energy in '000 TWh; GDP in constant 2021 $ Trillion

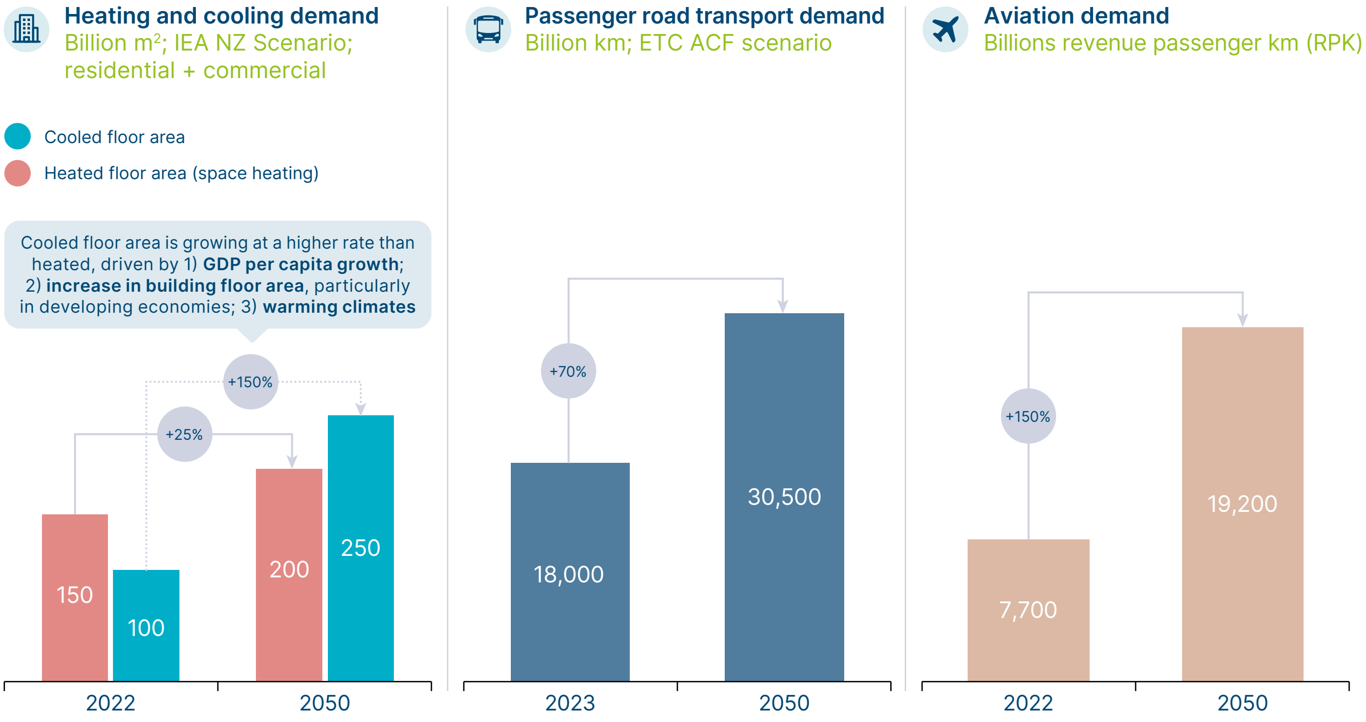


NOTE: Useful energy in 2050 was estimated by applying specific efficiency assumptions to each category of final energy demand. For electrified end uses, such as heating and cooling, assumed efficiencies reflect average performance of available technologies - e.g., 350% for heat pumps, 600% for air conditioners, and 80% for electric cooking. In road transport, EVs were modelled with 85% efficiency. Lighting efficiency was also assumed at 85% based on widespread LED adoption. For shipping and aviation, tank-to-wheel efficiencies remained unchanged at today's levels (30% and 40%). In industry, a decreasing final-to-useful energy ratio (starting from 1.4 in 2023 and falling 1% annually) reflects continued process improvements.

SOURCE: Systemiq analysis for the ETC; IEA (2025), *World Energy Outlook*; MPP (2023), *Hard-to-Abate Sector Transition Strategies*; ETC (2025), *Achieving Zero-Carbon Buildings*; ETC (2023), *Fossil Fuels in Transition*; BNEF (2023), *Electric Vehicle Outlook*; Systemiq (2022), *Planet Positive Chemicals*.

Exhibit 3.2

Underlying growth in energy services in specific sectors



Heating and cooling demand
Billion m^2; IEA NZ Scenario; residential + commercial

Passenger road transport demand
Billion km; ETC ACF scenario

Aviation demand
Billions revenue passenger km (RPK)

Cooled floor area is growing at a higher rate than heated, driven by 1) **GDP per capita growth**; 2) **increase in building floor area**, particularly in developing economies; 3) **warming climates**

NOTE: Revenue passenger km represents the number of paying passengers carried on scheduled flights multiplied by the number of km those seats were flown. ACF = Accelerated but Clearly Feasible Scenario.

SOURCE: IEA (2023), *World Energy Outlook 2023*; ETC (2023), *Fossil Fuels in Transition*; Maersk Mc-Kinney Moller Center for Zero Carbon Shipping (2022), *We show the world it is possible.*

3.1 Huge improvement possible in final energy productivity

Between now and 2050, final energy productivity (GDP per kWh of final energy) could improve by 3.7% per annum (see Exhibit 3.11 at the end of section 3.3 for more detail). In part this would reflect a continued shift towards a more service intensive economy which in the past has tended to be less energy intensive. However, it also reflects multiple opportunities for delivering energy services and consumer living standards with less energy input.

As Exhibit 3.3 shows these opportunities for energy productivity in final energy demand can be considered in three categories:

- Technical efficiency improvements which reduce kWhs of energy input required to deliver defined energy services, including through electrification, improvements in appliance or vehicle efficiency and improved building insulation.
- Service efficiency which reduces the need for useful energy to deliver consumer living standards. This can include both:
    - Operational efficiency improvement which requires no change in consumer behaviour (e.g., improved logistic systems which reduce the number of freight tonne kms required to support any given level of consumption).
    - Changes to consumer preference and behaviour (e.g., travel by train or bicycle rather than automobile).
- Material efficiency improvements which reduce the amount of material production required to support living standards (e.g., via better building design, longer building life, or greater reuse or recycling plastics).

The latter two categories of action will result in some form of reduced demand for energy services or for materials whose production in turn requires energy inputs. The first category reduces final energy demand while having no implications for the volume of useful energy services delivered.

Exhibit 3.3

Multiple levers exist to increase energy productivity

Target figure	Key lever	Impact	Example
Energy Productivity[A] (GDP per energy unit of input) =	Technical energy efficiency	Reduced kWh input per energy service delivered.	• Electrification of road transport or building heating. • Improvements in electrical appliances efficiency. • Improved building insulation.
	× Service efficiency	Reduction in energy service needed to deliver any given consumer living standard.	• Improved freight operations or aircraft utilisation rate (increase occupancy). • Transport mode shift from plane to train or auto to cycling.
	× Material efficiency	Reductions in the amount of material needed to support consumer living standards.	• Reuse and recycling of plastics, steel, aluminium, etc. • Better building design, longer building lifetime.

NOTE: A) Energy productivity is the inverse of energy intensity (energy input per unit of GDP), intensity is used for instance in many IEA reports.

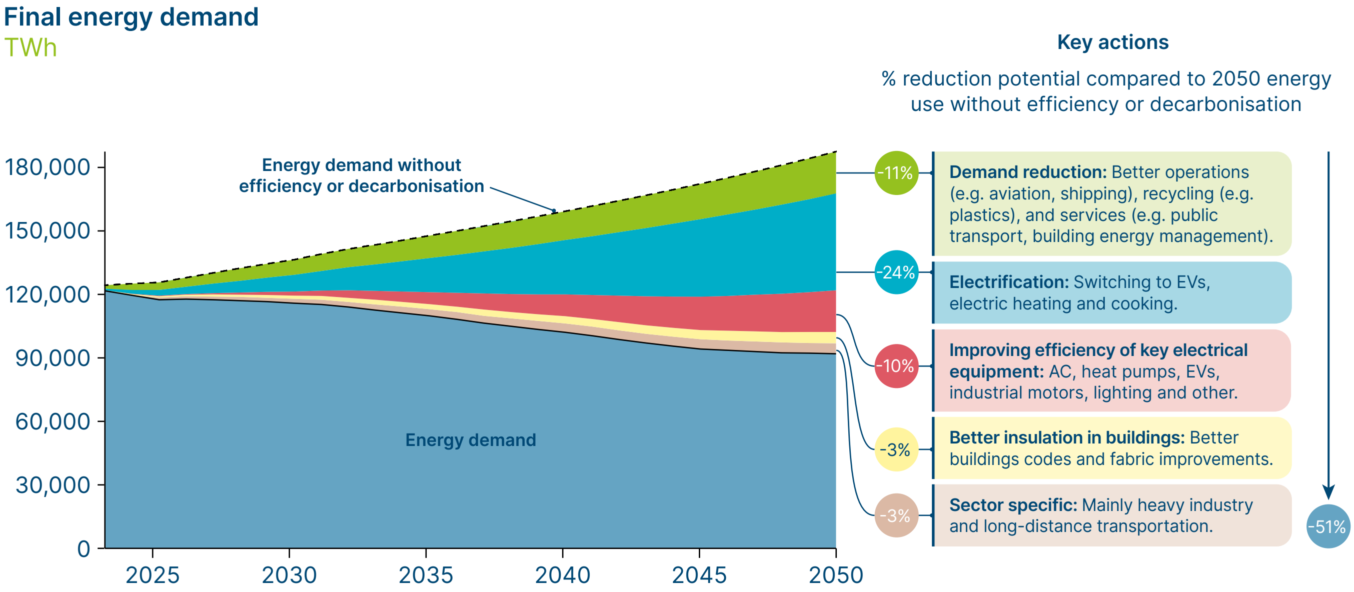
SOURCE: Systemiq analysis for the ETC.

3.1.1 Final energy improvement potential at the whole economy level

Exhibit 3.4 assesses the global whole economy potential to improve final energy productivity. While under a BAU scenario, final energy demand could grow from today's 122,000 TWh to reach 188,000 TWh by 2050 this could be reduced to 92,000 TWh through five sets of action:[18]

Exhibit 3.4

The combination of all productivity actions could lower final energy demand by ~50%



Demand reduction: Better operations (e.g. aviation, shipping), recycling (e.g. plastics), and services (e.g. public transport, building energy management).

Electrification: Switching to EVs, electric heating and cooking.

Improving efficiency of key electrical equipment: AC, heat pumps, EVs, industrial motors, lighting and other.

Better insulation in buildings: Better buildings codes and fabric improvements.

Sector specific: Mainly heavy industry and long-distance transportation.

SOURCE: Systemiq analysis for the ETC; IEA (2025), *World Energy Outlook*; MPP (2023), *Hard-to-Abate Sector Transition Strategies*; ETC (2025), *Achieving Zero-Carbon Buildings*; ETC (2023), *Fossil Fuels in Transition*; BNEF (2023), *Electric Vehicle Outlook*.

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[18] In our sector-by-sector analysis, the order of levers was determined based on their likelihood or ease of implementation. For example, in steel, material efficiency—such as increased recycling—is expected to come before major technology shifts, while in aviation, behavioural changes are likely to be the last lever applied. When aggregating this into an economy-wide view, we maintained this sector-specific logic. Therefore, although demand reduction is presented first in this section, it does not mean it is the first lever applied in every sector. Rather, the order of levers here reflects the general sequence of action at the system level, starting with those that are typically the most accessible.

1. A potential reduction of 11% in demand for energy services or for materials which are energy intensive to produce. These reductions entail three sub categories [Exhibit 3.5]:
    - **Operational efficiency** improvements including via automation. These include opportunities to improve logistic system efficiency in shipping and road freight, reducing freight tonne km travelled while not reducing the volume of products delivered; and opportunities to improve aircraft utilisation while not reducing the number of passenger km travelled. They also include significant opportunities to improve building energy management efficiency, as described as in the ETC's *Achieving Zero-Carbon Buildings* report. *The Road Ahead: Electrification, Design and Mobility Choices for Efficient Transport* report also assesses the potential impact of autonomous vehicles (AV) under this category which could either increase or reduce kms travelled and thus energy demands.
    - **Material and product efficiency** opportunities which do not require changes in consumer behaviour, could deliver a significant reduction in demand for cement, primary aluminium and steel, plastics and other materials. These could be achieved via better building design, extending building lifetimes, increased recycling within the commercial environment, and less material intensive product design.
    - **Demand reductions** for energy services or materials which do require some behaviour change. These include increases in reuse or recycling of plastics or other materials used within the residential environment, changed driving behaviours, and transport mode shifts.

    As Exhibit 3.5 shows, assumed changes in consumer behaviour account for only 36% of the 11% demand reduction potential shown on Exhibit 3.4 with changed consumer behaviour therefore reducing total final energy demand by just 4%.

    A conservative approach was used to assess the potential for changes in consumer preference and behaviour, and other analyses of energy productivity potential have often assumed more significant impacts. For instance, UNEP's International Resource Panel on its Global Resource Outlook from 2024 assumed a higher household occupancy for buildings, increased teleworking, expanded bicycle use and alternative tourism would decrease overall transport demand; in turn, economic growth would decouple from demand for travel and freight. If consumer preferences and behaviour do change to a greater extent than assumed in our analysis, additional energy productivity improvement could be achieved at minimal, zero or negative cost.

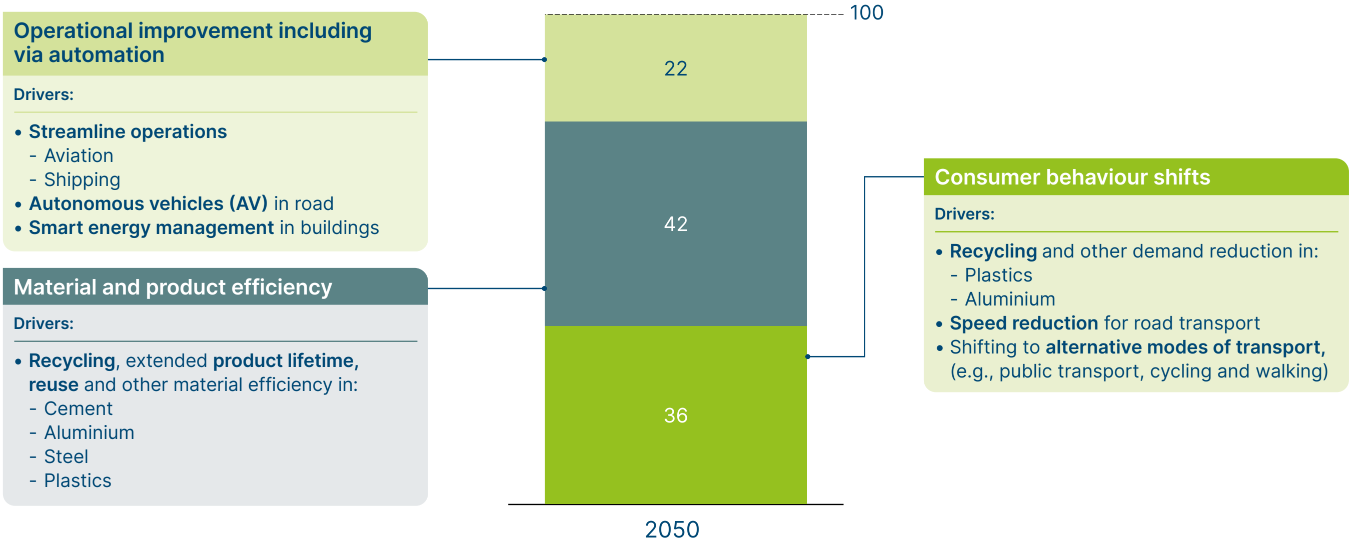
    But using a conservative assumption helps make a crucial point: dramatic improvements in final energy productivity could be achieved even if consumer behaviour does not change. The very significant reductions in final energy and primary energy shown on Exhibit 3.1 are thus not dependent on any assumption that rising consumer demand for energy services will be deliberately constrained.

Exhibit 3.5

Only 36% of demand reduction depends on end consumer behaviour change

Demand reduction deep-dive

Annual % reduction in 2050 relative to BAU



SOURCE: Systemiq analysis for the ETC.

2. **Electrification:** A 24% cut in final energy use (but with no reduction in useful energy) could be achieved automatically from the electrification of an increasing share of road transport, building heating and cooking, together with some further electrification in other sectors. This potential reflects the inherent energy efficiency advantage of electric solutions which was highlighted in Exhibit 1.2.

   - Heat pumps are three times more efficient than gas boilers at turning energy input into heat delivered into a building, and can be applied also for the production of low and medium temperature industrial heat (e.g., 100 to 400°C).
   - EVs are around three times more efficient than ICEs at turning energy input into the battery or fuel tank into kinetic energy in the wheels.
   - Electrification of cooking will eventually deliver dramatic efficiency improvements vs. traditional uses of biomass (TUOB), which may however initially transition to liquefied petroleum gas (LPG) or other low carbon fuels. It can also, via induction systems, deliver significant improvements vs. gas.

3. **Efficiency of electrical equipment:** An additional 10% reduction in final energy demand could come from improving the efficiency of electrical equipment and road vehicles.

   - AC systems currently deployed vary between 3 to 12 in seasonal energy efficiency rating (SEER), which is a multiple of electricity input to 'cool' energy output, indicating very significant opportunities to improve the average by shifting to more efficient models. In addition, there is significant opportunity to further increase the best in class efficiency of new air conditioners and heat pumps (which are essentially the same technology).[19]
   - High efficiency refrigerators use 25% less energy than typical models.[20]
   - LED light bulbs use 80% less electricity than incandescent bulbs per lumen of light delivered, and there remain major opportunities – particularly in developing countries - to replace the existing inefficient light bulb stock.
   - Newer industrial motors, the IEA5 standard, are 40% more efficient than two generations before, the IE3 standard. See Box B.
   - Finally, for road transport vehicles, in addition to the big efficiency gain which will automatically result from electrification, there are major opportunities to improve the efficiency of future EVs, by, for instance, reducing vehicle weight (including via lighter batteries), improving aerodynamics to reduce drag, and increasing powertrain efficiency, including potentially via in-wheel motors. It is estimated that the combination of these and other measures could cut the energy required per km travelled by as much as 50% by 2050.[21] More details of these technologies and the potential pace of application is provided in our *The Road Ahead* report.

Standards & labelling (S&L) programmes and policies to encourage more rapid replacement of older models with newer ones, will be essential to accelerate the pace at which gains from electrification and improved appliance/vehicle efficiency are captured [Box B].

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[19] SEER are measured in watt of cooling output per watt of energy input; See ETC (2025), *Achieving Zero-Carbon Buildings: Electric, Efficient and Flexible.*

[20] Comparison between Canada and Korea 1,000 litres refrigerator-frezer annual energy consumption in 2019.

[21] ETC (2025), *The Road Ahead: Electrification, Design and Mobility Choices for Efficient Transport.*

BOX B

Appliance and equipment standards and labelling (S&L) programmes and the stock turn-over effect

Appliance and equipment S&L programmes have been proven to be an effective tool, particularly in the residential and commercial sectors. According to the IEA, S&L programmes operating the longest, in the US and EU for instance, deliver annual savings of about 15% in electricity demand and represented 7-10% of annual energy-related emissions reductions.[22] These programmes ensure a minimum efficiency for appliances sold in the market, phasing out the most energy-intensive models over time.

Yet, the global rollout of S&L programmes remains uneven - fewer than 25% of developing economies have adopted comprehensive frameworks, despite being the fastest-growing markets for air conditioners, refrigerators, and other energy-consuming appliances. But there is also an opportunity for newer or emerging S&L programmes: by leapfrogging directly to the most efficient technologies, these countries can capture the falling costs of more efficient technology. Indeed, prices for LED lighting and inverter air conditioners continue to fall, becoming increasingly cost-competitive - even outperforming less efficient options on price in many cases, and encouraging their uptake, drive down costs still further.[23]

The United Nations estimates that in developing economies, high performance S&L for typical household appliances and motors could save approximatly 3,400 TWh/year by 2050, equivalent to the current electricity consumption of all of Africa, Oceania, Central Asia, Latin America, and the Caribbean combined.[24]

Benefits of appliance and vehicle efficiency are also enhanced by stock turnover. The stock turnover effect refers to the gradual replacement of older, less efficient appliances and vehicles with newer, more efficient models. This turnover is essential to ensure that energy savings from technological improvements are realised in practice. Even if highly efficient appliances and EVs are available on the market, their impact on energy demand remains limited unless outdated models are retired and replaced at scale. Accelerating stock turnover - through policies like scrappage schemes, purchase incentives, and mandatory efficiency standards - ensures that consumers benefit from the latest innovations. For instance, cars on the road typically last around 18 years, which means that a retiring vehicle in 2024 was a new model in 2006, and an ICE 2006 model consumes on average 37% more fuel than a 2024 model. The ETC's *The Road Ahead* report addressed the effects of insufficient stock turnover, even with electrification, the global passenger fleet emissions could be 5 $GtCO_2$ higher by 2050.[25]

However, accelerating stock turnover must be paired with robust end-of-life recycling systems to minimise waste and reduce the environmental footprint of increased production. Without circular approaches, scrappage schemes risk driving overconsumption and material inefficiencies that could undermine long-term productivity goals.

4. **Improved building insulation** could reduce final energy demand for cooling and heating by another 3% which would be equivalent to reducing building energy demand by 10%. The importance of improved building insulation is however far greater than this 3% reduction total energy demand implies, since improved insulation can reduce peak electricity demand by far more, and a large share of total electricity system costs, particularly in decarbonised systems significantly dependent on renewables, are driven by peak rather than total demands, as discussed in the ETC's recent report, *Power Systems Transformation: Delivering Competitive, Resilient Electricity in High-Renewable Systems*.

   Improved insulation enables buildings to provide demand side flexibility by shifting energy use away from peak times. For instance, well-insulated homes can be pre-heated before morning and evening peaks, reducing the strain on the electricity grid during these high-demand periods; a typical home in the UK loses 3°C of indoor temperature within five hours, whereas an average home in Norway loses just 0.9°C over the same period.[26]

   It is therefore essential to ensure high insulation standards in new buildings. This is particularly important in emerging markets, where over 60% of the floor area expected to exist in 2050 is yet to be built.[27] In addition, cost effective opportunities to improve the insulation efficiency of existing buildings should also be seized.

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[22] IEA (2018), *Achievements of Energy Efficiency Appliance and Equipment Standards and Labelling Programmes.*

[23] ETC (2025), *Achieving Zero-Carbon Buildings: Electric, Efficient and Flexible.*

[24] Council of Engineers for the Energy Transition (2024), *Energy Rating Labels and Potential for Energy Savings Across the Global South.*

[25] ETC (2025), *The Road Ahead: Electrification, Design and Mobility Choices for Efficient Transport.*

[26] Test occurred in 2019/2020 with a temperature of 20°C inside and 0°C outside. Tado (2020), *UK homes losing heat up to three times faster than European neighbours.* Available at *www.tado.com/en-gb/uk-homes-losing-heat-up-to-three-times-faster-than-european-neighbours* [Accessed May 2025].

[27] 3% improvements comes from a 20% improvement in energy use in buildings applied to all new buildings from 2023 onwards, 50% of existing buildings that need heating and 80% of existing buildings that need cooling. These assumptions are applied after electrification of heat and aligns with analysis from our report, Achieving Zero-Carbon Buildings. See ETC (2025), *Achieving Zero-Carbon Buildings: Electric, Efficient and Flexible.*

5. A further 3% reduction in final energy requirement can come from multiple other specific initiatives. Though a small number in aggregate, each of these initiatives can deliver significant energy savings within each sector. These include significant opportunities to improve energy efficiency improvement in heavy industry, such as more efficient combustion in furnaces and kilns, and more efficient planes and ships, for instance by making design lighter and/or more aerodynamic. The opportunities in the harder to abate sectors will be described in a forthcoming annex.

3.1.2 Sectoral improvement potential in final energy demand

Exhibit 3.6 sets out the sectoral breakdown of reductions in final energy demand which could be achieved by 2050. It shows both the final energy demand which might result under a BAU scenario and the extent to which that could be reduced under a maximum energy productivity scenario.

The greatest reduction potential lies in buildings and transport which together account for 68% of these reductions. Chemicals and "other industry" (i.e. light industry) account for 10% each, with smaller contributions from heavy industry sectors and long distance transportation (aviation and shipping). Details by sector are set out in the following ETC publications: *Achieving Zero-Carbon Buildings: Electric, Efficient and Flexible; The Road Ahead: Electrification, Design and Mobility Choices for Efficient Transport;* Hard-to-Abate Annex (forthcoming).

Key features by sector are:

Buildings: Final energy demand for buildings could be reduced by around two-thirds vs. BAU by 2050, despite growth in global floor area of 50%.[28] Exhibit 3.7 shows the key drivers of these reductions which are described in more detail in the ETC's *Achieving Zero-Carbon Buildings*.

- Electrification of building heating (space and water) is the biggest factor, potentially reducing total demand by close to 20%. This reflects the fact that heating alone accounts for 45% of total building energy use and that heat pumps can be four times more efficient than gas boilers.
- Cooking, especially in developing economies, is a major area of opportunity. Traditional Use of Biomass (TUOB) is both hugely energy inefficient and a cause of major adverse health effects; replacing it initially with Liquefied Petroleum Gas (LPG) and then subsequently with electrified cooking will deliver huge benefits. In addition, there are major opportunities to improve efficiency by switching from gas to electric cooking and to improve the efficiency of electric cooking equipment (e.g., via induction hobs). By 2050, with 90% of cooking electrified and TUOB eliminated, total energy use for cooking could be 57% below the 2023 level.[29]
- Improvements in the efficiency of non-heating electrical equipment (including AC, lighting, and multiple forms of electrical appliance) which together account for 27% of energy use in buildings today, could deliver a further 20% reduction.
- Better insulation in both new and existing buildings could deliver a further ~10% reduction and the use of advanced building management systems an additional 3%, but the importance of both these levers is much higher than these figures suggest given their potential to reduce peak electricity demand.

Road transport: Demand for passenger road transport could rise 70%[30] and for freight traffic 90% but final energy demand could potentially fall by 80% through the combination of the levers shown in Exhibit 3.8.

- Electrification of 90% of the vehicle fleet by 2050 would lead to a more than 50% reduction in final energy demand vs. BAU scenario. This reflects the fact that EVs are 3–4 times more efficient than ICE vehicles
- Improvements in the technical efficiency of EVs could add a further ~20% reduction, with a small contribution also from further improvements in the final generations of ICE vehicles. We have also assumed a small shift towards smaller vehicles.
- Reductions in demand for road transport useful energy could deliver another 10% reduction. About half of this would depend on consumer behaviour change driven by speed limits, but half would result from changes in commercial driving practice and the impact of autonomous vehicles in the commercial fleet. We assume no net impact of AVs on passenger demand.

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[28] In this analysis, buildings are accounted for based only on their operational energy use, not the embodied carbon from their construction. Emissions and energy demand related to materials like cement and steel used in construction are included under the cement and steel sectors, respectively. For a detailed discussion on embodied carbon in buildings, see ETC (2025), *Achieving Zero-Carbon Buildings: Electric, Efficient and Flexible.* Period assessed between 2022 and 2050.

[29] Our main assumptions include electrification of heat and cooking in buildings (95% of heating demand in 2050, being 75% met with heat pumps at 300% efficiency and 90% of cooking demand in 2050), road electrification (90% of road demand in 2050), a small electrification in short haul flights (2% of aviation demand in 2050) and shipping (5% of shipping demand in 2050) and further electrification in industry (e.g. heat below 200oC, EAFs in steel and inert anodes in aluminium). The 73% remaining energy use comes from heating and cooking. ETC (2025), *Achieving Zero-Carbon Buildings*..

[30] Between 2023 and 2050.

In the heavy industry sectors, growth in product demand by 2050 is assumed to be about 100% for aluminium, 70% for petrochemicals (including plastics), 50% for cement and 25% for steel. But there is significant opportunity to increase material efficiency through better product design, product life extensions, reuse and recycling, and this together with some electrification could reduce final energy demand vs. BAU by 44% for petrochemicals, 33% for cement and 27% for steel. In some sectors, however, new decarbonised production processes will produce an increase in primary energy demand relative to final. This is discussed in Section 3.2 below.

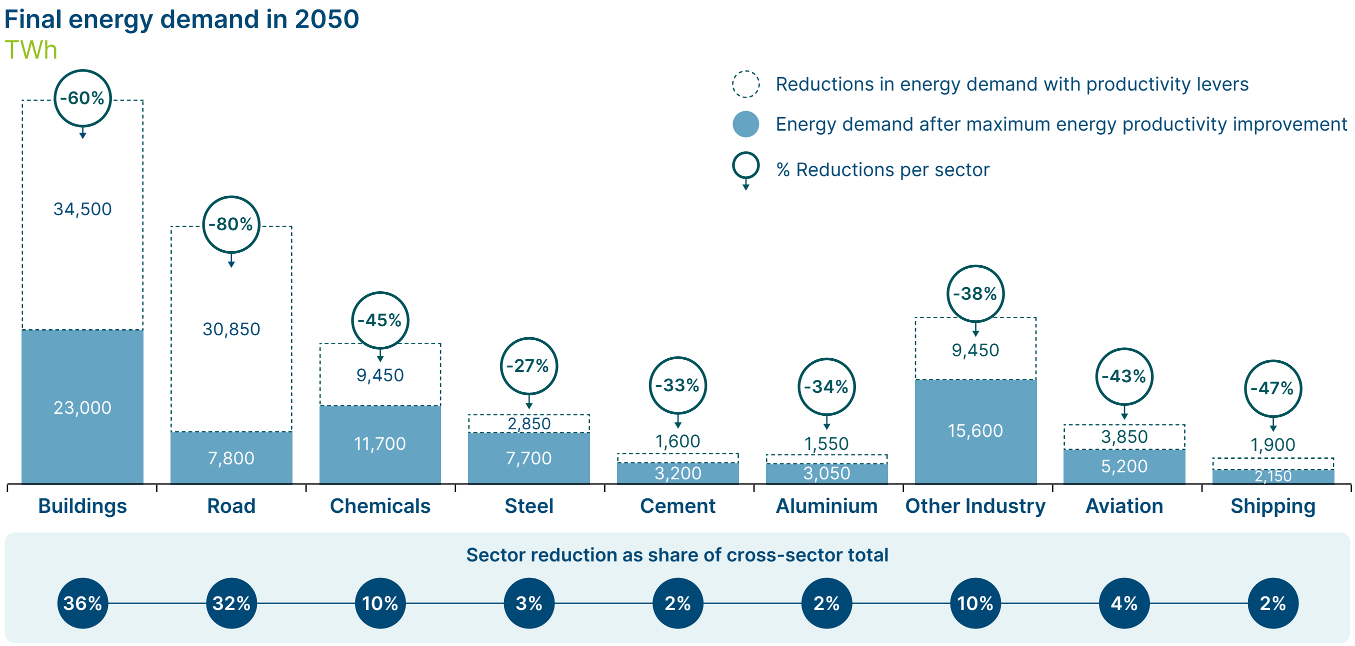
Aviation and shipping: Final energy demand in aviation could more than double by 2050 under a BAU scenario, while shipping energy demand could increase by 45%.[31] We conservatively assume that at least up to 2050 electrification of shipping and aviation will only be technically and economically feasible for very short distances and will therefore deliver only a 1% energy demand reduction. But in aviation better air traffic control and other operational improvements could reduce energy demand by 13%, and more fuel efficient planes by 60%, while for shipping, reductions of 16% and 28% could be achieved from operational and technical efficiency improvements. In both cases, however, switching to decarbonised fuels will result in the increased ratio of primary energy demand to final which is discussed in Section 3.2.

Other/light industries: These include food and beverage, pulp and paper, textiles and multiple variants of product manufacturing including automotive, electrical appliance computing and TV equipment, solar panels and wind turbines. Together these sectors accounted for about a third of total industry energy use in 2023 and final energy demand for these sectors could grow 50% by 2050 under a BAU scenario. This could in principle be reduced by 38% through a combination of:

- The use of heat pumps to generate low and medium temperature heat.
- Improved efficiency of high temperature heat production (e.g., in ceramic and glass production), including via improved heat recovery from sintering and melting, and electric boosting systems in fuel firing, which can lead to up to 17% energy savings.[32]
- Significant potential for improvements in the efficiency of electrical motors [Box B].

Exhibit 3.6

Buildings and road transportation hold ~70% of the potential productivity gain in final energy demand compared to a BAU scenario



NOTE: Does not include fuel switch nor CCS for net-zero.

SOURCE: Systemiq analysis for the ETC; IEA (2025), *World Energy Outlook*; MPP (2023), *Hard-to-Abate Sector Transition Strategies*; ETC (2025), *Achieving Zero-Carbon Buildings*; ETC (2023), *Fossil Fuels in Transition*; BNEF (2023), *Electric Vehicle Outlook*; IEA (2021), *Net Zero by 2050.*

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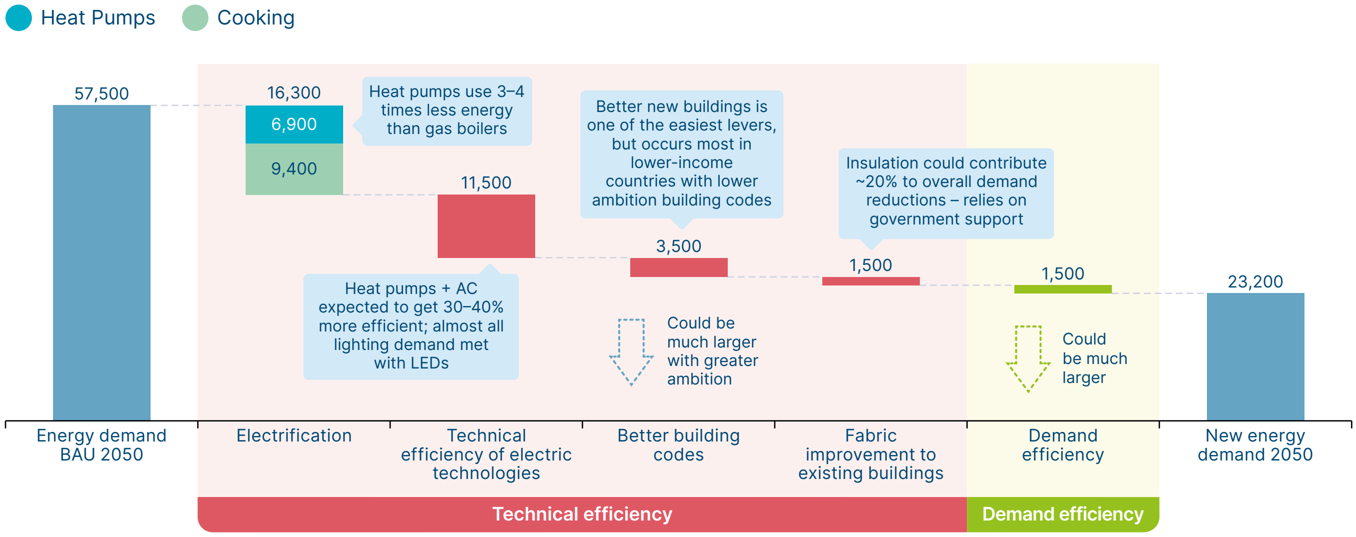
[31] Between 2023 and 2050.

[32] Electroglass (2023), *Electric Melting and Boosting for Glass Quality Improvement*. Available at https://www.electroglass.co.uk/resources/electric-melting-and-boosting-for-glass-quality-improvement-part-1/. [Accessed May 2025].

Exhibit 3.7

Final energy demand can be decreased by 60% in buildings

Final energy demand in 2050 and impact of productivity levers – residential + commercial
TWh



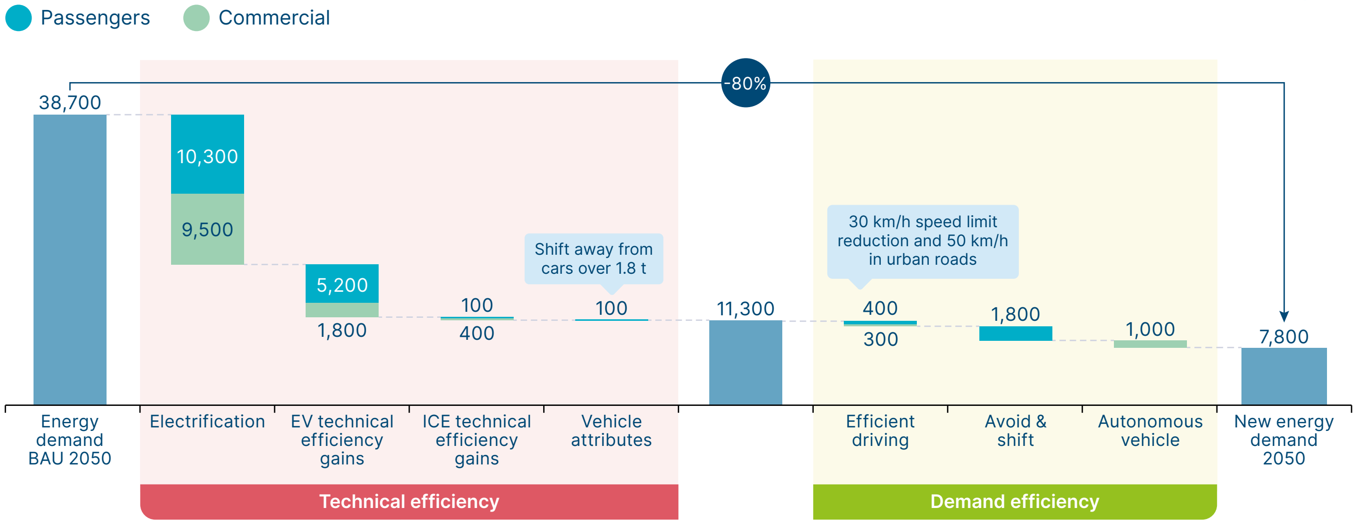
NOTE: Building cooking energy excluded from analysis. For primary energy conversion, 83% efficiency is assumed for renewables power (e.g., electricity conversion and transmission losses), and 85% for fossil fuels to boilers.

SOURCE: Systemiq analysis for the ETC; ETC (2025), *Achieving Zero-Carbon Buildings;* Page 26; IEA (2023), *World Energy Outlook 2023*; IEA (2021), Net Zero by 2050.

Exhibit 3.8

Switching to electrification is the most crucial factor in reducing final energy demand for road transport by 2050

Final energy demand in 2050 and impact of energy productivity levers
TWh



NOTE: ICE = internal combustion engine vehicles, EV = electric vehicles. Productivity levers: 20% efficiency gains for ICEs by 2050, 50% efficiency gains for EVs by 2035, 20 km/h speed limit reduction on highways and 30 km/h speed limit in urban areas, 36% demand reduction by 2050 through Avoid & Shift levers. Final energy demand attributed by lever with LMDI (logarithmic mean divisia index) methodology. For primary energy demand, energy efficiency of 85% from fossil fuel extraction to tanker, and for renewables power (e.g., electricity conversion and transmission losses) is taken.

SOURCE: Systemiq analysis for the ETC; ETC (2023), *Fossil Fuels in Transition: Committing to the phase-down of all fossil fuels.*

Box C

Increasing standards for motor efficiency could deliver large benefits for light industry

Electric motor-driven systems are responsible for over 50% of global electricity use, making them a critical focus for industrial energy efficiency - particularly in light industry. However, two-thirds of the global motor stock still consists of low-efficiency models.[33]

To address this, countries have increasingly adopted Minimum Energy Performance Standards (MEPS) for electric motors. Coverage grew from just 5% of industrial motors in 2000 to 53% by 2022, with 62 countries implementing MEPS. The International Energy Agency (IEA) estimates that to stay on track for net-zero by 2050, all new industrial motors must adopt best-in-class technologies by 2035.[34]

Adopting high-efficiency electric motors offers a strong business case, often delivering payback within just 2–3 years through energy savings. Yet, uptake remains slow. In particular, small motors, which typically last up to 40 years, are often only replaced at the end-of-life. This reflects the fact that while there is an economic benefit from changing earlier, it is often small relative to total production costs.

Moreover, a large share of light industry is made up of Small and Medium Enterprises (SMEs), which often face limited access to finance or remain sceptical of energy efficiency investments. Financial institutions also often lack a portfolio of products around energy savings. Although the business case is clear, more awareness of the cost-saving opportunities is needed.

Advanced motor classes such as IE3 (Premium Efficiency) and IE4 (Super Premium Efficiency) are the most cited in MEPS. IE3 motors are suitable for continuous operations and deliver high efficiency across output ranges from 0.75 kW to 355 kW. IE4 motors, currently the highest efficiency class, are ideal for near-continuous use and are designed to reduce energy consumption in the most demanding settings, with outputs from 2.2 kW to 230 kW.[35] But it is important to keep pushing standards: IE5 (Ultra-premium efficiency class) already offers up to 40% lower energy losses compared to IE3 induction motors.[36]

Beyond motor replacement, system-wide improvements, such as optimising component design, ensuring regular maintenance, and using variable speed drives, can unlock further savings. A systems approach in light industry can reduce energy demand by 10% in fan systems, 24% in pumps, and up to 30% in compressed air systems.[37]

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[33] The figures provided include motors in household appliances as well. Clasp (2025), *World's Best MEPS: Tracking Leaders in Appliance Energy Efficiency Standards.* Available at: *https://www.clasp.ngo/tools/worlds-best-meps/*. [Accessed July 2025].

[34] IEA (2023), *Light Industry*. Available at: *https://www.iea.org/energy-system/industry/light-industry*. [Accessed July 2025].

[35] Hoyer (2023), *Understanding the differences: IE1, IE2, IE3, and IE4 motors.* Available at: *https://hoyermotors.com/about-hoyer/information/knowledge-bank/differences-between-ie1-ie2-ie3-and-ie4-motors/*. [Accessed July 2025].

[36] Dutypoint (2024), *IE5 Motors: The Importance, the Benefits and How We're Using Them*. Available at: *https://www.dutypoint.com/ie5-motors/*. [Accessed July 2025].

[37] Clasp (2025), *World's Best MEPS: Tracking Leaders in Appliance Energy Efficiency Standards.* Available at: *https://www.clasp.ngo/tools/worlds-best-meps/*. [Accessed July 2025].

3.2 Improving the ratio of primary to final energy demand

Exhibit 3.1 illustrated that while final energy demand could be reduced by 24% compared to today's levels (despite a 64% increase in useful energy), primary energy demand could be reduced by a larger share: 36%. This reflects the potential to reduce the energy conversion losses which occur between primary and final energy.

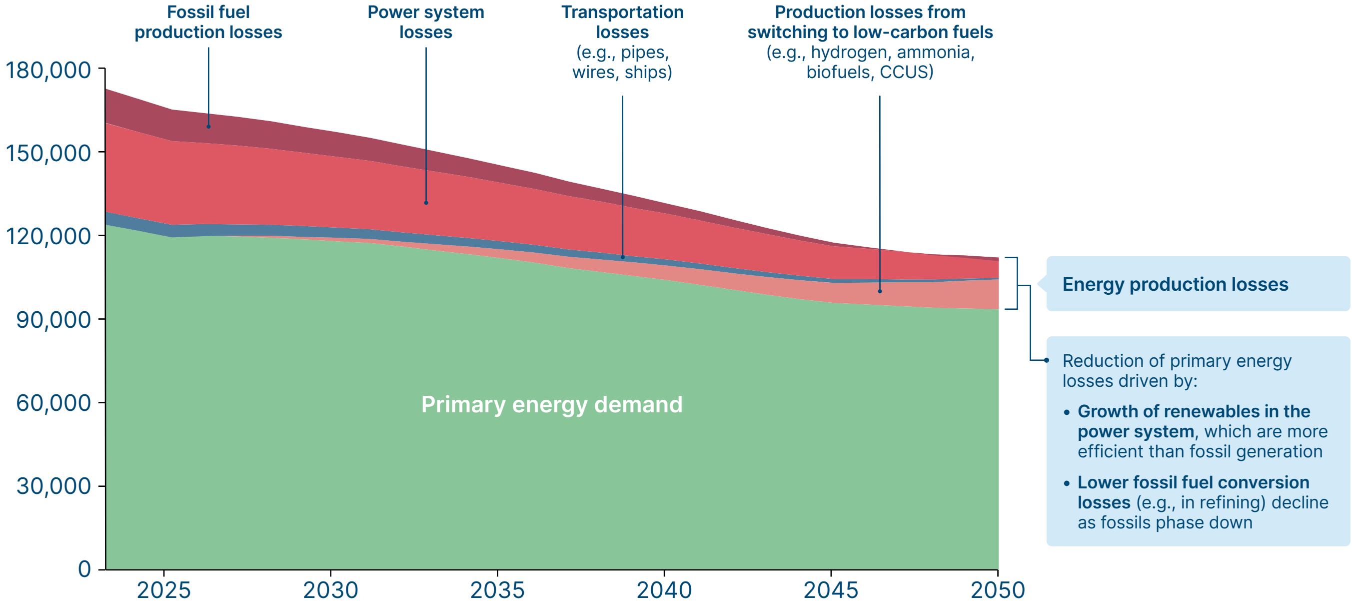
Exhibit 3.9 shows the three sets of factors which produce a net reduction in the primary to final ratio, with two driving a reduction, while the third reflects some increases.

- Power generation conversion losses will fall as power generation is decarbonised. As Exhibit 1.1 showed, for wind and solar generation, there are no conversion losses, and renewable power is therefore 2–3 times more efficient than average thermal generation. Even after transmission losses and conversion losses when electricity is stored in batteries, the shift to renewable electricity drives a big reduction in the primary to final ratio.
- Electrification and a shift to non-fossil fuels will also drive a significant reduction in the conversion losses currently faced in fossil fuel refining.
- Conversely, some decarbonisation technologies will result in an increase in conversion losses or in additional processes which require energy input. If carbon capture and storage (CCS) is applied to remaining fossil fuel or bio energy-based power generation, or industrial processes such as cement production, this will increase primary energy demand, given the significant electricity and heat inputs required in carbon capture. In aviation and shipping, meanwhile, moving from conventional jet fuel and marine fuel to bio jet fuel, synthetic jet fuel, hydrogen, or ammonia will result in higher conversion losses than currently imposed by fossil fuel refining. As Exhibit 3.10 shows for aviation, increased conversion losses between primary and final energy supply could offset about half of the reduction in energy demand, which better operations and more fuel-efficient planes could deliver.

Exhibit 3.9

The phase down of fossil fuel consumption, along with the switch from thermal generation to renewables, are main drivers of lower primary energy demand

Primary energy demand
TWh



Energy production losses

Reduction of primary energy losses driven by:

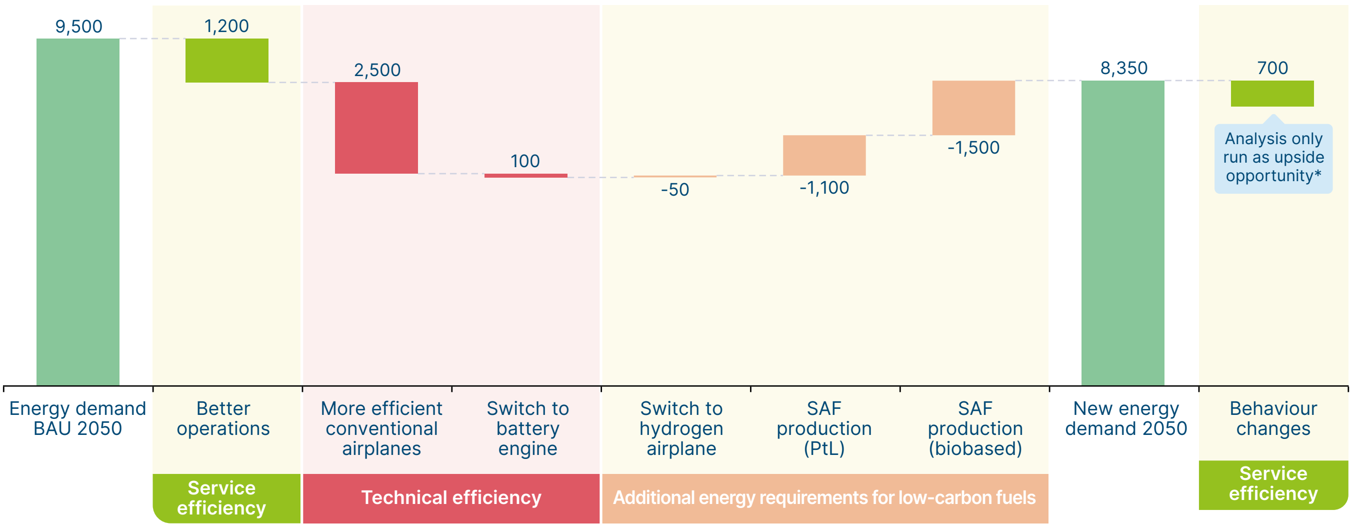
- **Growth of renewables in the power system**, which are more efficient than fossil generation
- **Lower fossil fuel conversion losses** (e.g., in refining) decline as fossils phase down

SOURCE: IEA (2025), *World Energy Outlook*; MPP (2023), *Hard-to-Abate Sector Transition Strategies*; ETC (2025), *Achieving Zero-Carbon Buildings*; ETC(2023), *Fossil Fuels in Transition*; BNEF (2023), *Electric Vehicle Outlook*; RMI (2024), *The Incredible Inefficiency of the Fossil Energy System.*

Exhibit 3.10

In aviation, making conventional airplanes more efficient is the single most important efficiency lever

Primary energy demand in 2050 and impact of productivity levers
TWh



NOTE: *Behaviour changes for aviation, i.e. shift toward rail or other transport modes, are not included in ETC's energy demand projections for 2050. BAU = Business as Usual; SAF = Sustainable Aviation Fuel; PtL = Power to liquids.

SOURCE: Schäfer, A. (2019), *"Technological, economic and environmental prospects of all-electric aircraft" Nature Energy. 4 (2): 160–166*; Mission Possible Partnership (2022), *Making Net-Zero Aviation Possible.*

3.3 Implications for annual energy productivity improvement

We have focused our analysis on the potential for energy productivity improvement over the next 25 years. Across that whole 25-year period, our analysis implies that primary energy productivity could improve at an average rate of 4.3% per annum, and final energy productivity at 3.7% per annum.

To assess how the pace of improvement varies by sector, we have estimated possible future developments in the metric shown in Exhibit 2.4 - the sectoral energy intensity. On that metric, at the final energy demand level, road transport productivity improves at an average rate of 7.2% per annum, buildings at 4.4% per annum, while industry, aviation and shipping improve at rates in the 1.5–3.1% range.

Estimating feasible annual improvements in energy productivity over the shorter term is highly sensitive to some crucial assumptions.

- Progress on final energy productivity over the next 5–10 years will be heavily influenced by the pace at which passengers and commercial EVs replace ICE vehicles, and the pace at which heat pumps replace boilers in residential heating.
- Progress on primary energy productivity will be significantly influenced by the pace at which China and other key countries, such as India and Indonesia, phase out coal generation of electricity.

In Exhibit 3.11, we present an illustrative scenario of what our 25-year view, together and feasible early progress towards it, might imply compared to the COP28 target of a 4% annual improvement rate achieved by 2030.
It shows that:

- Across most of the 25-year period, primary productivity improves at around 4–4.5% per annum, while final energy productivity improves at about 3.5–4.2%.
- Annual improvements slow down significantly in the 2040s: this is implied by our assumption that the electrification of road transport and residential heating will be largely complete by that time, and renewables generation will have scaled up. It illustrates that electrification of these and other sectors makes possible 20 years of much more rapid energy productivity improvement than has been achieved in the past or than is likely in the very long term.

- Achieving a 4% annual improvement rate by 2030 would represent a very rapid acceleration from the growth rates of 1.2% (for final energy productivity) and 1.4% (for primary energy) achieved over the last 8 years. It will only be possible if countries put in place strong policies to grasp the highest potential opportunities.

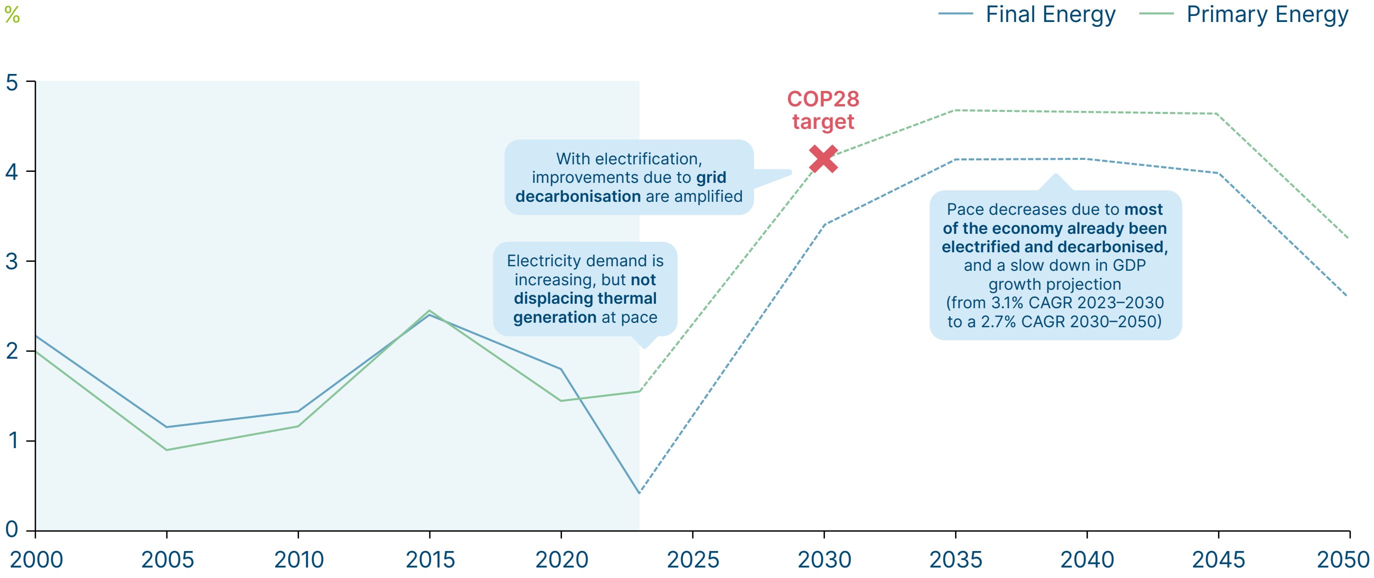
Overall, two conclusions follow:

- Achieving acceleration to a 4% per annum energy productivity growth rate will be challenging.
- But 4% per annum is a reasonable objective for what can and should be achieved over the next 20-25 years.

Exhibit 3.11

Realising COP28 targets for a 4% improvement in energy intensity by 2030 will depend on immediately accelerating efforts in energy productivity

5-Year CAGR energy productivity improvement projection



NOTE: CAGR = Compound annual growth rate. GDP growth projections are aligned with that of the International Monetary Fund.

SOURCE: Systemiq analysis for the ETC; World Bank Group, GDP, PPP (constant 2021 international $). Available at: https://data.worldbank.org/indicator/NY.GDP.MKTP.PP.KD. [Accessed August 2025]. Our World in Data, Global GDP over the long run. Available at: https://ourworldindata.org/grapher/global-gdp-over-the-long-run. [Accessed August, 2025]; IMF Real GDP Annual Growth. Available at: https://www.imf.org/external/datamapper/datasets/WEO. [Accessed on August 2025]; IEA (2024), *World Energy Outlook 2024*; International Institute for Applied Systems Analysis, IIASA PFU Dataset. Available at https://tntcat.iiasa.ac.at/PFUDB/dsd?Action=htmlpage&page=about. [Accessed May 2025].

3.4 Opportunities: Potential reductions in required investment and resource input

Our analysis suggests huge potential to reduce final and primary energy demand while growing useful energy services and human welfare.

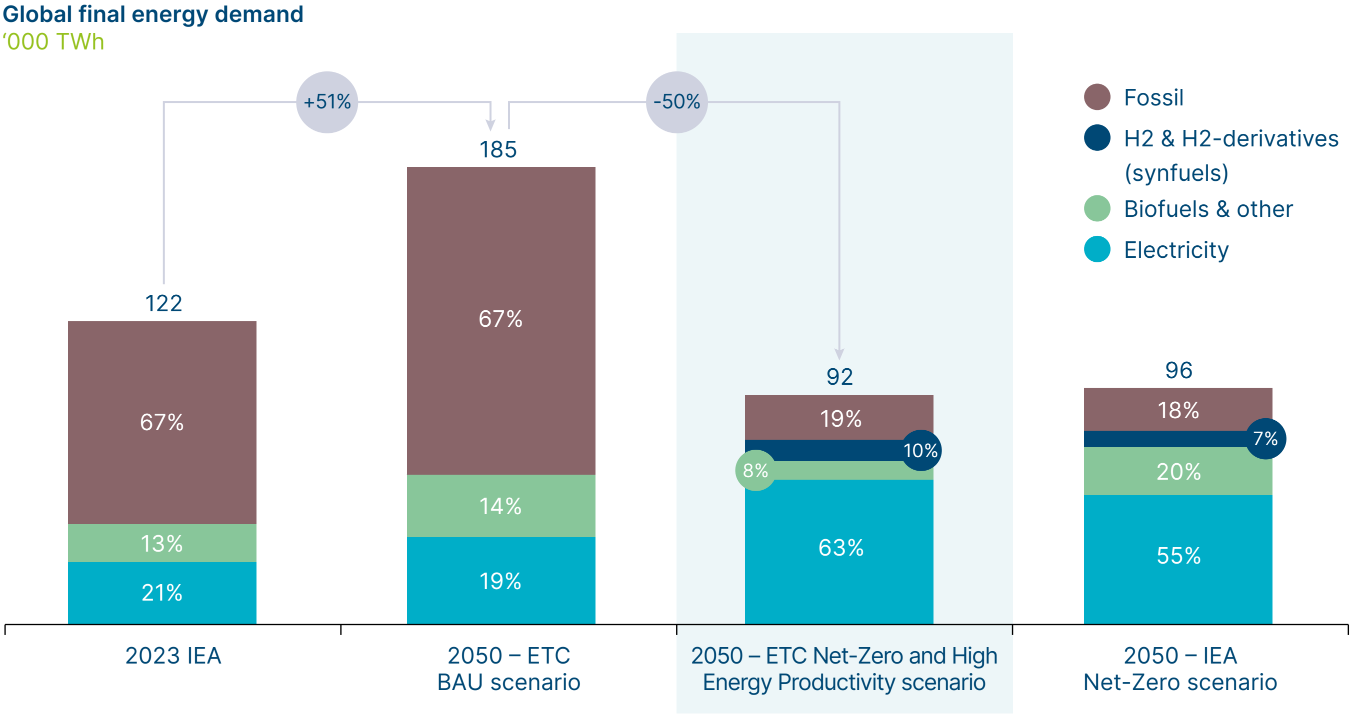
- Under a BAU scenario, which assumes minimal change in the sources of energy from today and limited growth in energy efficiency, final energy demand could grow 51% by 2050.
- But it could fall by 24% in absolute terms and by 50% versus BAU in a high energy productivity scenario [Exhibit 3.12].

This is in line with the findings of other organisations, including the IEA, whose net-zero scenario suggests that final energy demand could fall 21% by 2050 despite rapid growth in useful energy services and GDP [Exhibit 3.12].

The most important driver of increased final energy productivity is electrification, and the most important driver of additional primary energy productivity improvement is the power sector decarbonisation. Our high energy productivity scenario sees the use of electricity growing from around 21% of total final energy demand today to 63% by 2050.

Exhibit 3.12

Reaching net-zero whilst maximising energy productivity gains can lead to lower energy demand without compromising on living standards



NOTE: BAU = Business as usual.

SOURCE: Systemiq analysis for the ETC; IEA (2025), *World Energy Outlook*; MPP (2023), *Hard-to-Abate Sector Transition Strategies*; ETC (2025), *Achieving Zero-Carbon Buildings*; ETC (2023), *Fossil Fuels in Transition*; BNEF (2023), *Electric Vehicle Outlook*.

But it is important to note that even this increase understates the importance of electrification, since final energy demand will grow far faster than electricity demand [Exhibit 3.13]. Even when 50% of road passenger energy services are electrified (i.e. 50% of total kilometres travelled), which we project for about 2037, electricity will only account for 20% of final road passenger energy demand: even when 80% of km travelled is electrified, 50% of measured final energy demand will come from fossil fuels.

Beyond electrification, there are also large opportunities to improve energy productivity via demand reduction, appliance efficiency, better insulation and the other actions discussed in Section 2.1. Achieving this reduction is not absolutely essential to decarbonisation, since it would be physically possible to provide sufficient zero-carbon electricity and bioenergy to meet the growing level of demand and to deploy CCS on the scale required to offset emissions resulting from the remaining fossil fuel demand.

But it is highly likely that a significant proportion of the productivity potential indicated on Exhibit 3.11 will be cost-effective, and it is important to note that reducing energy demands will also reduce both the total investment needed to achieve a net-zero emissions economy and the demand for natural resources.

The cost-effectiveness of improving energy productivity will vary by sector.

- **In road transport,** passenger EVs already have a lower total cost of ownership than ICE vehicles, and will soon be cheaper to buy upfront (indeed, they already are in China).[38] As a result, significant energy productivity improvement can be achieved at zero or negative costs.
- **In the building sector,** regulations which mandate gradually rising appliance efficiency are likely to impose minimum costs once allowance is made for learning curve effects in technology development and manufacturing. Improving building insulation will impose very little cost, provided regulations require that it is included upfront during new build construction.[39]

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[38] IEA, (2025), *Global EV Outlook 2025*.

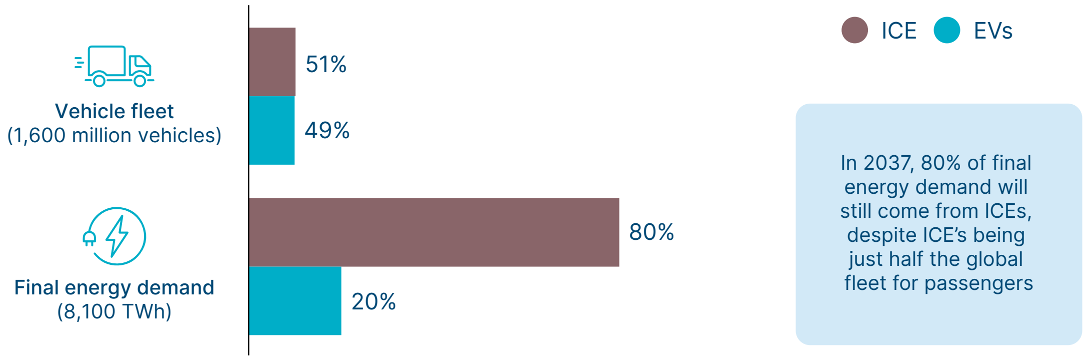
[39] ETC (2025), *Achieving Zero-Carbon Buildings*.

Exhibit 3.13

The electricity conundrum: Despite higher penetration, electricity accounts for disproportionately lower final energy demand, due to its higher efficiency

Case study: Passenger road transport in 2037

Billion km; TWh



In 2037, 80% of final energy demand will still come from ICEs, despite ICE's being just half the global fleet for passengers

SOURCE: Systemiq analysis for the ETC; BNEF (2023), *Electric Vehicle Outlook*.

Exhibit 3.14

Typical cost effectiveness of different actions[1]

🟢 Cheaper than current alternative 🟡 Comparable or slightly higher than the current alternative 🔴 Considerably higher than the current alternative

			Example of main technologies	Capital cost	Running cost	Total cost
Main productivity actions	Final Energy	Electrification	Passengers EVs	🟢	🟢	🟢
			Heat Pumps	🔴	🟢	🟢
			Electric cooking[2]	🟡	🟡	🟡
		Equipment/vehicle efficiency improvement	Efficient air conditioners	🟡	🟢	🟢
			Industrial motors	🟡	🟢	🟢
			LEDs	🟡	🟢	🟢
		Better insulation in buildings	New buildings: envelopes and fabrics	🟡	🟢	🟢
			Retrofit buildings: envelopes and fabrics	🔴	🟢	🟡[3]
		Heavy industry + long distance transportation	Lightweight aircrafts	🟡	🟢	🟢
			Aerodynamic vessels	🟡	🟢	🟢
			Heat recover in heavy industry	🔴	🟢	🟢
		Reduced demand	Plastics recycling (mechanical)	🟡	🟢	🟡
			New public transportation and/or cycling lanes	🟢	🟢	🟢
			Buildings smart energy system	🟡	🟢	🟢
	Primary Energy	Power sector decarbonisation	Clean power generation & balancing	🟡	🟢	🟢
		Low-carbon fuels	Hydrogen and derivatives	🔴	🔴	🔴
			Biofuels	🟡	🔴	🔴

NOTE: 1. Scores represent typical cost impact for each category of action, but with significant variation by individual circumstance. Cost indications are before the impact carbon prices to offset any green cost premium / 2. Cooking counterfactual in the table is biomass, for gas costs should be comparable. / 3. Can be cost effective for specific well designed combinations of measure.

SOURCE: Systemiq analysis for ETC; IEA (2025), *Global EV Outlook 2025;* ETC (2025), *Achieving Net-Zero Buildings;* CLASP (2025), *World's Best MEPS*. Available at: https://www.clasp.ngo/tools/worlds-best-meps/ [Accessed July 2025]; ICCT (2013), *Long-term potential for increased shipping efficiency through the adoption of industry-leading practices;* MPP (2022), *Making Net-zero Aviation Possible;* Systemiq (2022), *Planet Positive Chemicals*.

- **Installing heat pumps** to replace boilers in existing homes and industrial applications will, however, impose significant upfront investment costs.
- **In the petrochemical sector,** reducing demand by reducing, re-using and increasing plastics recycling will require higher investment in waste management systems, but the impact on end-product prices is modest—with consumer goods prices rising by only a few percentage points even under ambitious circularity scenarios.[40]
- **For aviation, shipping and heavy industry,** the full scope of energy efficiency improvements will not be achieved without carbon pricing or regulation, which increases the cost of energy derived from carbon-intensive sources, forcing businesses to either use more expensive zero-carbon energy sources or to improve energy efficiency.

The additional investment needed to achieve energy productivity improvement will be offset by lower energy consumption bills and reduced need to invest in new energy supply, and in particular, in electricity generation, transmission and distribution. By 2050, the difference in electricity demand between an electrified and high productivity scenario and an electrification-only would be of 29,000 TWh, i.e. 50% higher. This would imply 13.8 TW less of installed renewable capacity - solar and wind with four hours of storage - reducing cumulative investment need by $15 trillion, or $0.6 trillion per annum over the next 25 years.[41] This sum would be even bigger if avoided investments in grid extensions and longer-term storage were accounted for.

In addition, reducing electricity demands will make it easier to achieve the energy transition by reducing requirements for natural resources, and in particular, land devoted to renewables. We estimate that our maximum energy productivity scenario would reduce land area requirements for solar PV from around 0.6 million km² to around 0.4 million km².[42] This reduction would be equivalent to Ecuador's land size.

Finally, for many countries, reducing energy demand will improve energy security by cutting reliance on imports. We estimate that German energy imports could be reduced by 25% by 2035, cutting the import bill by €20 billion in 2023 prices, through a combination of electrification and energy productivity improvement.[43]

There is therefore a strong rationale for countries to set energy productivity improvement targets broadly in line with the COP28 commitment, and to design policies to meet these targets in a cost-effective way. These policies are discussed in Chapter 5.

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40 Systemiq (2022), *Planet Positive Chemicals.*

41 We assume 11 TW of solar and 2.8 TW of wind, at capacity factors of 20% and 40%, and a global average CAPEX for 2025–2050 period for 1 KW of wind and solar with 4 hour storage is estimated at $1841 and $863 respectively. Global average based on seven representative countries: Australia, China, Germany, India, Japan, US and UK. The global average CAPEX for wind and solar is not representative of the higher capital costs that developing economies face. Source: IRENA (*https://balticwind.eu/irena-report-onshore-and-offshore-wind-the-most-cost-competitive-power-generation-globally*, RENEWABLE ENERGY STATISTICS 2025), BNEF LCOE Data Viewer.

42 See exhibit 0.2 in ETC (2023), *Material and Resource Requirements for the Energy Transition*.

43 The exercise consists on an extrapolation of primary energy demand in Germany coming down by 28%, aligned with the global projections, mainly due to an increase in electrification, and maintaining at least the same amount of primary production. Eurostat data. [April, 2025]; Clean Energy Wire (2025), *Fossil fuel imports to Germany go down as costs increase.*

Fundamental drivers of long-term energy growth: Rebound effects, AI and limitless long-term potential

4

As Exhibit 2.1 showed, over the long run, human energy use has grown massively, as improvements in energy productivity have been less than the growth of GDP. This reflects the fact that energy has huge benefits for human welfare.

In Chapter 3, we identified a potential fall in final energy use over the next 25 years, breaking this historic trend. This is due to the one-off impact of electrification in specific sectors, in addition to more rapid progress along other dimensions of efficiency improvement. We also identified the potential for a bigger still fall in primary energy use, and thus a decrease in the primary to final ratio, as a result of reduced energy conversion losses in the power sector in particular.

This latter improvement in the primary to final energy ratio can endure permanently. But there are reasons for believing that in the long-term, the growth in final energy demand will resume; and it is possible that final demand growth over the next 25 years could be significantly higher than our projections. If that is true, it becomes even more important to pursue cost-effective energy productivity improvement while planning for large-scale expansion of the global power system.

Three factors might lead to higher than projected energy, and in particular, electricity growth.

1. The rebound effect

As energy services get cheaper, people tend to use more of them, and since increased energy efficiency reduces the amount of final energy required to deliver energy services, it reduces their cost. It is therefore likely that improvements in energy productivity will be partly offset by a “rebound effect”. For instance, as LEDs have dramatically reduced the cost per lumen of light delivered, many consumers have increased their use of lighting.[44]

A review of 21 empirical studies of this effect, published in 2021, shows that on average, a 58% rebound effect has been observed.[45] If true across the whole of the economy, this would imply that only 42% of the potential reduction in final energy use, relative to a BAU scenario, as shown in Exhibit 3.1 would actually be achieved, while energy services would grow even more than indicated Exhibit 3.2.

A key driver of the rebound effect is reduced cost of a service. The effect will not be seen in all sectors, since in some sectors no net cost reduction is likely to be achieved. In shipping and aviation, for instance, any improvement in final energy efficiency is likely to be offset by the increase in the primary to final energy ratio discussed in Section 3.2, and prices for shipping and aviation services are likely to rise. In these sectors, improved energy efficiency will simply reduce the scale of price increase.

But in the sectors which account for the biggest energy efficiency improvement potential - road transport and buildings - large rebound effects are possible. For instance, improved energy efficiency of AC systems and the resulting reduction in electricity input costs could induce people to cool more rooms and lower target temperatures.

This effect could be particularly important where existing applications are electrified for the first time, and where electrification entails high upfront costs but low operating costs:

- Households switching to heat pumps will face a higher upfront cost than when buying a gas boiler, but will face lower marginal costs of operation. For some households and for some time, the impact of the upfront investment on household budgets may lead them to limit their heat use to no higher than when they had a gas boiler. But over time and for higher-income households, the price elasticity effect is likely to dominate, with households potentially choosing to heat their homes more.
- In the case of EVs too, the upfront costs are currently higher than for ICEs in countries other than China, but this upfront cost premium will soon disappear. The price elasticity effect of much cheaper operating costs is therefore bound to dominate, and it is possible that once people have bought EVs, they will choose to use them more than ICEVs, e.g., in place of potentially more expensive train journeys. In some environments, however, these effects may be offset by policies such as congestion charges.

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[44] IEA, Lighting. Available at www.iea.org/energy-system/buildings/lighting. [Accessed September 2025].

[45] Brockway et al. (2021), *Energy efficiency and economy-wide rebound effects: A review of the evidence and its implications.*

Overall, it is therefore likely that a significant element of the reduction in final energy demand indicated in Chapter 3 might be offset by rebound effects.[46]

2. Electricity demand for data centres and artificial intelligence (AI)

AI could help achieve several of the energy efficiency improvements described in Section 3.1, in particular those which reduce average energy demand via greater operational efficiency, and peak electricity demand via increased demand side flexibility. A study by Systemiq suggests that AI can increase solar and wind's load factor by up to 20%.[47] As described in ETC's 2025 report, *Power Systems Transformation: Delivering Competitive, Resilient Electricity in High-Renewable Systems* report, AI could also help improve the efficiency of grid operations, significantly reducing required investment in grid expansion.

Conversely, deployment of AI will also be a major driver of electricity demand, with growing electricity use in data centres both to train models and to support AI queries ("inference"). However, the range of credible estimates for how large this effect could be is extremely wide. This reflects the inherent uncertainty both around the scale of AI deployment and the efficiency with which AI will operate in both the training and inference stages.

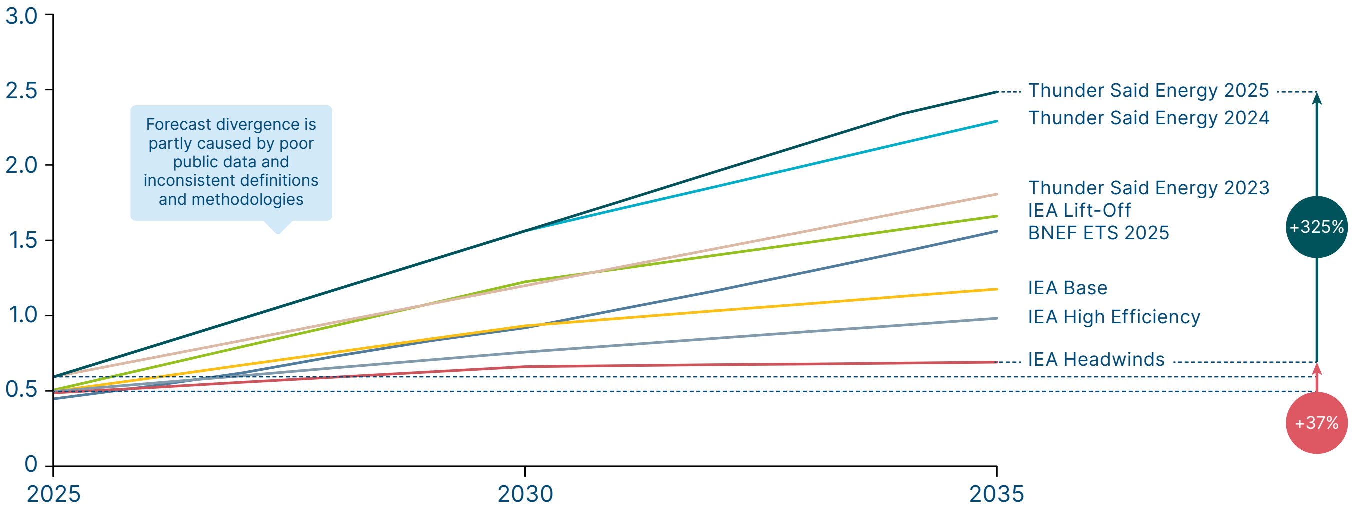
For instance, between April 2024 and February 2025, Thunder Said Energy increased its 2030 projection for the number of AI models and the volume of queries by 10 times, but revised down 90% of its estimate of the energy intensity of training (measured in GFLOPS per watt) and 85% of its estimate for the energy intensity of inference (measured in Wh per query). As a result, Thunder Said's estimates of 2030 AI electricity demand remained unchanged at 1,000 TWh.[48] However, electricity demand in data centres goes beyond that of AI.

Forecasts for 2030 total data centre electricity demand, including but not just limited to AI training and interference, range from IEA's 650 TWh (Headwinds) to Thunder Said Energy's 1600 TWh (2025) [Exhibit 4.1]. By 2035, different projections suggest that the overall electricity demand for data centres could range anywhere between 2,500 TWh (Thunder Said Energy 2025 analysis) to 700 TWh (as per IEA Headwinds scenario).

Exhibit 4.1

Data centre demand growth scenarios have large uncertainty, but their concentration make grid operations critical in certain geographies

Global data centre annual demand projections by scenario
'000 TWh/year



SOURCE: BNEF (2025), *New Energy Outlook*; IEA (2025), *Energy and AI*; Thunder Said Energy (2025), *AI energy: industrial demand and the Jevons effect?*

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[46] Zenon (2023), *Beyond primary energy.*

[47] Stern et al. (2025), Green and intelligent: the role of AI in the climate transition. Available at: *https://www.nature.com/articles/s44168-025-00252-3* [Accessed July 2025].

[48] Thunder Said Energy (2025), *AI energy: industrial demand and the Jevons effect?* Available at: *https://thundersaidenergy.com/downloads/ai-energy-industrial-demand-and-the-jevons-effect/.* [Accessed July 2025].

Beyond 2035, projections become even more uncertain given the potential for both further growth in AI model complexity and scale of deployment, and further massive potential for improvements in efficiency. This efficiency improvement potential reflects the fact that the current energy efficiency of AI models is thousands or even millions of times away from the theoretical limits.[49]

Thunder Said Energy suggests further growth in total data centre demand to 3,750 TWh in 2050. In our 2050 projections for global electricity demand, we have included a higher assumption of 3,900 TWh. This represents a significant but not dramatic portion of the total projected electricity demand in 2050, less than 7% of electricity demand in our Net Zero & High Energy Productivity scenario, and 11% in the BAU case.

However, even if the long-term impact on total global demand remains moderate, the short-term impact on required growth is dramatic and could lead to a rush to invest in gas capacity as the simplest and quickest way to meet short-term demands.

As AI grows, two dimensions of public policy could therefore be desirable:

- Regulations or incentives to ensure that as much AI electricity use as possible is met by renewable, nuclear or other zero-carbon generation rather than fossil fuels.
- Incentives and encouragement to increase the energy efficiency of AI operations.

3. Entirely new uses of energy

Rebound effects relate to already existing categories of energy service, and AI is already a known application. In addition, it is possible that energy, and in particular electricity, will be used for currently undeveloped applications.

One already known but undeveloped possibility is the use of energy to produce synthetic protein, but other new applications could emerge. In the early 20th century, almost nobody could have anticipated that television, computing, the internet and AI would emerge as important applications which depend on electricity input. As electrified energy systems become more efficient, and the costs of those clean electricity inputs also continue to fall – as witnessed in the dramatic cost reductions already seen in solar and batteries – new uses of energy may arise. Increasing energy use has been vital to rising human prosperity, and it is likely to continue to be so in future, including in ways which we cannot now anticipate.

Implications

For the combination of reasons set out above, it is highly likely that over the long term, human demand for energy services, and therefore for useful energy, will continue to grow rapidly. But this can be combined with 2–3 decades of falling final energy demand because of the very large one-off impact of the improvement in energy efficiency made possible through electrification. Rapid improvements in energy efficiency - whether achieved through electrification or the other levers considered in Chapter 3 - could significantly reduce the costs of the required energy transition to a zero-carbon economy, and reduce the demand placed on potentially scarce natural resources.[50]

It is therefore essential to:

- Achieve energy productivity improvements wherever possible and cost-effective.
- Plan for a very large-scale expansion of electricity systems despite the big one-off energy productivity improvement which electrification will enable.

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[49] Thunder Said Energy points out that 2023's best rated computers still use 200m times more energy than the Landauer Limit's thermodynamic minimum . And some studies estimate that an AI LLM currently requires 9 MW of power to do calculations which the human brain could do with just 20-30 watts; this implies that if human levels of energy efficiency could be achieved, energy use would fall 360,000 times. Available at: *https://www.sydney.edu.au/news-opinion/news/2024/08/16/how-the-human-brain-is-inspiring-energy-efficient-ai*. [Accessed July 2025].

[50] IRP (2024), *Bend the trend: Pathways to a liveable planet as resource use spikes.*

Policies to seize the productivity improvement opportunity

5

Chapter 3 has described the huge potential to reduce primary and final energy consumption while increasing useful energy and supporting growth in consumer living standards. As Section 3.4 described, the precise optimal balance between increasing energy productivity and decarbonising energy supply cannot and does not need to be predicted in advance. But it is certain that very significant improvements in energy productivity could be achieved in a cost-effective fashion. This will only occur if countries put in place:

- National policy frameworks to achieve the COP28 commitment to double the pace of energy productivity growth.
- Specific policies to drive significant improvements in final energy productivity.
- Policies to reduce the primary to final energy ratio, primarily through power sector decarbonisation.

5.1 National policy frameworks to achieve COP28 target

At COP28 in Dubai, 133 nations committed to increasing the rate of energy productivity improvement from around 2% per annum in 2023 to around 4% by 2030. This is a useful high-level ambition, and as Section 4.3 discussed, it is in principle achievable, with a 4% per annum improvement then maintained for around two decades thereafter.

But this improvement will only be achieved and maintained over time if translated into national policy frameworks which identify where the highest potential lies, and which define the specific policies required to seize sector-by-sector opportunities.

Policy frameworks to achieve final energy productivity improvement will include some features common to all countries, together with areas of focus which reflect different national circumstances:

- In all countries, the electrification of road transport should be a central priority.
- In high latitude countries with large building heating needs, policies to drive a transition from gas boilers to heat pumps will be among the most important.
- In many developing countries, ensuring that rapidly rising cooling demands are met in an energy-efficient fashion will be crucial, with a strong focus required on both (1) stock-turnover of AC to high-efficiency models and (2) high-quality insulation in new buildings.
- In addition, parts of South/Southeast Asia and Africa will need to transition away from the traditional use of biomass for cooking towards LPG and, in the longer term, ideally electric cooking.

Policies to reduce the primary to final energy ratio will in all countries need to focus primarily on decarbonising power generation, but with the optimal mix of technologies and feasible timescale varying by country.

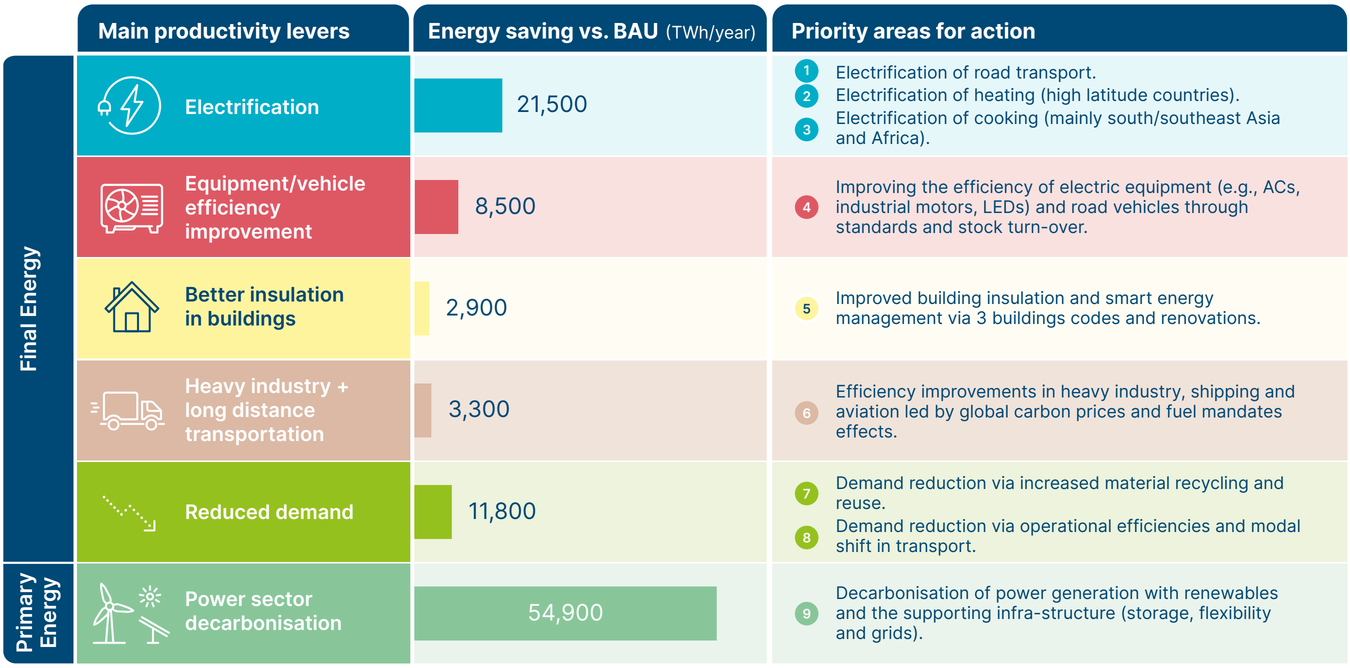
A summary of priority actions is provided in Exhibit 5.1 and is detailed in Section 5.2 (for final energy) and Section 5.3 (for primary energy).

5.2 Improving final energy productivity: driving electrification and technical efficiency improvement

The highest potential levers to improve final energy productivity are those relating to electrification and improving the average efficiency of electrical equipment and road vehicles. Regulations and incentives are also needed to drive improvements in building efficiency; carbon pricing should play a key role in incentivising efficiency in heavy industry and long-distance transport; and appropriate regulations can help seize the opportunity to increase plastic recycling and reuse.

Exhibit 5.1

There are 9 priority areas of action to maximise energy productivity opportunities



	Main productivity levers	Energy saving vs. BAU (TWh/year)	Priority areas for action
Final Energy	Electrification	21,500	① Electrification of road transport. ② Electrification of heating (high latitude countries). ③ Electrification of cooking (mainly south/southeast Asia and Africa).
	Equipment/vehicle efficiency improvement	8,500	④ Improving the efficiency of electric equipment (e.g., ACs, industrial motors, LEDs) and road vehicles through standards and stock turn-over.
	Better insulation in buildings	2,900	⑤ Improved building insulation and smart energy management via 3 buildings codes and renovations.
	Heavy industry + long distance transportation	3,300	⑥ Efficiency improvements in heavy industry, shipping and aviation led by global carbon prices and fuel mandates effects.
	Reduced demand	11,800	⑦ Demand reduction via increased material recycling and reuse. ⑧ Demand reduction via operational efficiencies and modal shift in transport.
Primary Energy	Power sector decarbonisation	54,900	⑨ Decarbonisation of power generation with renewables and the supporting infra-structure (storage, flexibility and grids).

SOURCE: Systemiq analysis for the ETC.

Electrification of road transport: a priority in all countries. Key policies which can accelerate a shift to electric vehicles include:

- Introduce/maintain future bans on ICE vehicle purchase - ideally setting 2035 as the date for passenger vehicles and 2040 for heavy vehicles.
- Initial subsidies focused on low-cost EVs.
- Fleet purchase mandates for public and corporate fleet purchases to include a minimum percentage of EVs.
- Support for charging infrastructure development.
- Policies to increase the pace at which ICEs are replaced with EVs [Box D].

Electrification of residential heating: a priority in some countries. Policies are needed here to overcome the barriers created by high upfront costs; they include:

- Subsidies, tax incentives or low-interest loans for lower-income families.
- Rebalancing gas and electricity prices to increase the operational cost benefits of shifting to heat pumps (e.g., by removing gas subsidies and other price distortions).
- Encouraging time-of-use tariffs (and other price signals) to enable the use of cheaper off-peak electricity while enabling dynamic balance to grid loads.
- Banning the installation of gas boilers in new homes, and setting a date beyond which boilers cannot be installed in existing buildings.

Policy approaches which achieve economies of scale via a coordinated national approach should also be considered [Box E].

Electrification of residential and commercial cooking: a priority in South/Southeast Asia and Africa. Policies should address accessibility of clean cooking, even if that entails more than one stage from now to 2050:

- An interim solution until 2030 to install improved cookstoves that are much more efficient and safer.
- By 2040, strong policies to transition to cleaner cooking fuels, including LPG - e.g., China and India providing free stoves and subsidies for canisters.

- By 2050, improved access to electricity, from grid or distributed generation, will enable the majority of the global population to transition away from fossil fuel cooking, coupled with a strong rollout of electric cooking even before fossil fuel assets reach end-of-life.

Improving the efficiency of electric equipment and road vehicles: a priority in all countries. Policies here should be designed both to increase the efficiency of new equipment/vehicles and to speed the replacement of existing equipment. These objectives can be achieved via:

- Reinforcing/introducing labelling and minimum energy performance standards (MEPS), in household appliances, EVs and industrial motors
- Scrappage schemes and other policies that encourage the early retirement of older, less efficient appliances/ vehicles. In low-income countries, policies to discourage the purchase of inefficient second-hand equipment from richer countries are also potentially high impact [Box D].
- Raising the awareness of financiers, SMEs and consumers of the business case for investing in more energy-efficient new appliances and industrial motors, and developing financial products to support purchase.

Improved building insulation and smart energy management: focus differs by country. As Section 4.1 describes, improvements in building insulation standards and in the application of smart energy management systems are more important than implied by the 3% potential reduction in total electricity demand, since these measures can have a much bigger impact on peak demand. Specific policies required are discussed in the ETC's 2025 report, *Achieving Zero-Carbon Buildings: Electric, Efficient and Flexible*. They include:

- Building codes and other regulations to ensure improved energy efficiency of new buildings: this is particularly important in developing countries, where 60% of all new buildings will likely be built.
- A cost-effective approach to the retrofit of existing buildings in developing countries, focusing in particular on high impact low-cost measures.
- Urban design approaches which reduce cooling needs via, for instance, natural shading.
- Encouragement of demand side flexibility enabled by smart energy management systems, and by investment in rooftop solar and decentralised energy storage.

Efficiency improvements in heavy industry, shipping and aviation: a global priority. In sectors where consumers make purchase decisions which affect energy efficiency, regulation will often be more effective than carbon pricing in driving efficiency improvement. But in heavy industry, aviation and shipping, where energy costs are large relative to profits and decisions are made by professional managers, carbon pricing will be a very powerful policy, forcing managers to achieve emission reductions via an optimal combination of actions which decarbonise energy input (e.g., substituting SAF for conventional jet fuel) and reduce energy demand (e.g., increase in aircraft utilisation, or slower shipping speeds).

In aviation and shipping, globally agreed carbon prices - or fuel mandates which specify minimum shares of clean fuel - would be optimal, and a major step forward towards that was taken by the International Maritime Organisation (IMO) in April 2025.[51] In heavy industry, as the ETC's 2025 report on *Global trade in the energy transition* describes, similar carbon prices applied by all countries are ideal, and can be encouraged if those countries (such as the EU) which move first towards carbon pricing, apply carbon border adjustment mechanisms (CBAM).[52]

Demand reduction via increased material recycling and reuse. In Exhibit 3.5, the biggest identified opportunity to reduce demand for energy services at no cost to consumer living standards was via increased recycling and reuse of plastics, aluminium, steel, and other materials. To achieve this requires:

- Policies to encourage/require better sorting of waste streams from both households and businesses.
- Extended producer responsibility (EPR) schemes to manage end-of-life materials more effectively, making manufacturers accountable for product recovery, reuse, and recycling - especially for appliances, batteries, and vehicles.
- Mandatory management of material demand by embedding circularity principles in product design, e.g., modularity, repairability, and recyclability, so that products last longer and materials stay in use.
- Demand reduction via operational efficiencies and modal shift in transport.

The two other categories of demand reduction potential noted on Exhibit 3.5 were:

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[51] IMO (2025), *IMO approves net-zero regulations for global shipping*. Available at: *https://www.imo.org/en/mediacentre/pressbriefings/pages/imo-approves-netzero-regulations.aspx*. [Accessed July 2025].

[52] ETC (2025), *Global Trade in the Energy Transition*.

- Multiple forms of operational efficiency improvement - carbon pricing will also be relevant here (e.g., with higher aviation and marine fuel costs incentivising better aircraft utilisation and shipping logistics management).
- Modal shift in transport. This can be enabled via urban design to create more walkable cities, integrated public transport, safe cycling infrastructure, and competitive rail versus short-haul flights.

BOX D

Speeding the transition to more efficient equipment

The average efficiency of equipment in use at any time is a function of both the efficiency of new equipment being purchased and of the pace of stock turnover - i.e. how rapidly older, less efficient equipment is replaced.

Policies to drive faster stock turnover and more rapid uptake of new, more efficient equipment can therefore have a powerful impact on the pace of average efficiency improvement. Examples of successful policies include:

China's trade in schemes for appliances and vehicles

- In 2024, China launched a large-scale consumer goods trade-in programme aimed at replacing outdated appliances and vehicles with more efficient and low-emission alternatives. Supported by RMB 300 billion ($42 billion) of public expenditure, the programme offers subsidies such as up to RMB 20,000 (~$ 2,730) for electric vehicles, RMB 15,000 (~$2,050) for new, more efficient ICEs, and up to RMB 2000 (~$273) in 12 household appliance categories.[53]
- As of June 2025, the programme had enabled the scrappage of over 120 million items, including 2.9 million vehicles, and generated retail sales exceeding RMB 720 billion ($101 billion). In the buildings sector, the replacement of older air conditioners alone is estimated to reduce household cooling expenses by RMB 6.8 billion ($943 million) in 2025. In transport, the programme has supported sales of 3.7 million new vehicles and contributed to a 50.8% share of EVs and plug-in hybrids in April 2025 car sales.[54]

India's public support for the rollout of LEDs

- In 2015, India launched one of the world's largest energy efficiency programs, the Affordable LEDs for All (UJALA) scheme.[55] Implemented by Energy Efficiency Services Limited (EESL), a public sector entity under the Ministry of Power, the scheme combined bulk procurement with consumer outreach to reduce costs and drive mass adoption.
- Under UJALA, over 368 million LED bulbs have been distributed nationwide, resulting in estimated annual energy savings of nearly 47.9 billion kWh, avoided peak demand of 9,586 MW, and carbon emissions reductions of approximately 38.8 million tonnes CO_2 per year. The initiative also delivered major economic benefits, saving Indian households around ₹19,000 crore ($2.3 billion) in electricity bills annually.

African countries' restrictions on second-hand vehicle imports

- Several African countries have implemented restrictions on the import of used vehicles to reduce air pollution, improve fleet efficiency, and support local industry development. Kenya bans imports of vehicles older than 8 years and requires compliance with Euro 4 emission standards. Ghana prohibits vehicles over 10 years old and bans salvaged cars as part of an automotive development plan. Morocco allows only vehicles under 5 years old and mandates technical and emission inspections, while Egypt limits private car imports to under 3 years old and requires Euro 3 compliance or higher.

- Other countries use fiscal and logistical measures to discourage older vehicle imports. Rwanda imposes higher taxes on older vehicles and promotes electric mobility through policy incentives. Nigeria bans imports of cars over 15 years old and restricts second-hand vehicle imports through land borders. South Africa enforces one of the strictest regimes, prohibiting used vehicle imports for resale except in specific cases, with the aim of protecting domestic manufacturing and safety standards.

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[53] CSIS (2025), *Is Your Refrigerator Running? China's Trade-In Programs and Plans to Boost Consumption*. Available at: *https://www.csis.org/blogs/trustee-china-hand/your-refrigerator-running-chinas-trade-programs-and-plans-boost*. [Accessed May 2025].

[54] Bloomberg UK (2024), *China's Cash-for-Clunkers Policy to Fuel $26 Billion More EV Sales*. Available at: *https://www.bloomberg.com/news/newsletters/2024-08-19/china-cash-for-clunkers-to-fuel-26-billion-more-electric-vehicle-sales*. [Accessed May 2025]; Ember (2025), China's trade-in programme could reduce households $943 million in cooling bills this year. Available at *https://ember-energy.org/latest-updates/chinas-trade-in-programme-could-reduce-households-943-million-in-cooling-bills-this-year/*. [Accessed May 2025].

[55] India Brand Equity Foundation, *UJALA (Unnat Jyoti by Affordable LEDs for All)*. Available at *https://www.ibef.org/government-schemes/ujala-yojna*. [Accessed May 2025].

BOX E

National policies to drive major change: a historic UK example

Between 1967 and 1977, the UK undertook a comprehensive conversion program to transition from town gas, produced from coal, to natural gas following significant discoveries in the North Sea. A key component of this transition was the promotion and installation of gas boilers in households. This nationwide initiative installed approximately 40 million gas appliances in 14 million homes and businesses to ensure compatibility with natural gas.[56]

The Gas Council and regional gas boards actively encouraged consumers to adopt gas central heating systems, highlighting the benefits of natural gas, such as improved efficiency and convenience. This effort aimed to modernise home heating infrastructure and capitalise on the cleaner-burning properties of natural gas compared to coal-derived town gas.

The conversion program is often regarded as one of the most significant peacetime engineering projects in the UK, reflecting the government's commitment to leveraging domestic energy resources and enhancing energy efficiency in residential heating.[57]

5.3 Reducing the primary to final energy ratio: Decarbonising electricity supply

As Section 4.1 showed, there are two major means to reduce the primary to final energy ratio. One is to reduce conversion losses in the refining of fossil fuels - this will automatically occur as road transport is electrified. The other is the decarbonisation of power generation with renewables.

Power decarbonisation could also be achieved via greater use of nuclear power, which does not reduce the primary to final ratio. As a result, reducing the primary to final ratio should not be seen as an absolute objective, but it is the inevitable consequence of policies which drive reduced fossil fuel use in power generation and increased deployment of renewables.

These policies, which are described in more detail in the ETC's report on *Power System Transformation,* should include:

- Setting ambitious targets for power decarbonisation and the rapid phase down and, eventually, near total phase out of fossil fuel-based thermal generation.
- Setting targets for the pace of wind and solar installations and putting in place the power market contract structures (e.g., auctions), which will deliver them cost-effectively.
- Supporting the required investments in storage, flexibility and transmission and distribution grids.

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[56] Imperial College London (2019), *Insights from the UK's conversion from manufactured gas to North Sea Gas, 1966-1977*; Ertblog (2021), *Fifty years on: converting to North Sea gas*. Available at *https://robskinner.net/2021/10/07/fifty-years-on-converting-to-north-sea-gas/*. [Accessed May 2025]; Arapostathis, S., Laczay, S., & Pearson, P. (2019), *Steering the 'C-Day': Insights from the rapid, planned transition of the UK's natural gas conversion programme.*

[57] The New Deal Green Group (2020), *When 14 million homes and businesses switched fuel in less than a decade*. Available at *https://greennewdealgroup.org/when-14-million-homes-and-businesses-switched-fuel-in-less-than-a-decade/*. [Accessed May 2025].

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