ENGINEERING FUNDAMENTALS
OF
ENERGY EFFICIENCY

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Using energy more efficiently is essential if carbon emissions are to be reduced. According to the International Energy Agency (IEA), energy efficiency improvements represent the largest and least costly savings in carbon emissions, even when compared with renewables, nuclear power and carbon capture and storage. Yet, how should future priorities be directed? Should efforts be focused on light bulbs or diesel engines, insulating houses or improving coal-fired power stations?

Previous attempts to assess energy efficiency options provide a useful snapshot for directing short-term responses, but are limited to only known technologies developed under current economic conditions. Tomorrow's economic drivers are not easy to forecast, and new technical solutions often present in a disruptive manner. Fortunately, the theoretical and practical efficiency limits do not vary with time, allowing the uncertainty of economic forecasts to be avoided and the potential of yet to be discovered efficient designs to be captured.

This research aims to provide a rational basis for assessing all future developments in energy efficiency. The global flow of energy through technical devices is traced from fuels to final services, and presented as an energy map to convey visually the scale of energy use. An important distinction is made between conversion devices, which upgrade energy into more useable forms, and passive systems, from which energy is lost as low temperature heat, in exchange for final services. Theoretical efficiency limits are calculated for conversion devices using exergy analysis, and show a 89% potential reduction in energy use. Efforts should be focused on improving the efficiency of, in relative order: biomass burners, refrigeration systems, gas burners and petrol engines. For passive systems, practical utilisation limits are calculated based on engineering models, and demonstrate energy savings of 73% are achievable. Significant gains are found in technical solutions that increase the thermal insulation of building fabrics and reduce the mass of vehicles.

The result of this work is a consistent basis for comparing efficiency options, that can enable future technical research and energy policy to be directed towards the actions that will make the most difference.

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This thesis contains fifty six thousand words, eighteen figures and forty five tables. It is the result of my own work.

This thesis is printed on 100% recycled paper.

Previous publications

Some of the material in this thesis has been published in Journals and presented at conferences.

Journal papers (published)

1. The role of washing machines in life cycle assessment studies.
   Journal of Industrial Ecology, 13(1):27–37, 2009.
   `doi:10.1111/j.1530-9290.2009.00107.x`
   J.M. Cullen and J.M. Allwood

2. The efficient use of energy: tracing the global flow of energy from fuel to service. *Energy Policy*, 38(1):75–81, 2010.
   `doi:10.1016/j.enpol.2009.08.054`
   J.M. Cullen and J.M. Allwood

Journal papers (pending)

1. Theoretical efficiency limits for energy conversion devices.
   Accepted for publication in *Energy*, 2010.
   J.M. Cullen and J.M. Allwood

2. Options for achieving a 50% cut in industrial carbon emissions by 2050. Accepted for publication in *Environmental Science & Technology*, 2010.
   J.M. Allwood, J.M. Cullen, and R.L. Milford

3. Practical efficiency limits for passive energy systems.
   Energy Conversion and Management, 2009.
   J.M. Cullen, J.M. Allwood, and E.H. Borgstein

Conferences papers and posters

1. Limits to global energy efficiency. In *R'09 Twin World Congress: Resource Management and Technology for Material and Energy Efficiency*, Davos, Switzerland, September 2009.
   J.M. Cullen and J.M. Allwood

2. Steel, aluminium and carbon: alternative strategies for meeting the 2050 carbon emission targets. In *R'09 Twin World Congress: Resource Management and Technology for Material and Energy Efficiency*, Davos, Switzerland, September 2009.
   J.M. Allwood and J.M. Cullen

3. Determining the best options for improving global energy efficiency. In *Transitions Toward Sustainability, 5th International Conference on Industrial Ecology*, Lisbon, Portugal, June 2009.
   J.M. Cullen and J.M. Allwood

4. Prioritising energy efficiency opportunities for practical change. Awarded best poster, in *Sustainable Energy: New Solutions from Physics and Engineering*, Institute of Physics, London, United Kingdom, October 2008.
   J.M. Cullen and J.M. Allwood

5. Engineering fundamentals of energy efficiency. Keynote paper, in *2008 Global Symposium on Recycling, Waste Treatment and Clean Technology (REWAS)*, Cancun, Mexico, October 2008.
   J.M. Cullen and J.M. Allwood

6. Fundamental Analysis of Carbon Emissions for Manufacturing with Aluminium and Steel. In *4th International Conference of the International Society for Industrial Ecology*, Toronto, Canada, June 2007.
   J.M. Cullen and J.M. Allwood

7. Manufacturing with aluminium and steel: a fundamental analysis of energy use and carbon emissions. Awarded best paper, in *Institute for Manufacturing First Year Conference*, Cambridge, United Kingdom, May 2007.
   J.M. Cullen and J.M. Allwood

CONTENTS

1 INTRODUCTION: THE EFFICIENT USE OF ENERGY

Reducing energy demand by using energy more efficiently is the most cost effective strategy available for reducing carbon dioxide emissions. The International Energy Agency (IEA) asserts that 'energy efficiency improvements in buildings, appliances, transport, industry and power generation represent the largest and least costly savings' in emissions.[1(p.40)] Many nations agree, including the United Kingdom (UK) which claims the starting point for addressing climate change risks is 'to reduce our overall energy use through greater energy efficiency'.[2(p.107)] However, despite this great potential, energy efficiency is often neglected amidst the political excitement surrounding alternative strategies such as renewable energy and the resurgence of nuclear power. It is important that engineers are actively engaged in the climate change debate, and give equal focus to both the development of low carbon energy supplies *and* technologies which improve energy efficiency.

1.1 Climate change and energy related emissions

'Climate change is real, and the causal link to increased greenhouse emissions is now well established.'

David King[3(p.176)]
Chief Scientific Adviser (2000–2007), UK

Climate change is the most important environmental challenge facing our world today. The release of greenhouse gases (GHGs) into the atmosphere, at ever increasing rates, is pushing global temperatures to elevated levels. Worldwide GHG emissions are dominated by carbon dioxide (CO_2); the majority of CO_2 is released when fossil fuels are burned for human energy use. Therefore, any long-term strategy which promotes a low carbon future must reduce the consumption of energy from carbon bearing fossil fuels.

The latest report from the Intergovernmental Panel on Climate Change (IPCC)[4] asserts that atmospheric concentrations of the three primary GHGs—CO_2, methane (CH_4) and nitrous oxide (N_2O)—have increased significantly due to human activities over the last 250 years. Ice cores show that current GHG concentrations far exceed recorded levels over a period of ten thousand years. Furthermore, mid-range reference case forecasts suggest GHG emissions will continue to rise another 50% by 2025. GHG producing activities have historically been crucial for economic development making the reversal of this trend a daunting task for modern society.

The conclusion of the IPCC panel is that '[w]arming of the climate system is unequivocal',[4(p.5)] based on observations of increased air and ocean temperatures, rising average sea levels, and ice and snow melt. Average near-surface air temperature has risen 0.74 °C between 1906 and 2005, and the rate of temperature increase is accelerating. Eleven of the twelve warmest years, recorded since 1850, have occurred in the last twelve years (1995–2006), and global surface temperatures are projected to rise between 1.1 °C and 6.4 °C by the end of this century. This corresponds to an estimated sea level rise of 0.18 m to 0.59 m, without accounting for future rapid non-linear changes in ice flow. If the planet continues to warm at current rates, dramatic changes to the human environment are likely to occur.

The IPCC state that '[m]ost of the observed increase in global average temperatures since the mid-20th century is very likely [90% likelihood] due to the observed increase in anthropogenic greenhouse gas concentrations'.[4(p.10)] To stabilise global mean temperature rise between 2.0 °C and 2.4 °C above pre-industrial levels will require a minimum cut in total annual global emissions of 50% to 85% from 2000 levels, by 2050. Governments have responded to such forecasts by agreeing a global reduction of 50% before 2050 at the recent G8 Hokkaido Toyako summit.[5] National targets are entering policy as law, for example the UK Climate Change Act 2008 commits to reducing the net UK carbon account for the year 2050, by at least 80% below the 1990 baseline UK.[6]

The combustion of fossil fuels to provide energy releases large quantities of CO_2 emissions. The World Resources Institute (WRI) report *Navigating the numbers*,[7] using 100-year global warming potentials, shows that 77% of all GHG emissions are in the form of CO_2—some 32 Gt CO_2. The balance is composed of CH_4 (14%), N_2O (8%), and fluorintated gases (1%). Approximately 75% of all carbon emissions are derived from human energy consumption. This has led the IPCC to conclude that '[e]missions of CO_2 due to fossil fuel burning are virtually certain to be the dominant influence on the trends in atmospheric CO_2 concentration during the 21st century'.[8(p.12)] Thus, reducing energy-related carbon emissions has become a priority in the current debate surrounding climate change.

1.2 Technical options for reducing carbon emissions

> 'We need to actively reduce our dependence on fossil fuels, moving to a low-cost, carbon-free energy system, focusing on renewables and on energy-efficiency gains.'
>
> David King[9(p.781)]
> Chief Scientific Adviser (2000–2007), UK

Achieving climate change targets will require significant technical changes to the way that energy is supplied and used. The Kaya identity[10,11] expresses the generation of energy-based carbon emissions as the product of four drivers: population, affluence, energy intensity and carbon intensity. It has been used widely in literature, for instance in papers by Schipper *et al.*,[12] Ramanathan,[13] and Raupach *et al.*,[14] and forms the basis for the scenario models used in the IPCC assessment models.[4,8,15,16] It can be written in equation form as:

$$\text{Carbon} = \text{Population} \times \frac{\text{GDP}}{\text{Population}} \times \frac{\text{Energy}}{\text{GDP}} \times \frac{\text{Carbon}}{\text{Energy}} \tag{1.1}$$

The first two terms of the equation are socio-economic drivers. Placing limitations on population growth or access to economic wealth is unpopular, despite being influenced to some degree by political choices. Energy and carbon intensity (the third and fourth terms) are technical drivers influenced by trends in design and innovation. Thus, the technical options for reducing carbon emissions are to use energy more efficiently (which lowers energy intensity) and to de-carbonise the energy supply (which reduces carbon intensity).

A simple projection for 2050 is used to illustrate the large technical changes that will be required to balance modest forecasts of population and affluence. According to UN report, *World Population Prospects*,[17] the global population is estimated to grow from 6.5 to 9 billion over the period 2005 to 2050. Using Equation 1.1, this has the effect of multiplying CO_2 emissions by approximately one and half times. During the same period, the IPCC[8] expects global per capita income to rise by around 2% per year, or two and a half times by 2050. To maintain current CO_2 emission levels with this increase in the socio-economic drivers, will require a four-fold improvement from the technical drivers. Achieving this target will be demanding, and yet this makes no additional allowance for actually reducing annual carbon emissions to the atmosphere.

Emission reduction strategies have to date focused primarily on carbon intensity, by substituting carbon intensive fossil fuels with low-carbon energy sources. This bias is reflected in the

International Energy Agency (IEA) figures for worldwide research and development expenditure, where less than 10% is allocated to energy efficiency in comparison with 40% for nuclear fission and fusion.[1(p.173)] Viable decarbonisation options include switching to less carbon intensive fuels (for instance, from coal to natural gas), developing more renewable energy sources (for example, solar, wind, wave and geothermal energy), increasing the use of bio-energy (from wood and plants) and nuclear energy, or by developing Carbon Capture and Storage (CCS). Numerous publications describe the potential of such technologies, including the papers *Decarbonization: doing more with less* by Nakicenovic[18] and *Renewable energy strategies for sustainable development* by Lund.[19] Despite enthusiastic lobbies for nuclear and renewable energy and the apparent political preference for supply substitution, there is little evidence that sufficient renewable energy supply will be available to reach carbon emission targets.

MacKay[20] demonstrates in his book *Sustainable energy—without the hot air* that even before considering economic and social barriers, there is not sufficient renewable energy potential to meet current UK demand for energy. Van der Veer, the ex-chief executive of Royal Dutch Shell, explains that most Americans and Europeans believe renewable energy will replace fossil energy supply by 2050, whereas even the most optimistic forecasts involving significant technological breakthroughs limit the growth of renewable energy to around 30%.[21] Such opinions are supported by the IEA in their aggressive *BLUE* scenario which targets a 50% reduction in CO_2 emissions from current levels by 2050. They estimate that 21% of the emissions savings will come from renewable energy, 19% from CCS, 18% from fuel switching and 6% from nuclear generation. In comparison energy efficiency accounts for 36% of the estimated saving,[1(p.65)] and this figure is over and above the generous 0.9% per year baseline efficiency improvements. Energy efficiency gains can also be achieved at lower marginal costs than the alternatives.

If the forecasts above are correct, then a shift in engineering focus is required towards the development of energy efficieincy technologies.

1.3 Engineering: key to a low carbon future

> 'The engineering profession is uniquely placed to understand what technologies can be deployed to reduce carbon dioxide emissions as efficiently and effectively as possible because we are responsible for designing and developing new products and technologies.'
>
> Sue Ion[22]
> Vice-President of the Royal Academy of Engineering, UK

Engineers have a responsibility to be actively engaged in the climate change debate. Ulaby[23] states that it is important for scientists and engineers to remain at the centre of the climate change discourse. He laments, however, that the climate change debate 'has been co-opted by politicians whose agendas are more economic than scientific'.[23(p.1471)] Engineers, according to Ion,[22] are ideally placed to understand technologies that deliver materials, processes, products and services to society with significantly lower carbon emissions.

Nevertheless, it is simplistic to assume that technical efficiency solutions alone will lead to a corresponding reductions in carbon emissions. Gutowski[24] explains that introducing a new technology not only reduces environmental impact, but also acts to stimulate the economy, thus driving up per capita income. This is known as the *rebound effect* or *Jevons' paradox*,[25] after the economist's observation that producing and using a resource more efficiently (in his case coal) often led to greater consumption of the resource, rather than less (see Alcott[26] and Polimeni and Polimeni[27] for a discussion of this effect).

Princen[28] suggests that the dominant logic of coupled efficiency and expansion should be replaced with *sufficiency*. He argues that society should not only use energy more efficiently, but it must at the same time reduce energy consumption. Jevon's paradox is real and unavoidable, and requires a politically created constraint on total energy consumption to compliment technical advances in energy efficiency. Efficiency is concerned with delivering the most possible goods and services within the constraints that society places on energy use. Efficiency does not lead to demand reduction, but reduces the 'pain' of reaching the chosen reduction target. Engineers must be engaged in every aspect of this process, from the development new technical solutions to improve efficiency, to the debate concerning the wider economic and political implications of energy policy.

1.4 Organisation of this thesis

'All agree that *something* must be done urgently, but *what*?'

David MacKay[20(p.2)]
Author of *Sustainable energy—without the hot air.*

So, where should engineers focus their efforts? Are the greatest efficiency gains to be found in light bulbs or diesel engines, insulating houses or improving coal-fired power stations? What are the limits to energy efficiency? How should future research priorities be directed?

This research aims to provide a rational basis for assessing all future developments in energy efficiency. The task is approached in much the same way as MacKay tackles energy supply, in *Sustainable energy—without the hot air.*[20] It intentionally avoids ethical questions concerning how much energy humans should consume, or how best to distribute energy fairly between nations and people groups. Neither does it debate the sustainability of future growth in population, wealth and resource consumption. Instead it uses simple physical models to determine the fundamental limits to energy efficiency, limits which unlike economic or political benchmarks, do not change.

The analysis is global, and therefore imprecise. Energy quantities are rounded to the nearest exajoule ($\mathrm{EJ} = 10^{18}\,\mathrm{J}$), roughly the total primary energy supply of Portugal. It deliberately focuses on the technical pieces of equipment—'conversion devices' like engines and furnaces, and 'passive systems' such as cars and houses—where engineering solutions can be practically applied, rather than compare economic sectors or historical efficiency trends.

The chapter outline for this thesis is as follows. Chapter 2 presents a summary of techniques for measuring energy efficiency and reviews previous attempts to assess the potential of energy efficiency options. In Chapter 3 , a global map of energy flow from fuels to final services is constructed, allowing the identification of the technical components where large efficiency gains are likely to be found. A novel distinction is made between conversion devices, which upgrade energy into more useable forms, and passive systems, from which energy is lost as low temperature heat, in exchange for final services. The theoretical efficiency limits for energy conversion devices are explored in chapter 4 and the practical efficiency limits for passive energy systems, in chapter 5. Finally, in chapter 6 the implications of the research are discussed and a list of future research projects is proposed.

Together, these chapters aim to provide a thorough exploration into the *engineering fundamentals of energy efficiency.*

2 REVIEW: PRIORITISING ENERGY EFFICIENCY OPTIONS

In the 1975 conference *Efficient use of energy*, Ford *et al.*[29] state that the primary objective of any technical energy study is to define a target 'standard of performance' against which current energy consumption can be compared. Targets may be chosen from several different options, for example: current best practice, the extrapolation of an historical trend, the projected gains from a specific design innovation, or a fundamental physical limit. The difference between today's energy use and this target provides a measure of the possible energy savings, in a device, system or energy sector. This can be expressed as:

$$\begin{array}{c}\text{Potential for}\\ \text{saving energy}\end{array} = \begin{array}{c}\text{Scale of}\\ \text{energy flow}\end{array} \times \left[1 - \frac{\text{Target energy use}}{\text{Current energy use}}\right] \qquad (2.1)$$

The *scale of energy flow* can be measured using a variety of units—for example, joules, barrels of oil, cubic metres of natural gas, or economic cost—each with its own advantages. Furthermore, global energy flow can be broken down according to different groupings, such as regions, countries, economic sectors, technical devices, or consumer products. The first two sections of this chapter explore the diverse ways of measuring energy (§2.1) and methods for allocating energy use to activities (§2.2).

The ratio of *target energy use* to *current energy use*, is a simple proxy for energy efficiency. This measure and thus the potential for saving energy can vary greatly depending on the specific target performance that is chosen. For example, if a target constrained by market forces is selected then the *economic potential* is found, whereas a *technical potential* sets a target based on practical design and material limitations, and a *theoretical potential* reflects the constraints of thermodynamic limits. Figure 2.1, which is adapted from Dyer *et al.*[30 (p.4437)] summarises these approaches for calculating possible energy savings and demonstrates with indicative values the wide range of performance targets.

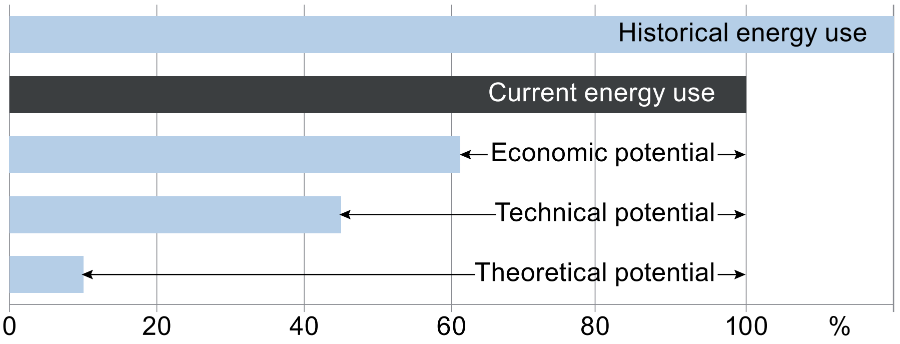

Figure 2.1 Diagram of the potential gains from energy efficiency

Selecting a suitable target efficiency that is both objective and technically defensible is essential if the full potential of efficiency measures is to be gauged. Basing long-term targets on economic potentials—by tracking historic efficiency indicators or surveying known technologies—is risky because future economic drivers are difficult to forecast over long time periods. This is in contrast to technical and theoretical efficiency limits which do not vary with time. The third section of this chapter (§2.3) presents a critical review of the current methods used for predicting future efficiency gains, divided into four groups: comparative methods, top-down models, bottom-up models and theoretical models.

In the fourth section (§2.4), a new technical framework for assessing future efficiency gains is proposed. The overall structure of this chapter is summarised in figure 2.2.

2.1 Units for measuring energy

Smil[31] in his book *Energy in nature and society*, provides a system-

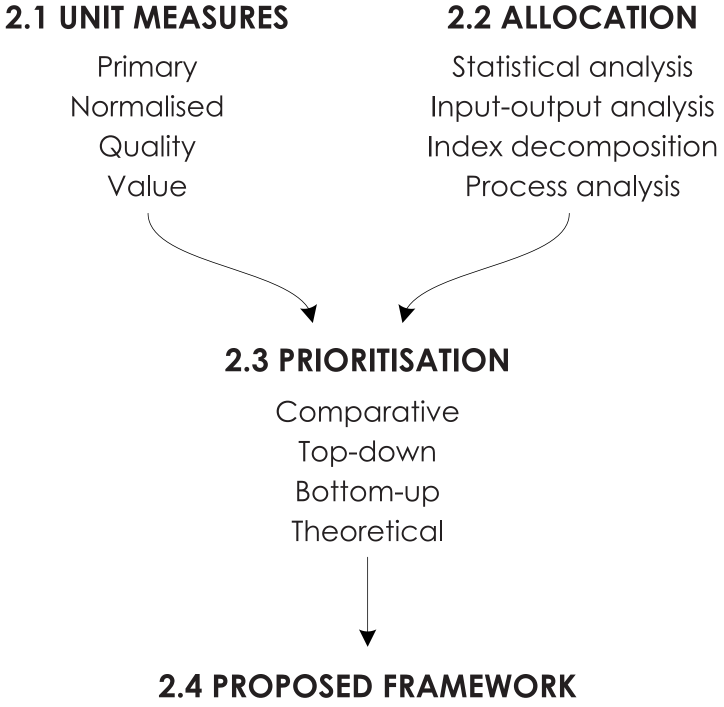

Figure 2.2 Outline of chapter

atic study of the energy sources, storages, flows and conversions, which form the complex energy network. The primary aim of this field of study, known as *energetics*, is to select unifying energy metrics which allow energy flows and transformation to be compared. Selecting an appropriate unit of measure is challenging.

A variety of measures have been proposed and used historically, but none has gained absolute universal acceptance. The most established is the simple unit for energy, the joule (J), which is useful for measuring the conversion of energy from one form to another. Alternative units have been developed: to make comparison simpler, to measure the quality of energy in addition to quantity, and to allow integration with economic measures. Various units for measuring energy use have been organised into four groups, as shown in table 2.1, and are described in this section.

Table 2.1 Units for measuring energy use

Group	Measure	Units
Primary	Energy	J, BTU, kcal
	Fuel energy	toe, boe, tce
	Electricity	kWh
	Fuel mass	kg
	Carbon dioxide	$\mathrm{t\,CO_2}$
Normalised	Energy intensity	J/£, J/kg
	Carbon intensity	$\mathrm{t\,CO_2}$ /J, $\mathrm{kg\,CO_2}$ /kWh
Quality	Entropy	J/K
	Exergy	J
Consumer	Price	£, $

2.1.1 *Primary measures*

Primary energy is the term used to describe the energy contained in raw fuels. Bullard and Herendeen[32 (p.268)] state that 'primary energy is extracted from the earth, is processed by the economy, and ultimately gravitates to final demand'. Energy is conserved through this process, according to the first law of thermodynamics, allowing final energy use to be calculated from fuel consumption data using conventional energy balance methods. The energy content of fuels can be measured directly in joules, or with the use of proxies such as mass, volume or carbon dioxide emissions. Most official statistics are published using primary energy units to measure supply or demand.

Consumption of primary energy is commonly measured in joules (J). Alternative energy units include British Thermal Unit (BTU) which is equal to 1,055 J, and kilogram calorie (kcal) which is equal to 4,184 J. Hydrocarbon fuels contain chemical energy and when combusted release energy which can be used to provide heat or converted into useful work. The most widely used fuels are oil, natural gas and coal. Consumption of electrical energy—which is not considered a form of primary energy—is compared with primary energy consumption by taking account of the particular mix of fuels used to produce the electricity, the conversion efficiency of power stations and the transmission and distribution losses. Electricity consumption, including energy from hydroelectric, renewable and nuclear sources, is normally measured in watt-hours (1 Wh equals 3,600 J).

Several *proxy* units of measure are used for convenience. Due to the dominance of oil and coal in international trade, energy statistics for fuels are normally quoted in homogenised units, such as tonnes of oil equivalent (toe), barrels of oil equivalent (boe), or tonnes of coal equivalent (tce). Consumption of natural gas is typically measured in normal cubic metres (m^3). Using mass or volume proxies allows comparisons to be made between differing fuels, however errors can arise in the conversion process if accurate enthalpies of combustion are not available.

More recently, primary energy consumption has been equated with environmental impact from the release of greenhouse gas (GHG) emissions to the atmosphere. GHG emissions are typically measured in equivalent tonnes of carbon dioxide ($t\,CO_{2e}$) using a 100-year weighting system from the IPCC.[8(pp.388–389)] Carbon dioxide emissions resulting from the combustion of fuels can be calculated using tables based on the stoichiometric products of combustion. Emissions derived from the production of electricity are estimated from a country's specific generation mix. For example, the United Kingdom (UK) DEFRA[33] has published emission factors (in $kg\,CO_2$ /kWh) for various fuels and for electricity supplied from the public network. The use of environmental pressure indicators, such as carbon dioxide, is valuable for focusing attention on the impacts of energy consumption.

Measuring energy use with primary measures is popular and well-understood. The use of simple units allows for uncomplicated aggregation and avoids the introduction of errors through additional mathematical manipulations. Energy quality and embodied energy are not implicitly measured, leading to some ambiguity when system boundaries are not defined carefully. Giampietro[34] also argues that the amount of useful work delivered to an economic system is more relevant than the amount of primary energy consumed. However, the use of primary measures affords comparison of direct energy consumption and provides an overall basis from which to prioritise energy reduction.

2.1.2 Normalised measures

The normalisation of energy data permits more meaningful comparisons between data groups (i.e. countries, sectors, processes or materials). Normalisation refers to the statistical method of dividing data series by a common variable. This permits the essential features of the data to be compared in the absence of any influence from the isolated variable. The most commonly used ratio or indicator is *energy intensity*, which broadly refers to the energy consumed per unit of activity, for example, energy consumption per unit of economic output (J/£). According to Schipper *et al.*,[12] the use of energy intensity allows for the comparison of wide ranges of data, but at the expense of inaccuracies introduced by using an economic normalisation variable.

Carbon intensity refers to the normalisation of carbon dioxide (CO_2) emissions on the basis of energy consumption ($t\,CO_2$ /J) or electricity generation ($t\,CO_2$ /kWh). This measure is commonly used to rate the environmental impact of different energy supply options. The term *carbon footprint* has been used more recently to define the CO_2 emissions per year ($t\,CO_2$ /year) for a person, household, organisation or country. Despite using the term 'footprint', it does not refer to a physical footprint of land and therefore differs in concept from the unit *ecological footprint.*

A separate approach measures energy consumption or carbon emissions, per unit output of final service. Patterson[35] describes this as physical-thermodynamic indicator for efficiency, expressed as:

$$\eta = \frac{\text{physical output (useful)}}{\text{energy input}} \tag{2.2}$$

or the inverse of this ratio, which Phylipsen *et al.*[36] have defined as the Specific Energy Consumption (SEC). Lovins, for example lists functions for the residential sector as: 'space heat, water heat, air-conditioning, refrigeration, cooking, lighting, clothes drying and other electrical'.[37(p.80)] Access to detailed physical data enables energy intensity to be defined in physical terms—for example, energy consumption per mass of clothes dried (J/kg). More recently, Schenk and Moll[38] have argued that the use of such *physical indicators* leads to a better understanding of energy consumption, whereas Farla and Blok[39] and Schipper *et al.*[12] settled on a hybrid approach using a mix of physical and monetary indicators for industry, manufacturing and service sectors, but relying on physical indicators alone for transport, freight and households.

These studies are useful for identifying structural changes in energy use over several years. However, considerable debate exists over the most appropriate intensity ratio for assessing changes in energy use patterns and no one measure is appropriate for all data. Smil proposes the use of fundamental unifying energy metrics, such as power density (W/m^2) and energy intensity (J/kg), for comparing energy flows and transformations, but also makes the qualifying statement that:

> 'There is no single or best yardstick to assess the performance of energy transformations; the most commonly used ratio is not necessarily the most revealing one; the quest for the highest rate is not always the most desirable goal; and inevitable preconversion energy losses may be far greater than any conceivable conversion improvement'.[40(p.15)]

Despite this, normalisation measures are particularly valuable for economic-statistical methods such as input-output analysis and index decomposition. Normalised energy data can also be compared easily to defined *benchmark* values, average consumption figures and Best Available Technologies (BAT).

2.1.3 Quality measures

Whereas primary and normalised measures are firmly based within the thermodynamic principle of energy conservation, *quality measures*, in addition, attempt to incorporate the second law of thermodynamics which asserts that energy has quality as well as quantity. Ahern[41] explains that 1 J of energy at 1000 K can perform more work than 1 J of energy at 100 K. Therefore, energy at a higher temperature is more valuable than energy at a low temperature. Work is a higher quality form of energy than heat since work can be completely converted to heat, whereas not all heat can be converted to work. Ford *et al.*[29] states that work is consequently the most valuable form of energy, equivalent to heat at infinite temperature. The same high value is given to electricity which for practical purposes is interchangeable with work.

In any real conversion process energy is degraded to a lower quality, meaning less work is available for any subsequent process. Irreversibilities in real processes are observed as an increase in entropy (S), that is not matched by an equivalent production of work. Thus minimising the generation of entropy is equivalent to conserving the quality of energy. Entropy is useful for defining the minimum theoretical energy requirement for a process, as demonstrated in the iron and steel making study by de Beer *et al.*[42] It is also a measure of the disorder or randomness of a system, and unlike energy, is not conserved.

In thermodynamic literature entropy is described as an extensive state variable (proportional to the size of the system) that is definable for any material substance or any system, and measured in joules per kelvin (J/K). It is calculated using the differential quantity $dS = \delta Q/T$ where δQ is the amount of heat absorbed in a reversible process (for a system state change), and T is the absolute temperature. However, Çengel and Boles[43 (p.331)] also describe entropy as a 'somewhat abstract property'. The problem for engineers is that classical thermodynamic approaches to reversible (ideal) and irreversible (real) processes involve complex physical and mathematical proofs, often bounded by specific theoretical conditions. These bear little resemblance to real processes and make aggregation of energy data problematic. In response, an engineering form of thermodynamic property entropy has been developed: exergy.

Exergy (B) is a measure of both resource quantity and quality, and is useful for aggregating heterogeneous energy sources and materials. Exergy can be defined as 'the potential work that can be extracted from a system by reversible processes as the system equilibrates with its surroundings', from Ayres.[44(p.192)] Other descriptions include: 'available work', 'the useful part of energy', 'the potential to do work', 'free energy', 'work capacity', and 'the useful work obtainable from an energy source or material' (see Ford *et al.*[29], Giampietro[34], Ahern[41], Cleveland *et al.*[45]). Exergy uses mechanical work rather than energy as the measurement basis—mechanical work being the highest quality, lowest entropy form of energy. Like energy, exergy is measured in joules (J).

Exergy can be neatly divided into four components: kinetic, potential (gravitational or electromagnetic), physical (pressure or temperature) and chemical. For most energy conversion processes only the chemical component of exergy is significant. Chemical exergy measures the available work, normally referenced relative to either the earth's crust, ocean or atmosphere, as discussed by De Meester *et al.*[46] Therefore, the standard chemical exergy per mole (B) is defined in reference to an equilibrium state (temperature (T_0), entropy (S_0) and the component species (μ_{i0})) found in standard exergy tables, for example Ayres and Ayres.[47(Appendix B–D)] Exergy is mathematically defined as:

$$B = (H - H_0) - T_0(S - S_0) + \sum_i N_i(\mu_i - \mu_{i0}) \tag{2.3}$$

where H denotes enthalpy and Ni are molar fractions of the chemical elements.

Exergy values for many material resources have been previously calculated. For fossil fuels, the ratio of chemical exergy to net calorific value is close to unity—exergy values are only 4–11% higher for typical fuels according to Ertesvag and Mielnik.[48(p.959)] The difference results from the inclusion of post-combustion water vapour (lower heating value) and flue-gas components in the exergy calculation. The conversion of heat, a lower quality form of energy, to exergy (or mechanical work) is performed by multiplying the heat energy by the reversible Carnot engine equation: $|\frac{T-T_0}{T}|$, where T is the temperature of the heat carrier and T_0 is the ambient temperature, both in Kelvin.

Despite the potential of exergy as an absolute measure of energy quality, it is seldom used in global energy analysis. De Meester *et al.*[46] reasons that exergy data for many resources, in particular mineral resources, is still incomplete and inconsistent. However, perhaps a greater barrier is the conceptually challenging nature of quality measures, and the economic preference for the more crude unit of measure, primary energy.

2.1.4 Value measures

The *price* paid for energy is perhaps the most comprehensive measure of the *utility* of a fuel. In neoclassical economic theory the price of a fuel (per energy equivalent) equals its marginal value product, or economic usefulness. Cleveland *et al.*[45] argue that a fuel's price encompasses factors such as energy density, scarcity, cleanliness, emission profile, flexibility and ease of storage. Price is therefore a value-based unit of measure. Economic transactions are measured in monetary currencies such as the British pound (£) or the United States of America (USA) dollar ($). For multi-country studies, transaction data is adjusted according to currency exchange rate indexes or Purchasing Power Parities (PPP) databases (for example the International Financial Statistics (IFS) database which is maintained by the International Monetary Fund (IMF)). Price data collated over longer time periods must be corrected for inflation.

The most obvious benefit of using price to measure energy is the availability of detailed data for analysis. Accounting practices ensure that energy production and consumption is measured in monetary terms at all levels of society. Price based measures are also familiar to consumers. However, the use of value measures is not immune to market imperfections—Cleveland *et al.*[45] report that energy prices often fail to include many negative social and environmental impacts (externalities) associated with energy consumption.

There are numerous ways to measure energy, each with its own advantages. Ideally, for a physical based study, a quality measure of energy would be chosen. Yet, Giampietro[34 (p.177)] comments that the 'history of energy analysis is the history of the struggle with the conundrum of how to deal with the problem of aggregation of energy forms of different quality'. In practice, the unit of measure is more likely to be selected based on the coverage and accuracy of the available energy data.

2.2 Allocating energy into suitable groupings

In order to compare the energy efficiency of two conversion devices, the energy flow through each device must be known. Several different approaches have been developed to allocate energy flow to diverse grouping such as countries, sectors, conversion devices or

Table 2.2 Methods for aggregating energy use

Method	Advantages	Limitations
Statistical analysis	Simple, established and commonly used; broad coverage	Measures only first order, direct inputs; errors from survey collection practices and aggregation methods
Input-output analysis	Aggregates data at the sectoral level; accounts for higher order inputs (direct and indirect)	Data collection is both time-consuming and error prone; conversion from monetary value to energy use is difficult
Index decomposition	Separates out the impacts of influencing variables; provides understanding	Mathematical models introduce errors; neglects contributions from non-energy emissions
Process analysis	Accurate and specific within a defined system boundary; highlights possible energy savings	Conditional on the chosen system boundary; truncation leads to errors

products. Four methods for collecting, ordering and allocating energy consumption data are described in this section; these are summarised in table 2.2. Three of the analysis methods—statistical, input-output and process—are derived from the original work of Chapman[49] in 1974. Input-output analysis and process analysis were also described in detail by Bullard *et al.*[50] four years later. Index decomposition, a more recently developed method, has been added to the list. A brief description of each method is given, followed by literature examples and a discussion of the advantages and limitations of each approach. The best choice of methodology is determined case by case, taking into account the accuracy of the energy data, the chosen unit of measure, the data coverage and the system boundary of the study.

2.2.1 Statistical analysis

General statistical energy data is collected and published by international organisations, governments, industry sector associations and large companies. Energy data is normally extracted from surveys completed by relevant stakeholders and published typically on a yearly basis. Attention is focused on primary energy from fossil fuels (coal, oil and gas) and electricity (nuclear, hydro and renewable sources) because it is easier to collect data from large centralised energy systems. Energy sources such as food, direct sunlight and biomass are typically ignored, despite preliminary estimates by Haberl[51] revealing that unaccounted biomass contributes 235 EJ/year or 39% of global human 'energetic' needs. The law of energy conservation allows primary energy data to be divided up according to various groupings and tracked through numerous energy transformations. Thus *snapshots* of energy use in society can be taken from almost any angle and energy data can be aggregated by simple addition.

Several international organisations collate primary energy data at a global level and publish annual energy reports. Examples include the United Nations (UN) *Energy Statistics Yearbook 2003*,[52] the International Energy Agency (IEA) *World Energy Outlook 2004*[53] and the World Energy Council (WEC) *Survey of Energy Resources 2004*.[54] In addition, some private companies report on global energy data, for instance BP[55] and Enerdata.[56] International publications report on trends in overall energy consumption rates and also track changes in energy distribution over time and between energy sources, countries and sectors. Entities such as the European Union (EU) and the Organisation for Economic Cooperation and Development (OECD) collate regional energy data from member countries.

In most cases, global energy data is sourced from the governmental agencies of individual countries. Government agencies typically publish their own energy statistics, for example, the UK

Department of Trade and Industry (DTI)[57] and the USA Energy Information Administration (EIA).[58] Detailed energy data is collected from numerous sources including trade records, private companies, government department records and fuel tax accounts. Trade sector associations represent commercial and industrial sectors at international and national levels and collect energy data from detailed surveys. Two such associations include the World Coal Institute[59] and World Steel.[60] Large companies aggregate energy information across numerous sites in order to assess performance against targets. Energy benchmarking of this type, especially in relation to climate change impacts, is an important aspect of corporate sustainability reporting.

Recent attention to climate change impacts has prompted organisations to collect and publish GHG emission data. From a global perspective, two reports are particularly valuable: *Navigating the Numbers* from the World Resources Institute (WRI)[7] and *Key GHG Data* produced by the United Nations Framework Convention on Climate Change (UNFCCC).[61] The UK Carbon Trust[62] has made an ambitious attempt to attribute carbon emissions from primary fuel consumption throughout multiple levels of the economy. Six 'carbon accounts' were chosen, culminating at the level of 'high-level consumer needs' including: recreation and leisure, space heating, food and catering, household, health and hygiene, clothing and footwear, commuting, education, other government and communication. Such methods of redistributing carbon emissions are important for linking consumer actions directly with environmental impacts.

Some reservations remain over the accuracy of statistical data analysis. Energy data is derived from first order energy inputs (or direct inputs) and therefore excludes energy inputs from higher orders. For example, the energy used in the process of refining oil or the energy required for construction of a steel mill, is typically ignored. Farla and Blok[63] also point out that survey collection practices are subject to errors from: incomplete surveys, limited sector coverage (requiring scale-up), errors in interpreting questionnaires and publication mistakes. Accounting for discrepancies in energy definitions, energy types, system boundaries, non-energy use and industry classifications, causes further errors according to Karbuz.[64] For these reasons, global energy statistics from different organisations rarely agree, and the aggregation of energy data from several different sources is difficult. However, statistical methods are well established, accepted and readily available for making energy comparisons.

2.2.2 *Input-output analysis*

Input-output analysis is an economic-statistical approach used to determine energy demand at lower sectoral levels. Monetary values of transactions between various sectors of an economy are collated into a square input-output matrix. Each sector is listed as a supplier (in rows) and a consumer (in columns) in the input-output matrix. For a matrix A, the element A_{ij} represents the supply of resources from a sector i in order to produce one unit of output from the sector j. The matrix approach has advantages over primary energy analysis because a *total* energy demand for each sector can be calculated which sums all direct and indirect energy inputs. This is demonstrated in the following input-output matrix example, adapted from Boustead and Hancock.[65]

Table 2.3 shows that to produce 1 unit of steel requires 0.1 units of steel and 0.2 units of electricity, and to produce 1 unit of electricity requires 0.3 units of steel and 0.4 units of electricity. These values measure the first-order or primary resource demand, and can be written mathematically as the matrix A.

The second order consumption for steel and electricity can be calculated using the same matrix, as shown in table 2.4.

Therefore the matrix for the second order consumption is:

$$\begin{vmatrix} 0.07 & 0.15 \\ 0.10 & 0.22 \end{vmatrix} = \begin{vmatrix} 0.1 & 0.3 \\ 0.2 & 0.4 \end{vmatrix}^2 = A^2$$

Table 2.3 Input-output matrix example

	Consumer	
Supplier	Steel	Electricity
Steel	0.1	0.3
Electricity	0.2	0.4

$$A = \begin{vmatrix} 0.1 & 0.3 \\ 0.2 & 0.4 \end{vmatrix}$$

It can be shown that the third order consumption corresponds to A^3 and so forth. The total resource consumption B is given by:

$$B = A + A^2 + A^3 + \ldots = (I - A)^{-1} - I \tag{2.4}$$

where I is the identity matrix.

Input-output analysis was originally developed by Leontief[66] to predict the economic effect caused by changes to an individual sector or industry. Vringer[67] shows that if energy sectors (e.g. coal, crude oil, natural gas, nuclear and hydro-electricity) are included in the matrix, energy demand can be attributed to each economic sector. The total energy requirement of final delivered goods is calculated by applying mathematical operators to the matrix in the form of the energy intensity vectors or physical intensity vectors.

The use of input-output analysis to determine total energy requirements was first applied in 1975 by Bullard and Herendeen[32] using 1967 data covering 357 USA sectors, and by Wright[68] using 1968 data covering 90 UK sectors. Other country specific energy

Table 2.4 Second order consumption for a unit of steel

To produce	0.1 units of steel	0.2 units of electricity	Total
Steel	$0.1 \times 0.1 = 0.01$	$0.2 \times 0.3 = 0.06$	0.07
Electricity	$0.1 \times 0.2 = 0.02$	$0.2 \times 0.4 = 0.08$	0.10
To produce	0.3 units of steel	0.4 units of electricity	Total
Steel	$0.3 \times 0.1 = 0.03$	$0.4 \times 0.3 = 0.12$	0.15
Electricity	$0.3 \times 0.2 = 0.06$	$0.4 \times 0.4 = 0.16$	0.22

analyses have been performed as economic input-output data has become available. Recent studies have also focused on: the energy impacts of trade between nations (for example, Mongelli *et al.*[69]); quantifying CO_2 emissions at the sector level (Rhee and Chung[70]); and evaluating energy-use in specific sectors such as household consumption (Kok *et al.*[71]).

The following limitations to input-output analysis have been summarised from Boustead and Hancock,[65] Bullard and Herendeen[32] and Wright:[72]

Monetary values Equating monetary transaction data with physical fuel quantities is difficult. The conversion depends on choosing accurate energy intensity values; these cannot account for fuel price variances between sectors, large and small consumers, and over time.

Available data Input-output data is collected separately from other national statistical data. The process is both time consuming and costly. Thus input-output data is often released several years late and not all countries collect data, preventing energy comparisons on a global scale.

Data accuracy Data is collected from industries and companies using surveys. Incomplete sector coverage, variance in collection methods and differing time periods lead to data error. Further inaccuracies are introduced from companies which produce multiple products of varying energy intensities. The approach also fails to capture the embodied energy in capital goods and non-combusted fossil fuels.

Trade The effect of imported and exported goods on energy-use is difficult to quantify. Typically it is assumed that foreign technology has the same energy intensity as domestic technology in the absence of accurate data from exporting countries.

Despite these limitations, input-output analysis has proved valuable for establishing sectoral trends for energy consumption.

2.2.3 Index decomposition

Index decomposition—sometimes referred to an indexing or factoral decomposition—is an approach used for isolating the drivers for change in resource consumption, over a time period. The technique has been applied to food, water, transport, manufacturing and household resource use. The recent trend to set and compare national energy efficiency and carbon emissions targets has resulted in numerous studies which decompose energy and carbon emission indicators.

Hoekstra and van der Bergh[73] report that decomposition begins with the identification of a suitable indicator, sub-groups and a time period, for which the driving forces are to be examined. Indicators for energy related decomposition include absolute energy use, energy intensity, carbon intensity and CO_2 emissions. Energy data may be disaggregated into sub-groups (sector, country, fuel type, etc.) according to the availability of data over the selected time period. The collected data is then decomposed to isolate the effect of drivers such as structural changes (e.g. the shift from heavy industry toward commercial activities), demand changes (increased overall resource consumption) and technology changes (which result from improved efficiencies of processes), for example see Liu and Ang.[74] Decomposed data can also be reaggregated into new groupings to reveal more valuable information.

According to Schipper *et al.*[12] decomposition of changes in energy use (E) can be described by the ASI equation:

$$E = \sum A_i \; S_{i,j} \; I_{i,j} \tag{2.5}$$

where A represents overall sectoral activity (value added) in each sector i, S is the structure of each sector i expressed as a share of subsector j, and I represents the energy intensity of each subsector j (in S).

If the dimension of fuel mix is introduced, changes in CO_2

emission (G) can be decomposed using:

$$G = \sum A_i \; S_{i,j} \; I_{i,j} \; F_{i,j,k} \tag{2.6}$$

where F represents the carbon content of each fuel k, used in subsector j of sector i. The Kaya identity (discussed in section 1.2) is frequently used in climate change literature for decomposing CO_2 emissions. Numerous decomposition models have been proposed; these can be divided by their mathematical form into additive or multiplicative models, as demonstrated by Hoekstra and van der Bergh.[73] A substantive review of energy and environmental decomposition studies has been performed by Ang and Zhang.[75] The authors classify 124 studies by: application area (energy and emissions), indicator type (quantity, ratio/index and elasticity) and decomposition scheme (multiplicative/additive and specific method).

Decomposition studies are valuable for separating out the effects of various influencing variables. Nevertheless, the method is limited by the accuracy of energy data (normally statistical or input-output based) and the choice of drivers. Care must be taken to avoid attributing changes to a single driver which in practice is influenced by several others factors, or overlooking large increases in one variable which are cancelled out by reductions in other variables, resulting in almost no variation at the indicator level. When used to decompose carbon emissions, the technique cannot account for non-energy related emissions nor the use of industry feedstock fuels.

2.2.4 Process analysis

For the three top-down approaches described above—statistical, input-output and decomposition—vast coverage of energy consumption comes at the expense of technological richness. *Process analysis* attempts to capture this detail by breaking down complex systems into a network of simple bottom-level operations. Using this modular approach 'all industrial processes, no matter how complex, can be subdivided into a sequence of operations linked by a flow of materials' (Boustead and Hancock[65 (p.71)]). The intention is to account for *all* embodied energy inputs to the system, including contributions from for instance: fuels, raw materials, capital, machinery, maintenance, prior processing of raw materials, transportation of inputs and outputs and business overheads.

Process analysis begins with the selection of a target product, which can be either a good or a service. *Direct* inputs required to make the target product are listed, including both energy inputs (e.g. fuels) and non-energy inputs (e.g. raw materials and machinery). For example, figure 2.3 shows four inputs to a target product, labelled A through D. Next, the *indirect* inputs required for the production of A are listed, and so forth for B, C and D. The final process energy requirement can be calculated by summing energy contributions from all direct and indirect inputs to the system.

Direct energy contributions are relatively easy to measure. Companies normally record inputs (material and energy) and outputs (products and wastes) in both physical and monetary values. However, Lenzen and Dey[76 (p.578)] point out that indirect (higher-order) energy contributions are 'manifold, complex and therefore difficult to assess'. Difficulties arise because of the energy interdependence between processes and industries. Quoting from Boustead and Hancock, 'The steel industry for example supplies a proportion of its output to the electricity industry which in turn feeds electricity to the steel industry'.[65 (p.67)] Energy contributions to capital items such as machinery are particularly problematic when the machine is made from the target product being evaluated. Chapman[49] suggests some practical solutions to deal with such feedback loops, which include estimating an approximate value and iterating or solving using simultaneous equations. Some materials (e.g. steel and cement) and energy sources (e.g. fuels and electricity) are, in practice, inputs to production process in almost every sector.

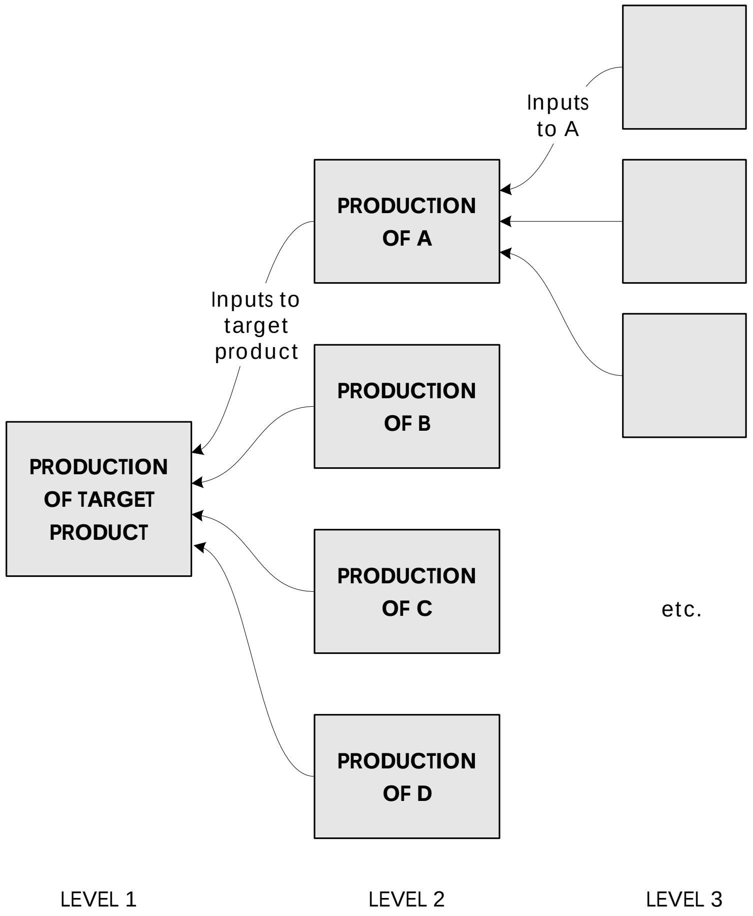

Figure 2.3 Levels in process analysis

In addition to complex feedback loops and interactions, higher-order inputs to a given target product are theoretically limitless. In theory, higher-order contributions diminish in importance allowing truncation of the analysis at a level where additional inputs are insignificant in relation to the sum of all the energy inputs. In practice, Lenzen and Dey[76] have found that for the manufacture of basic iron and steel products in Australia, process analysis underestimated the energy consumption by approximately half (19 MJ/kg), in comparison to input-output analysis (40.1 MJ/kg).

Examples of process analysis in literature include: Bates *et al.*[77] who evaluate potential emissions reductions for the EU transport sector, Michaelis *et al.*[78] and Sakamoto *et al.*[79] who study the iron and steel industry. Hybrid approaches have been proposed by Bullard *et al.*[50] and Treloar[80] to limit errors due to truncation. The hybrid method makes use of the accuracy of process analysis for direct and first-order inputs, and the wider coverage of input-output analysis for higher-order contributions. Thus the truncation errors of process analysis are replaced by smaller aggregation errors of input-output analysis.

Process analysis delivers results that are accurate and specific within a defined system boundary. Its main advantage is the intimate experience gained with the physical processes and equipment which use energy, permitting energy saving opportunities to be identified. However, the extensive energy and material flow data for both direct and indirect inputs makes it unsuitable for large energy studies. Truncation errors and higher-order energy contributions are inherent problems.

Four methods for the allocation of energy flow data have been presented: statistical analysis, input-output analysis, index decomposition and process analysis. If an appropriate unit of measure is selected and energy flow is carefully allocated, then the activities which use energy can be compared on an equal footing. The relative scale of energy use can then be evaluated and avenues for improving energy efficiency explored.

2.3 Determining energy efficiency targets

Good efficiency targets are based upon sound estimates of the potential savings from efficiency measures. This requires accurate energy consumption data, organised into relevant groupings, and a method for identifying and assessing potential efficiency gains. Efficiency studies found in literature range from comprehensive surveys of efficiency technologies to the review of a few isolated case studies, and from the tracking of top-down efficiency indicators to detailed thermodynamic studies.

Four generic approaches to prioritising energy efficiency opportunities have been identified:

Comparative methods which compare energy use or carbon emission data across countries, sectors or products

Top-down models which track historical trends in efficiency indicators and extrapolate these in the future

Bottom-up models which survey best-practice efficiency measures and aggregate the savings

Physical models which calculate efficiency limits based on physics and engineering principles

These approaches are described and critically reviewed below.

2.3.1 Comparative methods

A simple comparison of the energy use in different activities is helpful for identifying where efficiency measures are likely to deliver the greatest gains. For example, some countries consume more energy than others; these countries present an obvious place to begin looking for energy savings. Comparisons are typically made across very different groupings—international regions, countries, industrial sectors, consumer products or time intervals—and are sometimes based on alternative indicators such as carbon emissions.

The *Sankey diagram*, first used by the Irish engineer Riall Sankey in 1898,[81] has become an important graphical tool for comparing the scale of energy flow. In these diagrams the quantity of energy (or sometimes emissions) is traced through society as arrow or lines, with the line width being proportional to energy flow. This allows the dominant energy flows to be quickly identified. An early example, entitled *Pathways to end uses* maps the flow of energy in the United States Summers.[82(p.150)] More recent examples include the *Global energy flows* diagram produced by the IPCC[83(p.259)] and the *Navigating the Numbers, GHG diagram* by the WRI which attributes the worldwide greenhouse gas emissions to end-use activities.[7(pp.4–5)]

Energy and carbon emission data is also compared between industrial sectors and processes. For example, the UK DTI has published energy consumption tables comparing 23 industrial sectors against 9 end-use processes (e.g. lighting, motors, space heating, etc.). The impact of energy reduction initiatives can be assessed by monitoring changes in such indicators over time, and comparing to *benchmark* figures. The USDOE[84] and the EU[85] among others, publish *best-practice* energy technology case studies for comparative purposes.

Comparisons between consumer products are frequently performed using Life Cycle Analysis (LCA) principles. This offers a methodology for counting energy inputs and outputs across all life cycle phases of a product, and the ability to make comparisons with alternative products. The conclusions that result are accurate between equivalent product systems, but are not 'absolute' due to irregularities in boundary system definition. Cullen and Allwood[86] suggest that LCA studies underestimate the impact of indirect energy inputs (i.e. transport, equipment and capital goods) and introduce errors from overlapping product system boundaries, especially between product use phases. A consequence is that when LCA studies are used for prioritisation, they are in danger of overemphasizing the use-phase impacts and overlooking the impacts from indirect activities. For these reasons, Cullen and Allwood warn practitioners to be wary of using LCA for prioritising action.

Recently, several studies have attempted to measure the magnitude of end-use CO_2 emissions from consumer activities. For instance the Carbon Trust[62] compares the impact of 'high-level consumer needs' in order to make consumers aware of the activities that drive carbon emissions and point to possible emission reduction options. Such measures are helpful for highlighting the need for change, and for obtaining information about the latest energy reduction technologies.

Comparative methods make no attempt to quantify the potential to reduce energy consumption, making them largely unsuitable for determining efficiency priorities. Furthermore, statistical energy studies in their current form lack sufficient coverage and technical detail to be useful as a basis for setting global efficiency targets. Two specific problems are discussed in more detail: the failure to trace energy completely from fuels to services and the lack of focus on the technical areas where efficiency gains are found.

Fuel to service: Current statistical energy studies and Sankey diagrams stop short of tracing the entire length of each energy chain, from fuels to services. It is these final services—a comfortable thermal environment, the illumination of a work space, mobility for people and goods—that satisfy human needs and desires, not energy itself nor the complex network of energy chains. By terminating the energy flows at the sector level, current analyses fail to make a distinction between the devices which convert energy into useful forms (e.g. engines, electric motors, furnaces, and lightbulbs) and the energy systems which transform this energy into final services (e.g. vehicles, buildings, and factory systems). Yet devices and systems are interconnected, and energy savings in one reduces the potential for savings in the other.

This idea is explained using an example from the climate change literature. In their paper on stabilisation wedges, Pacala and Socolow[87] suggest two efficiency measures to improve the operation of the world's 2 billion cars in 2054. The first wedge requires increasing fuel economy in cars from 30 to 60 miles per gallon (mpg), saving 1 billion tonnes of carbon (Gt C). The second wedge involves decreasing the average annual travel per car from 10,000 to 5,000 miles per year, also saving 1 Gt C. In each option, half of the total carbon emitted from cars is saved. Yet, if both wedges were implemented perfectly, the reduction in carbon emissions would not equal 2 Gt C—found by adding the savings from both wedges—because this requires the 2 billion cars to produce no emissions at all. Instead, the savings would be only 1.5 Gt C found by multiplying, not adding, the carbon savings. Such examples of overestimating energy and carbon savings are common in the energy efficiency literature.

Significant reductions in energy demand and carbon emissions are available from improving the systems which deliver energy services. Increasing the insulation in buildings and reducing the mass of vehicle bodies are just two tangible examples. However, the separation between devices and systems is seldom mentioned in literature and almost never used in the calculation of practical efficiency limits. Nakicenovic *et al.* introduced the term 'service efficiency', defined as 'the provision of a given task with less useful energy without loss of "service" quality'.[88(p.422)] The intention was to separate efficiency measures, for example using a more fuel-efficient engine, from conservation measures, such as improving the flow of traffic or improving the car aerodynamics. They comment that in many cases, the conversion of energy in upstream devices is highly efficient, yet the 'low efficiency of the last link in the chain, namely the provision of energy services, drastically reduces the overall efficiency'.[88(p.435)]

The Untied Nations Development Programme (UNDP) *World Energy Assessment* report makes a distinction in theory between conversion devices and the 'technology producing the demanded services',[89(p.176)] and provides examples including building materials, window systems, insulation, and light-weight vehicles. They argue '. . . energy efficiency can be improved—and energy losses avoided—during the often overlooked step between useful energy and energy services'.[89(p.175)] However, in the detailed data analysis that follows the potential energy savings are still not separated into devices and systems, but instead aggregated under the broader category of end-use efficieincy.

Technical focus: Current comparative studies will typically trace primary energy through electricity generation, and then divide the energy flows into broad commercial sectors (e.g. transport, buildings and industry) for which statistical data is readily available. This approach proves useful for monitoring a sector's energy use over time or directing high-level energy policy, however it fails to focus on the specific technical components in each energy chain, from which efficiency gains are achieved. For example, electric motors are not found in a single economic sector, but have numerous applications across transport, industry and buildings. Therefore, an efficiency gain in electric motors will translate into savings across all sectors, and yet this is not implicitly clear from current energy Sankey diagrams. Attempts to map energy flows through technical devices have been made at the national level, most notably the United States Department of Energy (USDOE) *Energy footprints* for the industrial sector,[90] however a technically focused global diagram has yet to be published.

Comparative energy studies will continue to be the dominant choice for energy analysts. Knowing the scale of energy flow is critical for determining the potential of efficiency options. Yet for the purposes of this research, current statistical energy analyses fail to trace global energy flow completely from fuel to services, and focus on economic sectors rather than the technical devices and systems where efficiency solutions can be applied.

2.3.2 Top-down models

Scenario based projections of future energy use have become popular for energy policy decision making. Complex macroeconomic models, using top-down analysis, are required for determining the impact of factors such as economic growth, population growth, technology changes, scarcity of resources and climate changes. Scenarios are created by adjusting important variables to evaluate the effect of possible policy interventions. Historical data is collected over multiple years and is used to forecast future trends. Major international energy agencies publish multiple scenario studies including the IEA *World Energy Outlook 2006*,[91] the Intergovernmental Panel on Climate Change (IPCC) *Climate Change 2007:The Physical Science Basis*,[4] and the PricewaterhouseCoopers *The World in 2050*, prepared by Hawksworth.[92]

Top-down models are also used to track historical trends in efficiency indicators and extrapolate these into the future, to determine energy efficiency targets. By extrapolating historical trends in energy indicators, estimates of future advances in efficiency can be made independently of current technology options. For example, in the World Energy Outlook reference scenario, the IEA predicts that the global average energy intensity (a measure of global energy efficiency) will fall on average by 1.7% per year from 2004 to 2030, based on the past 30 year trend.[93] Others make similar projections: IEA[53] predicts global energy intensity (primary energy per Gross Domestic Product (GDP)) will fall by 1.5% per year until 2030; and Pacala and Socolow[87] forecasts a baseline 1.96% per year improvement in carbon intensity (carbon emissions per GDP) over the next 50 years, based on USA goal announced in 2002; and continuous improvements in energy and carbon intensity underpin the projections in the IPCC[16] scenarios.

Long range forecasts are particularly sensitive to small changes in such indicators. Given that historical trends in energy intensity are only documented over short periods (20–30 years) it seems imprudent to extrapolate these trends as far as 50 years into the future. This raises the question of whether economists can accurately model such trends over long periods and thus places the accuracy of long-range forecasting in doubt. Two specific problems with long-range forecasts are presented in further detail.

Firstly, the extrapolated efficiency target may be unachievable because it exceeds some theoretical or practical limit. An annual improvement in efficiency of 1.7% equates to a 35% saving by 2030 and an impressive 55% by 2050. For many technical devices, such gains may not be physically possible, leading to an exhaustion of the innovation potential if alternative solutions cannot be found, as discussed by Blok.[94]

Secondly, these models assume that the underlying structural components of energy demand are stable and predictable over long periods. In contrast, Craig *et al.* assert that:

> '[l]ong-run forecasting models generally assume that there exist underlying structural relationships in the economy that vary in a gradual fashion. The real world, in contrast, is rife with discontinuities and disruptive events, and the longer the time frame of the forecast, the more likely it is that pivotal events will change the underlying economic and behavioural relationships that all models attempt to replicate.'[95(p.87)]

For example, Raupach *et al.*[14] show that the declining trend in global energy intensity from 1980 to 2000, has in recent years reversed, placing in doubt many predictions of future energy demand and associated carbon emissions. The difficulty of making accurate forecasts is also discussed by Farla and Blok,[63] Karbuz[64] and Focacci.[96] In practice, future predictions based on extrapolation of energy trends are rarely accurate, prompting a leading academic in the field of energy, Vaclav Smil, to comment that 'long-range energy forecasts are no more than fairy tales'.[31(p.154)]

Despite advances in modelling techniques and computational power, the engineer should avoid the temptation to view future scenarios as factual. Scenario based approaches are of limited value for setting efficiency targets because they do not assess the potential for energy reduction nor highlight new technical opportunities. They are useful only for predicting short term macroeconomic trends.

2.3.3 Bottom-up models

Bottom-up models survey best-practice efficiency technologies and estimate their combined potential for reducing energy demand. The identification of efficiency opportunities typically involves a detailed review of emergent technologies within a sector or intimate knowledge of an energy system. Mitigation potential is evaluated using energy, carbon and cost metrics, and the scope of analysis can range from case studies to full global assessments.

The case study approach typically starts with an energy reduction target in mind (often appropriated from a scenario) and then searches from the bottom-up for technologies with the potential to reduce energy consumption. Identified efficiency options are then analysed and ranked according to their energy reduction potential. Finally, the individual energy reductions are summed, or scaled up to be compared with the reduction target. Results of case studies are sometimes published in *popular science* format, for example: *Factor Four: Doubling Wealth, Halving Resource Use* by von Weizacker *et al.*,[97] and *Heat: How to Stop the Planet Burning* by Monbiot.[98] This format provides a valuable catalyst for public debate.

Industrial based case studies are often confined to single sector or a selection of individual efficiency options which are relevant to the process operation. Worrell *et al.* state that in many cases 'it is not possible to provide an all-encompassing discussion of technology trends and potentials.'[99(p.2)] Instead, in their report on emerging energy-efficient technologies in industry, they focus on a number of selected key technologies: near net shape casting, membrane technology, gasification, motor systems and advanced cogeneration. This process of choosing technologies is valid for industrial energy analysis, where time scales are short, but can be biased towards current and emerging technologies and risks overlooking a potentially valuable energy saving solution.

Wider scope assessments of efficiency options (and alternative mitigation options) have been performed by various international and governmental organisations. Some recent examples include: the EU *Action Plan for Energy Efficiency*,[100] the IEA *Energy Technologies at the Cutting Edge*,[101] and Her Majesty's Treasury *Energy Efficiency Innovation Review*.[102] These reports are substantial undertakings and typically cover a range of both supply and demand technologies. The *Action Plan for Energy Efficiency*, prepared by the EU,[100] specifically targets technologies within 4 end-use sectors, allowing the projected energy saving per sector to be compared (see table 2.5).

Table 2.5 Available energy savings from end-use sectors

Sector	Current demand 2005 EJ	Business as usual 2020 EJ	Potential savings 2020 EJ
Residential households	10.7	12.9	3.5
Commercial buildings	6.0	8.1	2.3
Transport	12.7	15.5	4.0
Manufacturing industry	11.4	14.6	3.6

Notes: data from EU.[100] $1\,\mathrm{EJ} = 10^{18}\,\mathrm{J} = 26.1\,\mathrm{Mtoe}$

A useful tool for visualising available energy or carbon savings is the abatement cost curve. These curves are constructed by plotting the marginal cost of abatement, for example in $£/\mathrm{t\,CO_2}$, versus the reduction potential in $\mathrm{t\,CO_2}$. Some well known examples of abatement curves include: the *Global climate abatement map* by Vattenfall;[103] the McKinsey Global Institute report, *Curbing global energy demand growth*;[104] the IPCC bottom-up analysis for sectoral mitigation in 2030;[83] the IEA marginal abatement cost curves for sectors in the report *Energy Technology Perspectives*.[1] Such studies provide a useful snapshot of current economic and technological drivers, and show where efficient technologies can be immediately applied.

Nevertheless, bottom-up models in their current form are incomplete for two reasons. Firstly, these models often ignore the complex chains of technical devices and systems in the energy network. Efficiency gains at different points in the network cannot simply be added together, because a saving in one device often reduces the potential for gain in a connected device. For example, a more efficient electric motor requires less electricity for the same load, reducing the demand for generation and therefore the absolute benefit of efficiency gains in that upstream generation.

Secondly, bottom-up models assess only known or emerging technologies that have evolved under today's economic drivers and technical conditions. Surveys of current efficiency options identify mostly incremental gains to existing processes and tend to overlook opportunities from novel disruptive technologies or divergent development pathways, which are beyond the influence of industry. If for instance, the cost of energy were to rise dramatically and hold for several years, then a completely new set of efficiency technologies would emerge, and require the practical efficiency limits to be revised. However, if an absolute measure which is independent of today's economic drivers is used, then the potential savings from future, yet to be invented technologies, can be found.

2.3.4 Theoretical models

When efficiency performance targets are based on the potential of existing technologies, they provide only one possible pathway for future development. They therefore fail to consider alternative pathways which are still unknown, and can become trapped in a particular technology route. Instead, in theoretical models, the targets are based on the theoretical limits to efficiency, derived from fundamental physical laws. Using this approach, current energy use is compared, not to the potential of best practice available technologies which will change with time, but to a fundamental minimum energy requirement which is static. This helps to identify the technical areas where further efficiency gains are likely to be found.

Theoretical models define an absolute target by calculating an upper efficiency limit based on thermodynamics. When using such models it is impossible to set a target which is thermodynamically impossible and the analysis is not constrained by currently known technologies or industrial practice. The thermodynamic property exergy (discussed in section §2.1.3 on quality units of measure) shows how far each device is operating from its thermodynamic ideal, allowing all energy conversion devices to be compared on an equivalent basis.

Detailed exergy models exist for many individual conversion devices and include useful breakdowns of exergy losses. However, the use of exergy modelling has tended to be confined to energy efficiency studies in industry. For example, de Beer *et al.*[42] calculate the minimum theoretical energy required for production of primary steel (using the blast furnace route) and secondary steel (using the electric arc furnace route), as shown in table 2.6.

Table 2.6 Energy consumption for steel 1990

Specific energy required ($\mathrm{GJ/t}_{\mathrm{steel}}$)	Primary steel	Secondary steel
Best practice	19.0	7.0
Minimum theoretical	6.6	negligible
Minimum realistic	†12.5	3.5
World-wide average		24

Notes: †A further reduction of up to 2.5 GJ/t steel may be achieved using heat recover techniques from hot steel. World-wide average is a weighted average of both production routes. Data from de Beer *et al.*[42]

Large differences between *best practice* and *minimum theoretical* energy requirements are noted: 12.4 $\mathrm{GJ/t}_{\mathrm{steel}}$ and 7.0 $\mathrm{GJ/t}_{\mathrm{steel}}$ respectively for primary and secondary steel. The *minimum realistic* values are based on the theoretical minimum, but include additional energy requirements that are practically difficult to eliminate. For example, although it is theoretically possible to make steel at room temperature, in practice steel is melted during production. Therefore, the minimum realistic values for primary and secondary steel include an additional 1.05 $\mathrm{GJ/t}_{\mathrm{steel}}$ required to heat and melt the steel. The margins between current and minimum energy have been divided by de Beer *et al.*[42] into energy loss groupings, in an attempt to qualify whether potential exists to reduce the consumption from each group.

The USDOE[84] *Industrial Technologies Program (ITP)* aims to improve the energy efficiency of industrial process in the USA. 'Energy bandwidth studies' have been published for the most energy intensive industries (for example, aluminium, cement, chemicals, forest products, mining, petroleum refining, and steel) covering 75% of all industrial energy consumption. An energy bandwidth analysis 'identifies the theoretical minimum amount of energy required for each major operation within a given industry, the current amount of energy that is used in that operation, and the difference between the two'. Sponsored reports are prepared for each intensive industry which draw from the published work of academic and industry stakeholders. For example the *Steel Industry Energy Bandwidth Study* prepared by Energetics[105] makes reference to reports by Stubbles,[106] Energetics[107] and Fruehan *et al.*.[108] This programme has proven invaluable for improving energy efficiency in industry.

Beyond the industrial sector, theoretical studies of entire societies are occasionally performed. The first exergy analysis of an entire society was published by Reistad[109] and estimated the overall efficiency of the United States to be 21%. A review paper by Ertesvag[110] summarises a further 15 societal exergy studies, including coverage of numerous countries, regions, and one global study by Nakicenovic *et al.*.[111] Rosen *et al.*[112] stress that exergy analysis has an important role to play in charting the increase of energy efficiency in society, because it clearly identifies possible efficiency improvements and reductions in thermodynamic loss. The analysis by Nakicenovic *et al.* estimates the global efficiency of energy conversion in 1990 to be about 10% of the theoretical limit, but the paper is highly technical and difficult to comprehend for a non-expert reader. Although many exergy analyses have been performed on individual conversion devices, these are also technical in nature and typically appear in specialist thermodynamic journals. Attempts to aggregate exergy information for conversion devices into an accessible global form are rare, and for this reason theoretical models are often overlooked when determining research priorities and creating energy policy.

Nevertheless, using a theoretical basis to assess energy conversion devices provides an absolute basis for identifying and ranking efficiency options. This requires comparing the current energy use conversion devices with the theoretical minimum energy to provide the same output. Using a purely theoretical measure of efficiency promotes an ideal which may not be practically achievable, either economically or technically. Yet it provides a useful theoretical target and an absolute basis from which to measure progress.

The four current approaches are summarised in table 2.7.

2.4 Proposed framework for assessing efficiency gains

Previous efforts to assess the potential savings from efficiency measures are useful for identifying options and directing responses in the short term. Yet, current efforts are unlikely to be accurate over the times scales being negotiated in climate change policy because of their reliance upon recent economic trends and known technical options. Using an absolute measure of efficiency, such as exergy analysis, avoids the uncertainty which results from the extrapolation of economic trends and captures the potential of yet to be discovered efficiency designs. However, the use of exergy analysis for directing priorities has to date had limited application, due to its perceived complexity and the lack of worldwide studies.

Table 2.7 Current approaches for prioritising energy use reduction

Approach	Description	Limitation
Comparative	Aggregated energy data is compared between regions, sectors, or products. Specific or average values can be compared to *best practice* technology.	Opportunities for energy reduction are not assessed. Failure to trace energy from fuel to services or focus on technical categories.
Top-down	Historical trends in economic and energy indicators are used to project future consumption and environmental impacts. Modelling approaches allow potential new technologies or policies to be introduced, and their impacts to be evaluated.	Targets can exceed a economic or technical limit. Assume key indicators (such as energy intensity) are stable over long time periods, which is unlikely.
Bottom-up	Current and emerging technologies for reducing energy use are systematically evaluated. Case studies are performed at the process or sector level. Carbon and energy abatement curves summarise and rank potential options according to predicted costs of implementation.	Time consuming. Based on surveys of known technologies which ignore future solutions. Overlook the complex energy network when adding efficiency gains.
Theoretical	Current energy use is contrasted with the theoretical minimum requirements. This provides an absolute measure of efficiency which is comparable between different energy conversion devices.	Set idealistic targets which cannot be achieved economically or technically. Exergy and entropy are not well understood.

A new framework is developed over the next three chapters to address these limitations and answer the research questions listed below, while the final chapter presents a discussion of the work.

Chapter 3

What is the global scale of energy flow, from fuel to final services?

How much energy flows through the technical components in the energy network?

How should conversion devices and passive systems be separated?

How can the results be presented visually in an accessible way?

Chapter 4

What are the theoretical efficiency limits in conversion devices?

In which devices are the largest efficiency gains likely to be found?

By what mechanisms is energy lost from devices?

Chapter 5

What is a passive system?

What are the practical efficiency limits in passive systems?

Which systems result in the greatest loss of useful energy?

Chapter 6

What contribution has been made to the field of energy efficiency?

What new conclusions can now be made?

Where are the opportunities for further research?

The resulting framework is global in scope, technical in focus, absolute in measurement and visual in presentation, and provides a rational basis for assessing all future developments in energy efficiency.

3 TRACING THE GLOBAL FLOW OF ENERGY FROM FUEL TO SERVICE

Claude Summers, in his 1971 paper entitled *The conversion of energy*, comments, 'A modern industrial society can be viewed as a complex machine for degrading high-quality energy into waste heat while extracting the energy needed for creating an enormous catalogue of goods and services'.[82(p.41)] The outputs of this complex machine are the final energy services demanded by human society: transport, thermal comfort, illumination and sustenance, to name a few. The inputs to this machine are the primary energy sources—fossil fuels, such as oil, gas and coal, renewable sources and nuclear energy. So complex is the energy network in between, that the numerous chains of conversion devices and energy systems are yet to be mapped at the global scale.

Without a complete map of the global energy network, it is difficult to attribute the carbon dioxide emissions from fossil fuel combustion to final energy services. Without a map, the overall efficiency of the energy network cannot be calculated, nor can valid efficiency comparisons be made between the technical components in the network. Therefore, the starting point for this chapter is to construct a technical map of global energy flow, from fuels to final services. This allows the energy devices and systems which are likely to deliver the largest efficiency gains to be identified.

3.1 Potential gains from energy efficiency

Finding the global improvement potential from energy efficiency measures necessitates tracing the scale of energy flow along the numerous energy chains that form the energy network, and calculating the efficiency limits for the individual technical components in each energy chain. Equation 3.1 is used to find the available energy savings for each energy conversion device or system:

$$\begin{array}{c}\text{Potential for}\\ \text{saving energy}\end{array} = \begin{array}{c}\text{Scale of}\\ \text{energy flow}\end{array} \times \left[\begin{array}{c}\text{Target}\\ \text{efficiency}\end{array} - \begin{array}{c}\text{Current}\\ \text{efficiency}\end{array}\right] \qquad (3.1)$$

where the energy terms are measured in joules (J) and the efficiency terms in percentages (%).

The key motivation for this research is to calculate the improvement potential using an absolute physical basis, which is independent of drivers in today's market, and also correctly maps the flow of energy through technical components. In particular, this chapter addresses the first term of equation 3.1, the scale of energy flow, by mapping the technical devices, systems and energy chains which form the global energy network.

To understand the complete picture of global energy use it is necessary to trace the complex chains of energy flow from fuels through to final services. The focus throughout should remain on the technical conversion devices and subsequent energy systems in each chain. This extension of the energy flow-path has been described qualitatively, yet to date no attempt has been made to map the global flow of energy in physical units, from fuels to the delivery of final energy services.

3.2 Drawing a map of global energy flow

The flow of energy from fuel to service includes the transformation of energy sources into refined fuels and electricity, and the conversion of the refined energy into final services. The first transformation, typically refining oil into petrol or burning coal to generate electricity, is well understood. However, in delivering the final service this refined energy is typically converted again by some end-use device into a useful form (mainly heat or motion) which drives the activity of a technical system (a car, fridge or house) to deliver the required service (passenger transport, sustenance, or thermal comfort).

In order to clarify the different stages of conversion the term *passive system* is introduced here for the first time, and refers to a system to which useful energy (in the form of heat, motion, light, cooling, or sound) is delivered. Passive systems are the last technical components in each energy chain, and in contrast to *conversion devices*, do not convert energy into another useful form, hence the descriptor ‘passive’. Instead, useful energy is ‘lost’ from passive systems as low-grade heat, in exchange for the provision of final energy services. Examples of passive systems include a car (excluding the engine) which delivers transport, or a house (without the boiler or lighting device) which provides thermal comfort and illumination.

Defining the boundary between the conversion device and the passive system is not always simple. For example, it could be assumed that the filament in a light bulb is the conversion device and the surrounding glass bulb is the passive energy system. However, the light (and unwanted heat) delivered into the bulb envelope is not yet in a usable form and must pass through the glass bulb and into the illuminated space before it can be considered *useful energy*. Therefore, the entire light bulb is defined as the conversion device, and the illuminated space as the passive system. Similarly, in a refrigerator, the rotational energy from the electric motor is of no practical use until it is converted in cooling. Therefore, the complete refrigeration system is defined as the conversion device and the insulated cold-box as the passive system.

The novel distinction between conversion devices and passive systems is shown schematically in figure 3.1. The flow of energy can be traced from energy sources (left) to final services (top-right) through three key conversion stages: fuel transformation; electricity generation; and end-use conversion. At each conversion stage the energy is upgraded into a more usable form, resulting in significant energy 'losses' (as low-grade heat with little practical use).

The challenge in constructing a map of global energy flow is to breakdown the generic energy flows in figure 3.1 into individual energy chains made up of technical components. For example, the flow through 'conversion devices' needs to be divided according to the different types of engines, furnaces and electrical devices; 'passive systems' should be broken down by various types of vehicles, industrial systems and building spaces. The aim is to select a manageable number of similar sized categories (approximately ten) which cover the entire energy flow, for each step in the flow-path. It is through mapping the connections between these technical categories in Summer's 'complex machine',[82] that potential opportunities for improving energy efficiency can be identified. The remainder of this section describes the process of allocating the global energy supply to conversion devices, passive systems and final services.

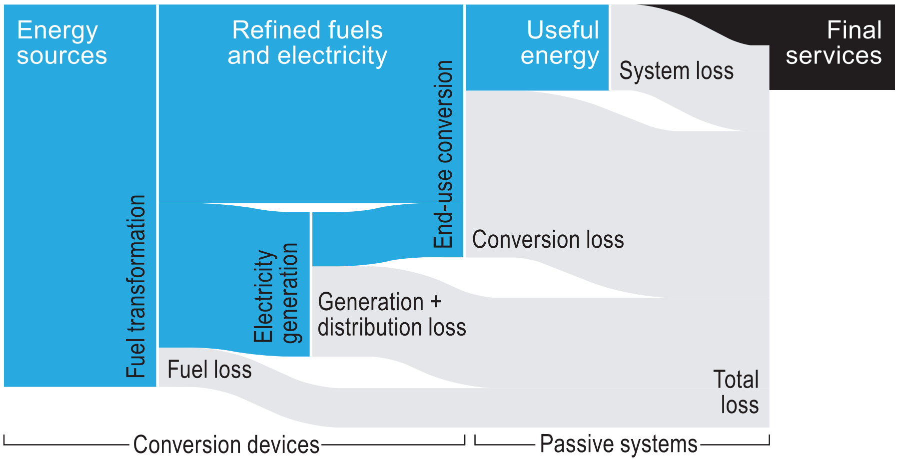

Figure 3.1 The flow-path of energy

3.2.1 Energy sources

Energy enters society from fossil fuel reserves, biomass matter, uranium deposits and renewable sources. However, Lightfoot[113] explains that the scales used to measure energy supplies differ between international data sources. The main differences arise from the way energy is calculated for electricity generated from renewable and nuclear energy, and the varied groupings for 'combustible renewables and waste'. In an attempt to avoid unnecessary errors in this analysis, Lightfoot's recommendation to use one data source with an absolute basis for measuring energy is followed.

Energy supply data is taken from the *2005 Balance Table for the World*, available from the International Energy Agency (IEA),[114] and divided into the energy source categories listed in table 3.1 (renewable energy is technically not a 'fuel' but included here for completeness). This source also provides the basis for allocating energy supply between direct fuel uses and electricity generation. The IEA category of *non-energy*—which consists of non-combusted chemical feed-stocks (e.g. nitrogen fertilisers and plastic products) and raw materials used directly for their physical properties (e.g. lubricants, bitumen, carbon black)—is omitted from this analysis as it has only a small effect on overall carbon emissions. Direct carbon emissions associated with fossil fuel energy supply for 2005 are taken from the IEA *Key World Energy Statistics*.[115(p.44)]

Fossil fuel energy data is typically published in joules (J) based on the standard enthalpy of combustion. These energy values are converted into exergy values (also in J) which provide a measure of the maximum work which can be extracted from the fuel. Using exergy provides a more equitable basis for comparing fossil fuels with uranium supplies or electricity, and for comparing heat with motion or light, because all forms of energy are measured by the same scale, their ability to perform work. In practice, using exergy as a measure increases marginally the fossil fuel energy values (4

Table 3.1 Energy sources and transfer mediums

Type	Description
Energy source	
Oil	Crude oil and petroleum products
Biomass	Combustible plant/animal products and municipal/ industrial waste
Gas	Natural gas and gas works
Coal	Hard coal, lignite and derived fuels (e.g. coke, blast furnace gas)
Nuclear	Heat equivalent of electricity (at 33% efficiency)
Renewable	Electricity/heat from hydro, geothermal, solar, wind, tide, and wave energy

to 11% across the sources, from Ertesvag and Mielnik[48 (p.959)] to account for the additional energy content of the post-combustion water vapour (lower heating value) and the flue-gas components.

3.2.2 *Conversion devices*

The grouping of conversion devices includes both upstream devices (fuel refineries and electricity generation facilities) and end-use devices (engines, furnaces and light bulbs). The IEA *2005 Balance Table for the World*[114] gives conversion efficiencies for fuel transformation and electricity generation. These have been transformed into equivalent exergy efficiencies. Most energy studies, including those of the IEA proceed to allocate the energy in refined fuels and electricity (secondary flows) to broad commercial sectors such as transport, industry and buildings. Yet, technical advances in energy efficiency are not found in these sectors, but instead are found in examining conversion devices such as engines, motors, burners and light bulbs.

In contrast, for this analysis, secondary energy flows have been allocated to the list of end-use conversion devices in table 3.2. These devices are chosen to be technically distinct and of significant scale. The allocation of energy to each conversion device is based on the study *Regional and global energy and energy efficiencies* by Nakicenovic *et al.*.[111 (tab. 3.3)] Minor corrections are made to match these fractions to the chosen device categories, and to reflect some structural changes which have occurred since the study was published. For example, for the allocation to transport fuels, the recent trend to switch from petrol to diesel powered cars is corrected using 2005 world refinery production data from IEA.[115 (p.20)]

3.2.3 *Passive systems*

The listing of passive systems in table 3.3 is novel. Each passive system is chosen from within three broad categories—vehicles, factories and building—to be technically discrete but also of sufficient scale in terms of energy flow. It is within these systems that *useful energy* in the form of motion, heat, light, cooling and sound, is lost as low-grade heat, in exchange for final energy services.

In previous studies, industrial facilities involved in manufacturing materials and goods have been treated as final energy services. For example, in Goldemberg[89 (p.76)] 'steel making' sits alongside 'illumination' and 'food storage' in the final row of energy services. However, humans desire the structural properties of steel rather than steel itself, and could in many cases be equally satisfied using an alternative such as aluminium. Thus, a distinction is required between the material, steel or aluminium, and the final service, structure. In this study, the energy delivered to factories has been divided into eight material production groups as described in table 3.4. The allocation is based upon the 2005 industrial energy data from IEA[1 (pp.476–7)] and the conversion device breakdown from USDOE[90 (pp.13–16)] after accounting for upstream generation and fuel losses.

3.2.4 *Final services*

The key consideration when creating a list of final services is to select a small number of distinct but comparable categories, for

Table 3.2 End-use conversion devices

Conversion device	Description
Motion	
Diesel engine	Compression ignition diesel engine: truck, car, ship, train, generator
Petrol engine	Spark ignition otto engine: car, generator, garden machinery (incl. two-stroke)
Aircraft engine	Turbofan, turboprop engine
Other engine	Steam or natural gas powered engine
Electric motor	AC/DC induction motor (excl. refrigeration)
Heat	
Oil burner	Oil combustion device: boiler, petrochemical cracker, chemical reactor
Biomass burner	Wood/biomass combustion device: open fire, stove, boiler
Gas burner	Gas combustion device: open fire, stove, boiler, chemical reactor
Coal burner	Coal combustion device: open-fire, stove, boiler, blast furnace, chemical reactor
Electric heater	Electric resistance heater, electric arc furnace
Heat exchanger	Direct heat application: district heat, heat from CHP
Other	
Cooler	Refrigeration, air con.: industry, commercial, residential
Light device	Lighting: tungsten, fluorescent, halogen
Electronic	Computers, televisions, portable devices

which physical data is available or can be inferred. Eight final energy categories are chosen for this study as listed in table 3.5. The physical values for final energy services are estimated using two methods. Where possible, bottom-up calculations from lit-

Table 3.3 Passive energy systems

Passive system	Description
Vehicle	
Car	Light-duty vehicle: car, mini-van, SUV, pick-up
Truck	Heavy duty vehicle: urban, long-haul, bus
Plane	Aircraft: jet engine, propeller
Ship	Ocean, lake and river craft: ship, barge, ferry
Train	Rail vehicle: diesel, diesel-electric, electric, steam
Factory	
Driven system	Refrigerator, air compressor, conveyor, pump
Steam system	Petrochemical cracker, reactor, cleaning facility
Furnace	Blast furnace, electric arc furnace, smelter, oven
Building	
Hot water system	Fuel and electric immersion boilers
Heated/cooled space	Residential/commercial indoor space
Appliance/ equipment	Refrigerator, cooker, washer, dryer, dishwasher, electronic, mechanical
Illuminated space	Residential/commercial, indoor/outdoor space

Table 3.4 Materials and products

Material	Description
Steel	Iron and steel production
Chemical	Chemicals and petrochemicals (excl. non-energy)
Mineral	Non-metallic minerals
Paper	Paper, pulp and printing, and wood products
Food	Food, beverages and tobacco
Machinery	Machinery and transport equipment
Aluminium	Aluminium and non-ferrous metals
Other	Textile, leather, mining, construction, non-specified

erature of the global final service in physical units are used. For example, Gantz *et al.*[116] estimate the size of the digital universe in 2007 (a measure of the throughput of digital information) to be 281 exabytes (281×10^{18} bytes) and the IEA calculates that 133 petalumen-hours (480×10^{18} lm s) of light was consumed in 2005.[117 (p.33)] For structural materials, global production in tonnes, is combined with material 'strength' properties (yield strength for steel, aluminium and plastic; compressive strength for concrete, from Ashby[118 (p.452)]) to give an estimate of the total structural strength of all materials.

Where bottom-up estimates are not available, published physical indicators (in energy use per final service output) are matched with global energy use (accounting for the conversion efficiency as required), to provide an estimate of the final service. For the provision of transport services, indicators are taken from IEA[119 (p.427)] in MJ/tonne-km and MJ/person-km. A weighted average of trains, trucks and ships is used for freight transport, and of cars and planes for passenger transport. For thermal comfort, the specific heat capacity of air ($1.2\,\mathrm{kJ/m^3K}$) is used to infer the total volume and temperature change of air as a result of heating and cool-

Table 3.5 Final services

Final service	Description
Passenger transport	Number of people transported by car and plane
Freight transport	Tonnes of goods transported by truck, train and ship
Structure	Materials used to provide structural support
Sustenance	Preparation, storage and cooking of food
Hygiene	Clothes washing/drying, hot water , appliances
Thermal comfort	Heating and cooling of air in buildings
Communication	Digital and written communication
Illumination	Provision of light

ing. This departs from the thermal comfort indicators used in literature, for example in Schipper *et al.*,[12] which take the housing floor area multiplied by the average temperature difference (MJ/m^2 degree-day). However, the chosen indicator is more representative of the actual quantity of heating and cooling achieved, rather than a proxy based on available data in collected statistics. The same approach is used for cooking and refrigeration of food, and the provision of hot water, using 3.0 kJ/kgK for food and 4.2 kJ/kgK for water. The remaining energy use in buildings provides mainly rotational work in many different devices. Rather than divide these further, they are left under the hygiene service category and measured in Newton metres (N m) of mechanical work.

In the absence of a global breakdown in literature, the allocation of materials to final services is based on regional product end-use data from: EUROFER[120] for steel; IEA[121] for chemicals; BCA[122] for minerals; FAOSTAT[123] for paper; and IAI[124] for aluminium. For example, the IAI[124] divide aluminium products (by final energy use) into five applications: engineering cables (18%), packaging (13%), building (25%), transport (28%) and other (16%). Based on this breakdown, energy use has been reallocated to the final services as follows: engineering cables and building are assumed to be part of the 'structure' service; packaging is allocated to 'sustenance'; transport is split evenly between 'freight transport' and 'passenger transport' services; and other is divided evenly between 'structure' and 'communication'. A similar allocation procedure is performed for all the material categories.

3.3 Results and discussion: what do we now know?

The energy data is presented in Sankey diagram form, in figure 3.2. The global flow of energy is traced along each individual energy chain from left to right, through four technical grouping: energy sources, conversion devices (including fuel transformation, electrical generation and end-use devices), passive systems (including materials) and final services. The thickness of each line represents the scale of energy flow, with colour used to distinguish different types of flow, and the vertical lines indicating where energy is reallocated into new categories. Energy values are reported in exajoules ($\mathrm{EJ} = 10^{18}\,\mathrm{J}$) and direct carbon emissions associated with the primary fossil fuels are shown in red circles in billion tonnes of carbon dioxide ($\mathrm{Gt\,CO_2} = 10^{9}\,\mathrm{t\,CO_2}$).

Having traced the flow of energy from fuel to services and identified the technical steps in each energy chain, what can we now say about the energy use in society? How should the energy map be interpreted and how does it help us identify the areas in which efficiency technologies will deliver benefit? To answer these questions it is useful to view the energy map in two ways:

Vertical from which meaningful comparisons of the scale of energy flow through technical components can be made within each of the four vertical slices

Horizontal for which alternative technical options for providing final goods and services can be compared if each horizontal energy chain is traced completely from fuel to final service

These two views are explored below, followed by a brief comment on the uncertainty of the analysis.

3.3.1 A vertical perspective of the energy map

The problem of adding, rather than multiplying, potential efficiency gains from sequential steps in the energy flow, has already been discussed on page 33, using the example of the Pacala and Soclow stabilisation wedges. This conflict also applies to absolute energy flows in the four vertical slices of the Sankey diagram: energy sources (including fossil fuels and electricity); conversion devices; passive systems (including the manufacture of materials and products); and final energy services. For example, more than

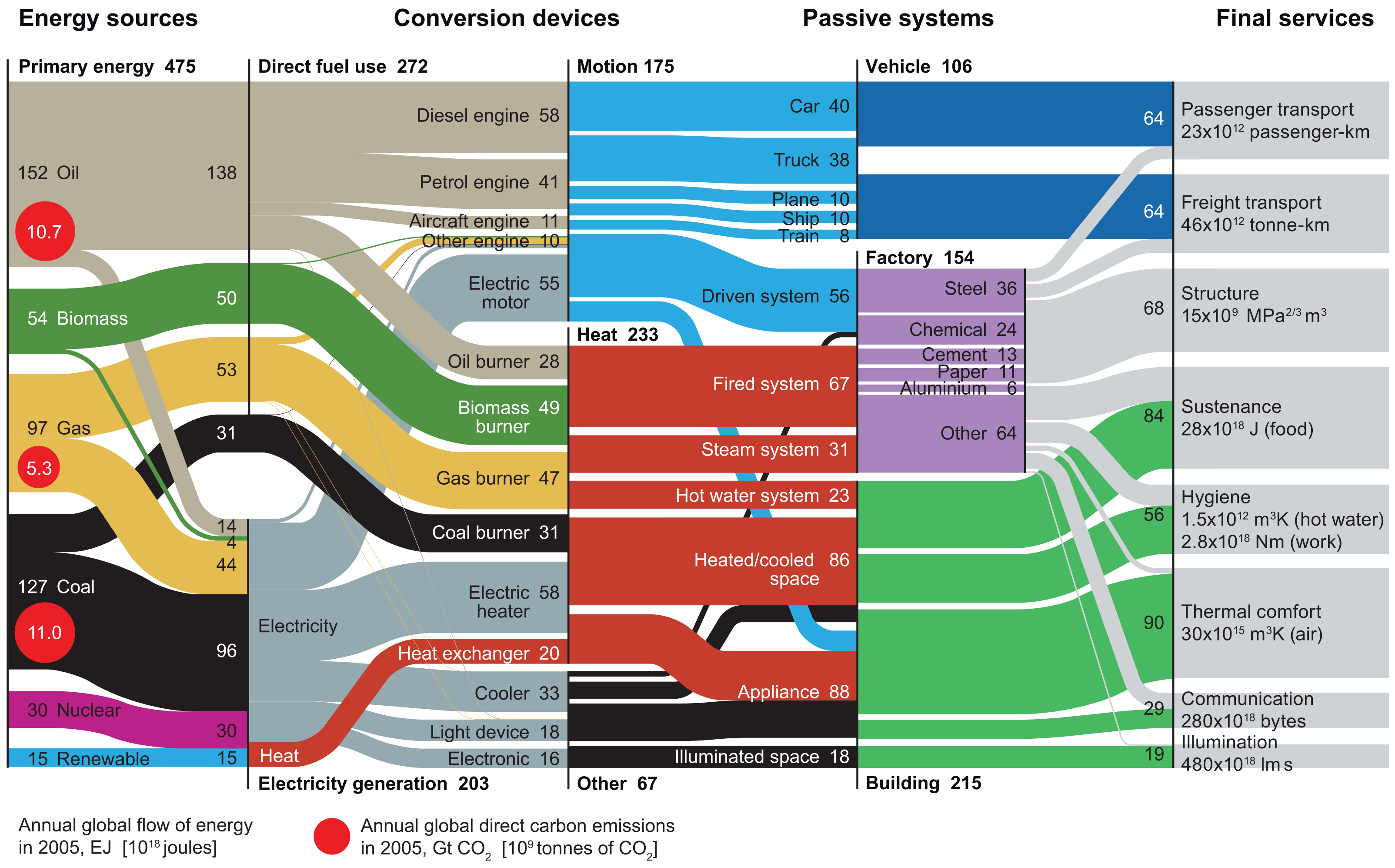

Figure 3.2 Tracing the global flow of energy from fuel to service

a third of the world's energy is used to generate electricity, a third is converted into heat, and a third is used in factories to make materials—but these three thirds do not add up to the whole, because they come from different vertical slices. Thus the absolute energy flows and potential improvements in efficiency can only be compared within each vertical slice, as shown in table 3.6. To add together energy flows or efficiency gains from different vertical groupings ignores the sequential flow of energy, and could potentially lead to exceeding the total energy supply, or an efficiency savings of greater than 100%.

Despite the current focus on low-carbon energy sources, table 3.6 shows that fossil fuels still dominate the first vertical slice of *energy sources*. Transportation is almost entirely powered by crude oil, and the majority of electricity is generated by burning coal and natural gas. Low-carbon sources (nuclear, biomass, and renewables) currently make up 20% of energy supply, and are dominated by nuclear, hydropower and biomass. With the exception of nuclear power, it will be difficult to expand supply of any renewable source to the scale of supply from fossil fuels. The remaining renewables—wind, solar, tide and geothermal—account for less than 1% of energy supply, thus de-carbonising the energy supply remains a difficult challenge when compared with alternative gains from energy efficiency. Efforts should be focused on improving combustion processes (as over 90% of energy sources are fuels which are combusted), and exploring technical options for converting the chemical energy of fuels, directly to electricity, heat or motion.

Conversion devices that produce heat and motion are shown to be important in the second vertical slice. Efficiency gains are more likely to be found in heaters, burners and engines, than in lighting devices, electronics and aircraft engines, due to the scale of energy flow through these devices. For instance, efforts aimed at promoting compact fluorescent light bulbs and reducing electronic standby losses are useful for raising public awareness of efficiency

Table 3.6 Technical components ranked by the scale of energy use

Energy source	EJ	Conversion device	EJ	Passive system	EJ	Final service	EJ
Oil	152	Diesel engine	58	Appliances/equipment	88	Thermal comfort	90
Coal	127	Electric heater	58	Heated/cooled space	86	Sustenance	84
Gas	97	Electric motor	55	Furnace	67	Structure	68
Biomass	54	Biomass burner	49	Driven system	56	Freight transport	64
Nuclear	30	Gas burner	47	Car	40	Passenger transport	64
Renewables	15	Petrol engine	41	Truck	38	Hygiene	56
		Cooler	33	Steam system	31	Communication	29
		Coal burner	31	Hot water system	23	Illumination	19
		Oil burner	28	Illuminated space	18		
		Heat exchanger	20	Plane	10		
		Light device	18	Ship	10		
		Electronic	16	Train	8		
		Aircraft engine	11				
		Other engine	10				
Direct fuel use	272	Heat	233	Buildings	215		
Electricity	183	Motion	175	Factory	154		
Heat	20	Other	67	Vehicle	106		
Total	475	Total	475	Total	475	Total	475

issues, but will have little effect on global energy consumption. Similarly, future improvements in aircraft engine efficiency will lead to weight and cost benefits, but will have only a small impact on global carbon emissions. Thus, if the scale of energy flow is considered, devices such as light-bulbs, electronics and aircraft engines can be given less emphasis in policy initiatives because they cannot deliver the required large reductions in carbon emissions.

The challenge for *passive systems* is to design technologies that make better use of energy, by preserving and recovering the heat in buildings, the materials in products, and the momentum in vehicles. For buildings, space heating and cooling is predictably at the top of the priority list, with a significant fraction of energy used to maintain a temperature difference between the building interior and exterior. Reducing heat transfer through the building fabric, by insulating and preventing air leaks, remains a priority especially for existing building stock. However, the high ranking for energy use in appliances and goods is surprising and requires further investigation because of the diverse nature and much shorter life of products in this grouping. Almost one third of energy is attributed to the production of materials and goods in industry. Options for reducing energy use in material production have been surveyed by Allwood *et al.*[125] including improving material efficiency through substituting less energy intensive materials, light-weighting products and designing for reuse and recycling. Advances in vehicles, such as reducing aerodynamic drag and friction losses, should be applied to cars and trucks in preference to planes, ships and trains.

Improvements in the fourth vertical slice can only be made by reducing the demand for *final services*, through behavioural and lifestyle changes. Nevertheless, it is helpful to examine these services because the entire energy network exists solely for their provision. Passenger and freight transport, when added together, dominate the final services. The provision of sustenance is the single largest category, because modern methods of growing (with fertiliser), distributing, preparing and cooking food are energy in-

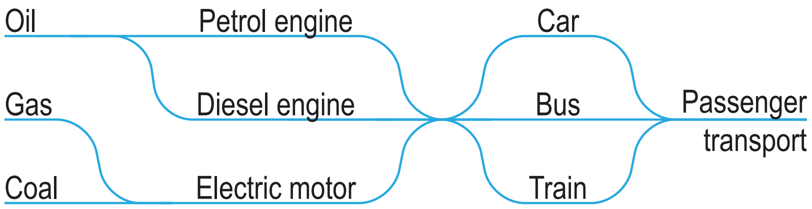

Figure 3.3 Delivering passenger transport using alternative energy chains

tensive. Thermal comfort ranks high on the list and can be targeted by reversing the practice of using high quality fossil fuels to supply low temperature heat. Significant savings are available from the wider use of heat pump technology and improving the insulation of buildings.

3.3.2 A horizontal view of the energy map

It is through the process of mapping the complex global energy network and comparing the scale of energy flow within the four vertical slices, that technical priorities for improving energy efficiency can be identified. However, energy use or potential efficiency gains cannot be aggregated between vertical groupings. Instead, to make comparisons between alternative horizontal energy flows, the entire energy chain from fuel to service must be considered. This concept of improving energy efficiency by selecting alternative horizontal energy chains is illustrated using the example of delivering passenger transport, in figure 3.3.

Swapping conversion devices and systems within their vertical slices leads to alternative energy chains, and potential savings in energy. For example, switching all petrol engines (∼12% efficiency) to diesel engines (∼20% efficiency) would save approximately 4 EJ worldwide. However, switching one component in an energy chain will often force changes to the components upstream, resulting in new component efficiencies at every step along the energy chain. For example, if a petrol driven car is replaced with an electric driven train, the flow of energy through the motor drive and electricity generation must also be considered. Yet this simple concept is often overlooked in comparative energy studies, where fuel efficiency values for vehicles are based on the volume of fuel (L/km), irrespective of the type of fuel (diesel or petrol) and the upstream energy losses associated with the fuel choice. The specification of electrical vehicles, in kWh/km from the socket, which ignores the upstream efficiency losses from electricity generation, is potentially even more misleading.

Tracing each alternative chain back to primary energy (and carbon emissions) enables meaningful comparisons to be made between the scale of energy use, the impact of associated carbon emissions, and the overall efficiency of the energy chain. Reductions in energy use for passive systems are particularly attractive, because any saving in energy is compounded in the upstream steps, resulting in a larger overall energy reduction. These compound savings can only be identified when passive systems are separated from conversion devices.

3.3.3 Data accuracy

All energy data is at best a good estimate, being dependent on the accurate completion of energy surveys and the time delay between collection and analysis. Significant differences of opinion exist over how to measure primary energy supply, according to Lightfoot,[113] and energy institutions do not publish error analyses with their data. Rigorous data for the allocation of energy to conversion devices, passive systems and final services is more difficult to obtain due to the lack of global studies. Therefore, in the absence of any specific uncertainty analysis for IEA data, the energy values reported in this analysis are rounded to the nearest EJ.

Despite these limitations, the accuracy of the global energy map is sufficient for determining the scale of energy flow through the energy network. Patterns of energy consumption are certain to change in the future, driven by structural changes, energy efficiency improvements and human behaviour. However, in the long-term, the actions taken by society to improve energy efficiency are likely to dwarf any data inaccuracies in this study. It is important to use the best available data to direct priorities now, rather than wait for more accurate data in the future.

3.4 Conclusion

The energy map presented in figure 3.2 provides a framework for assessing the global scale of opportunity for energy efficiency measures. The analysis makes four unique contributions to our understanding of energy efficiency by:

- tracing the global flow of energy from fuels to final services in Sankey diagram form
- focusing on the technical steps, rather than economic sectors, within each chain of energy
- clearly defining the distinction between conversion devices and passive systems
- identifying the key areas where technical innovation is likely to deliver the greatest efficiency gains

The next two chapters, calculate the technical potential for energy efficiency gains in conversion devices (§4) and passive systems (§5). The target efficiencies for individual technical devices are then overlaid back onto the global map of energy flow to provide an absolute physical measure of improvement potential.

4 THEORETICAL EFFICIENCY LIMITS IN CONVERSION DEVICES

Using a theoretical basis to assess energy conversion devices provides an absolute framework for identifying and ranking efficiency options. This requires comparing the current efficiency of conversion devices with their theoretical minimum, while considering the complex interactions between technical devices in the global energy network. Inevitably, using a purely theoretical measure of efficiency promotes an ideal which may not be practically achievable, either economically or technically. However, such an approach provides a useful theoretical target to direct priorities and and a absolute basis from which to measure progress.

This chapter attempts to answer three key questions:

- how can the efficiencies of energy conversion devices be compared on an equivalent basis?
- in which conversion devices are the greatest efficiency gains likely to be found?
- how does categorising the avoidable losses according to energy loss mechanisms help understanding?

4.1 Constructing a map of global energy efficiency

The section constructs a visual map of global energy efficiency, which allows options to be identified and compared according to an absolute basis, independent of benchmarks based on economic or technical limitation. Three components are required to create such a map. The first is to determine the global scale of energy flow through conversion devices, which is provided in chapter 3. The second, requires determining the theoretical efficiency limit for each type of conversion device, and superimposing these onto the device energy flows. Finally, it is important to present the results in a visually accessible format—such as a Sankey diagram—permitting the maximum savings from efficiency measures to be visualised.

4.1.1 Selecting a consistent measure of efficiency

To calculate the theoretical efficiency limit for each conversion device an appropriate measure of energy efficiency is required. Conventional energy efficiency, which is based on the first-law of thermodynamics, is typically defined for a conversion device as:

$$\eta = \frac{\text{energy output (useful)}}{\text{energy input}} \tag{4.1}$$

A natural gas power plant operating at 40% efficiency, an electric motor that is 95% efficient, and an air conditioner with a Coefficient of Performance (COP) of 1.8, are all typical examples of reported first-law efficiencies. However, this measure of efficiency is of limited use when comparing different types of conversion devices because it is possible to have a maximum efficiency greater than 100%, and the quality of energy is not considered. For example, in space heating applications, a typical 'high-efficiency' gas burning furnace has a first-law conversion efficiency of 95%, and an electric heating system is 100% efficient. Based on these figures, it could be assumed that space-heating devices are already approaching their maximum efficiency limits. However, a typical heat pump has a COP of 3 (equivalent to an efficiency of 300%) and under ideal conditions can approach 10 (or 1000%).

Such large variances in efficiency result from the failure of conventional efficiency definitions to consider the quality of energy—

electricity and mechanical work are more valuable energy carriers than low temperature heat. Conventional energy efficiency (based on the first law of thermodynamics) does not take into account this difference in quality and hence is not an objective basis for evaluating energy conversion devices.

In contrast, exergy efficiency (based on both the first and second laws of thermodynamics, and similar in concept to effectiveness or availability) provides a more equitable measure of conversion efficiency. It uses mechanical work rather than energy as the basis for comparing devices with each other and their thermodynamic ideal. Exergy efficiency is defined for a device as:

$$\epsilon = \frac{\text{exergy output}}{\text{exergy input}} = \frac{\text{work output}}{\text{maximum possible work output}} \tag{4.2}$$

By definition, the theoretical limit of exergy efficiency for an individual device or a chain of multiple conversion devices, is always unity.

Mechanical work is chosen because it is the highest quality, lowest entropy form of energy. Electricity, which can be perfectly converted into mechanical work, is another high quality form of energy. Thus for a device which converts one form of mechanical energy to another (e.g. gearbox), or electrical energy to mechanical energy (e.g. electric motor), exergy efficiency and energy efficiency are almost the same. However, when the input or output of the device is heat (e.g. space-heater), the energy value of the heat must be downgraded into equivalent units of mechanical work.

The importance of using an absolute measure of efficiency is explained using an example of lighting devices. It is sometimes argued that replacing incandescent light bulbs with more efficient compact fluorescent bulbs saves little energy, because the buildings space heating requirements are offset by the bulb's waste heat production. Ignoring the fact that in many climates space heating is not required in summer, and that waste heat from the bulb may compete with air-conditioning systems, the argument is flawed because it ignores the 'quality' of the energy. According to the first law of thermodynamics, 100% of the electricity input to the bulb is converted to either light or waste heat. Yet, from a second-law perspective the electricity is high quality energy (it can be converted into work almost completely), whereas the bulb's waste heat is a low quality form of energy (it is at low temperature, so is difficult to convert to mechanical work). If a more efficient lighting device was installed, the electricity saved could be used to run a high efficiency device like a heat pump that could deliver 3 times more of the same low quality heat than the light bulb (assuming a typical COP of 3). Clearly, not all forms of energy are equal in quality or usefulness, and therefore a consistent measure such as exergy is needed to equate device efficiencies.

Exergy efficiency can be calculated directly, by finding the ratio of the output to input exergy flows through the device, but in practice this is complicated. Instead, if the conventional energy efficiency (η) is known, then the exergy efficiency (ϵ) can be estimated using:

$$\epsilon = \eta \times \nu \tag{4.3}$$

where a dimensionless quality factor (ν) is used to correct for the loss of energy quality in the conversion process, which results from two sources. Firstly, the chemical exergy in a fuel is marginally higher than the standard enthalpy of combustion due to the additional contribution of the post-combustion water vapour (lower heating value) and the flue-gas components. Ertesvag and Mielnik[48 (p.959)] give values called 'exergy factors' which vary by between 4 to 11% across typical fuel sources. Secondly, where energy is converted into heat, the heat output must be downgraded to be measured as mechanical work, using the thermal efficiency defined by a reversible Carnot engine (defined as $|\frac{T-T_0}{T}|$, where T is the heat carrier and T_0 is the ambient temperature, both in Kelvin).

4.1.2 Calculating efficiency limits in conversion devices

Creating a map of global energy efficiency requires assigning average efficiencies to each conversion device in the energy network, including fuel transformation, different modes of electricity generation and end-use applications. It is important to select efficiency values that are representative of the global device average, calculated in a consistent way, and are from credible sources. The input and output energy flows for the upstream conversions—fuel transformation and electricity generation—are well defined in the energy literature, allowing efficiencies to be deduced. However, global energy flow data is not available for end-use conversion devices, instead the efficiency values must be found by a survey of literature.

The conversion efficiencies for **fuel transformation** and **electricity generation** are calculated from the *2005 Balance Table for the World*, produced by the International Energy Agency (IEA).[114] This table provides values for the global energy supply broken down by fuel type, and for the 'final' energy delivered to consumers in the form of refined fuels and electricity. Thus the average energy and exergy efficiencies for fuel transformation, electricity generation and heat production, can be inferred from these flows and other literature sources, as shown in table 4.1.

Some minor differences are found between efficiency for combustion based electricity generation (ν<100%). The input to these devices is increased when it is changed from energy to chemical exergy, while the electricity output remains unchanged. Thus the ratio of electricity output to chemical exergy input is reduced, by the factor ν, and the exergy efficiency is lower. For CHP and Utility heat plants, the difference between energy and exergy efficiency is larger because the heat output of these devices must be downgraded to mechanical work. In contrast, no difference is found for fuel transformation ($\nu = 100\%$) because the inefficiency relates to material losses during processing, nor is there difference for nuclear and renewable sources because the device input remains unchanged.

Finding representative efficiency values for the global stock of **end-use conversion devices** is difficult. Efficiencies cannot be inferred from statistical studies of global energy flows, as this data is not available for end-use devices. Instead published values for

Table 4.1 Energy and exergy efficiencies for conversion devices

Device	Description	η %	ν %	ϵ %
Electricity generation from:				
Oil	Crude oil and petroleum products	37^a	94	35
Biomass	Combustible plant/animal products and municipal/industrial waste	25^b	90	23
Gas	Natural gas and gas works	40^a	96	38
Coal	Hard coal, lignite and derived fuels (e.g. coke, blast furnace gas)	34^a	94	32
Nuclear	Nuclear fission (heat equivalent of electricity)	33^c	100	33
Renewable	Hydro, geothermal, solar, wind, tide, and wave energy	80^b	100	80
Fuel transformation	In petroleum refineries, gas works, coal preparation, liquefaction, distribution and own use	93^d	100	93
CHP	Combined heat and power plants (all fuels)	56^d	62	35
Heat	Utility heat plants (all fuels)	85^d	24	20

Notes: η=energy efficiency, ν=quality factor, ϵ=exergy efficiency
[a] IEA[126 (p.73)], [b] estimated, [c] IEA[127 (p.138)], [d] calculated from IEA[114]

energy and exergy efficiency must be used, but these vary considerably depending on the technology and vintage of the equipment surveyed, the chosen system boundary for each device and the geographical scope of the study. Table 4.2 presents a review of 10 studies, covering the last 40 years, that list conversion device efficiencies. The review indicates whether the values are first (energy) or second law (exergy or equivalent), the number of devices categories given, and describes the scope of the study.

The study by Nakicenovic *et al.*[111] is easily the most comprehensive and consistent analysis of global energy and exergy efficiency values. Unlike other studies, which use device case studies to estimate best practice values, Nakicenovic *et al.* aggregate data from 11 sub-regions and across 6 fuels types, to create average global values of energy efficiency (η) and exergy-quality factors (ν). The analysis also allocates global energy flows for 1990 to the selected devices, which helps to verify the efficiency values. The list of end-use conversion devices includes:

Residential/commercial sector cooking, washer/dishwasher, space heating, hot tap water, space cooling, refrigeration, mechanical energy, lighting, Electronic Data Processing (EDP)/television, other household appliances

Industry process heat (low and medium temperature), high temperature heat/electrolysis, mechanical energy, other industrial uses

Transport bus/truck (Diesel), car/truck (Otto), airplanes, internal navigation (by water), rail, other

However, three adjustments are required to bring the Nakicenovic *et al.* efficiency values into a form which is suitable for directing technical priorities today.

Firstly, some individual device efficiencies are updated to reflect changes in system boundaries. The energy efficiencies for ‘mechanical energy’ devices (relating to electrical motors) are reported as 70% in industry and 54% in residential. However, USDOE[90] calculate an average efficiency of 45% for the entire motor driven system, including the pump or compressor. This lower value more

Table 4.2 Survey of conversion device efficiencies

Reference and scope	First-law	Second-law	No. of devices
Summers[82 (p.151)] Chart of best available technology, by the type of energy conversion	✓		25
Reistad[109 (p.431)] Table of US data, including electricity generation at 38%	✓	✓	23
Ford *et al.*[29 (p.50)] Table, system boundary includes upstream electricity generation		✓	17
O'Callaghan[128 (p.108)] Chart,system boundary includes upstream electricity generation	✓		38
Culp[129 (p.33)] Chart of typical operational efficiencies	✓		28
Gilli *et al.*[130 (p.11)] Chart of end-use devices, with range of efficiencies shown	✓	✓	17
Nakicenovic *et al.*[111 (p.228)] Global values for energy and exergy efficiency, categorised by fuel	✓	✓	20
Hammond and Stapleton[131 (pp.152–157)] Charts and tables, by domestic, commercial, industrial and transport applications	✓	✓	11
USDOE[90 (p.1)] Table of US power generation and industrial equipment	✓		14
Warr *et al.*[132 (pp.34–35)] Charts of UK devices		✓	10

accurately describes the boundary system for a end-use conversion device used in this research—the device output is measured in its final useful form, in this case fluid motion. Ayres *et al.*[133 (p.1117)] provides a breakdown of industrial electricity use in the United States, which is used to separate refrigeration (6% of total net demand) from the broader Nakicenovic *et al.* category of mechanical energy. The efficiency for internal navigation (by water) is also applied to transport by international marine vessels, and biofuel powered engines are assumed to have an efficiency of 10%.

Secondly, the reported efficiency values represent 1990 technology and are therefore outdated. Thus the efficiencies are scaled to match historical improvements in global energy intensity using the IEA reported sector improvements (cumulative from 1990–2004, updated for 2005): buildings 13.3%, industry 22.7% and transport 8.2%.[134] Applying a uniform efficiency improvement across the devices in each sector might lead to device efficiencies greater than 100%. Instead the historical scale factors are applied uniformly to the loss from each conversion device, grouped by economic sectors.

Thirdly, the devices presented by Nakicenovic *et al.* are grouped by economic sectors instead of individual technologies. For example, the electrical motor could be listed as a distinct technology, but instead is included in four different categories: ‘mechanical energy’ (both industry and residential/commercial), ‘other household appliances’ and ‘other industrial uses’. The diesel engine is also hidden in these same four categories, and in four additional transport categories: ‘bus/truck’, ‘internal navigation’, ‘rail’ and ‘other’. The selected device categories also vary considerably in scale of energy flow, from as low as 0.1% of global energy demand for ‘washer/dishwashers’ to greater than 16% for ‘space heating’. It is preferable to organise the efficiency data into technically discrete categories of conversion devices, of approximately equal scale of energy flow.

Therefore, the efficiency values and quality factors reported in Nakicenovic *et al.*[111] are adjusted and regrouped into the 14 end-use conversion devices shown in table 4.3.

Table 4.3 Energy and exergy efficiencies of end-use conversion devices

End-use device	Description	η %	ν %	ϵ %
Motion		**26**	**90**	**24**
Diesel engine	Compression ignition diesel engine (truck, car, ship, train, generator)	22	95	21
Petrol engine	Spark ignition otto engine (car, generator, machinery)	13	99	12
Aircraft engine	Turbofan, turboprop engine	28	99	27
Other engine	Steam or natural gas powered engine	47	53	25
Electric motor	AC/DC induction motor (excl. refrigeration)	60	93	56
Heat		**58**	**24**	**14**
Oil burner	Oil combustion device (boiler, petrochemical cracker, reactor)	61	25	15
Biomass burner	Biomass combustion device (open fire/stove, boiler)	34	20	7
Gas burner	Gas combustion device (open fire/stove, boiler, reactor)	64	21	13
Coal burner	Coal combustion device (open-fire/stove, boiler, blast furnace, reactor)	59	31	19
Electric heater	Electric resistance heater, electric arc furnace	80	30	24
Heat exchanger	Direct heat application (district heat, CHP)	87	15	24
Other		**60**	**14**	**8**
Cooler	Refrigeration, air conditioning (commercial, residential)	104	6	7
Light device	Lighting (tungsten, fluorescent, halogen, etc)	13	90	12
Electronic	Computers, televisions, portable devices	20	30	6
All devices		**51**	**50**	**25**

Notes: η = energy efficiency, ν = quality factor, ϵ = exergy efficiency

4.1.3 Grouping energy losses by engineering mechanisms

A perfect conversion device has no energy loss and therefore is considered reversible (both the system and surroundings could be returned to their original state). O'Callaghan[128] states that for a process to be reversible it must be:

- adiabatic (no heat exchange between the system and surroundings)
- isothermal (system temperature is constant)
- fully resisted (no unrestrained expansion or throttling of gases or liquids, and no 'paddle-work')

However, for any real process (and thus energy conversions) there are always thermodynamic irreversibilities present. To provide further insight into how energy is lost, and therefore what strategies could prevent energy loss, the losses from global conversion processes are aggregated into ten engineering loss mechanisms as described in table 4.4.

There is no single study which provides a breakdown of global energy losses across the range of conversion devices considered. Instead a number of exergy analyses of individual conversion devices are consulted: Dunbar and Lior[135] and Prins and Ptasinski[136] for generic combustion processes (applicable to engines, heaters and fossil fuel based electricity generation); Dunbar *et al.*[137] and Durmayaz and Yavuz[138] for electricity generation using nuclear fission; Ertesvag and Mielnik[48] for hydroelectricity; Rakopoulos and Giakoumis[139] for diesel engines; Ford *et al.*[29] for petrol engines; Turgut *et al.*[140] for aircraft engines; Mecrow and Jack[141] and USDOE[90] for electric motor drives; Kotas[142] for refrigeration. The exergy breakdowns do not always correlate directly with the conversion device categories or efficiencies used in this study. In these cases scale factors, interpolation and estimation were used to complete the data.

Table 4.4 Energy loss mechanisms

Combustion	
Internal heat exchange	Heat transfer between product molecules leaving the reaction site (with kinetic and photon energy) and neighbouring unreacted molecules, leads to unrecoverable exergy loss. Internal heat exchange can be avoided if the reactant and product streams are separated.
Oxidation	Chemical interactions (intra-molecular, radiation, thermo-mechanical) result from the reaction of oxygen and fuel, producing irreversible changes of energy. Conversion of chemical energy to a useful form without combustion, for example in fuel cells, can prevent some of this loss.
Mixing	Spontaneous mixing of reactants in the pre-combustion stage, and products in the post-combustion stage, cannot be reversed without additional energy input. It is difficult to avoid mixing in combustion processes.
Heat transfer	
Heat exchange	Heat transfer through a finite temperature produces irreversibilities (e.g. from combustion gases to steam). Minimising the temperature difference reduces losses, but increases the heat exchanger costs. Avoiding the use of high temperature fuel combustion for low quality applications (space and water heating), and cascading heat can reduce losses.
Exhaust	Thermal and chemical potential of stack and tailpipe emissions. Extracting heat from water vapour (condensing boilers) and completely oxidising fuel can prevent some loss.
Heat loss	Heat transfer from equipment to the environmental reference state. Losses can be minimised using insulation, preventing leaks of hot gas and liquids, and ensuring reactants and products leave the system at the surrounding temperature.

Continued…

Table 4.4 Energy loss mechanisms (continued)

Other	
Electrical resistance	Resistivity (I^2R), eddy currents and magnetic hysteresis losses in devices (e.g. power distribution, electric motor, light bulb, electronic). Can be minimised by selecting superior materials/metals for electrical components, and by reducing the length of electrical wires through miniaturisation of electronics and localisation of electricity supply.
Friction	Friction (sliding and fluid flow), inelastic deformation and unrestrained compression/expansion leads to non-recoverable energy losses (e.g. in motors, turbine, engine, pump and pipe). Losses are reduced by using lubricants, reducing fluid flow velocities, and resisting expanding gases.
Fission (nuclear)	Highly irreversible fission and heat transfer processes result in losses. Can be partially reduced by using fossil-fuel fired superheat and reheat units in the downstream steam system.
Fuel losses	Transformation, own-use, distribution and transmission of primary fuels results in physical losses (e.g. oil and gas leaks from pipelines). These can be reduced with good design and maintenance, or by using a more localised energy source.

4.1.4 Results

The global map of energy conversion efficiency is presented in figure 4.1. Energy flow is traced from primary energy sources (left), through fuel transformation, electricity generation and end-use device conversion, to useful energy (top-right). The thickness of each line represents the scale of energy flow, with the use of colour to help distinguish different energy flows. Useful energy, in the form of heat, motion, light, sound and cooling, is collected in the top-right corner and indicates the energy required if the current conversion devices were all to operate at their theoretical maximum efficiency. The vertical lines show where energy is converted in a new form, with any loss of energy being separated from the main flow and collated in the bottom-right corner. Energy values are reported in exajoules ($\mathrm{EJ} = 10^{18}\,\mathrm{J}$) and direct carbon emissions associated with fossil fuels are shown in the red circles in billion tonnes of carbon dioxide ($\mathrm{Gt\,CO_2} = 10^{9}\,\mathrm{t\,CO_2}$) (based on 2005 data from the IEA *Key World Energy Statistics*[115(p.44)]).

4.1.5 Data accuracy

Rigorous data for estimating conversion device efficiencies and allocating energy losses, is not readily available. Few global studies exist, therefore national and sector publications are used to build a detailed picture of energy use. Energy allocation varies considerably between countries and energy efficiency differs between devices depending on the age, operation and type of device. Although some energy loss breakdowns are available for specific devices, the methodology used differs between studies and it is difficult to translate this data into a consistent global analysis. For these reasons, and in the absence of any specific uncertainty analysis for the collected energy data, the energy values reported in this analysis are rounded to the nearest EJ.

However, one simplifying factor in this analysis is the allocation of energy use directly to the physical devices which convert energy. There is no need to *embed* the energy associated with upstream conversion processes such as electricity generation, or non-direct energy inputs such as transport and capital equipment. These energy inputs are allocated directly to the conversion device. This avoids the complex boundary issues associated with other energy analysis methods, such as Life Cycle Assessment, where the allocation of non-direct impacts is subject to truncation and double-counting errors, as discussed by Cullen and Allwood.[86]

Despite these known imperfections in data accuracy, the use of best available energy data provides a much needed basis for

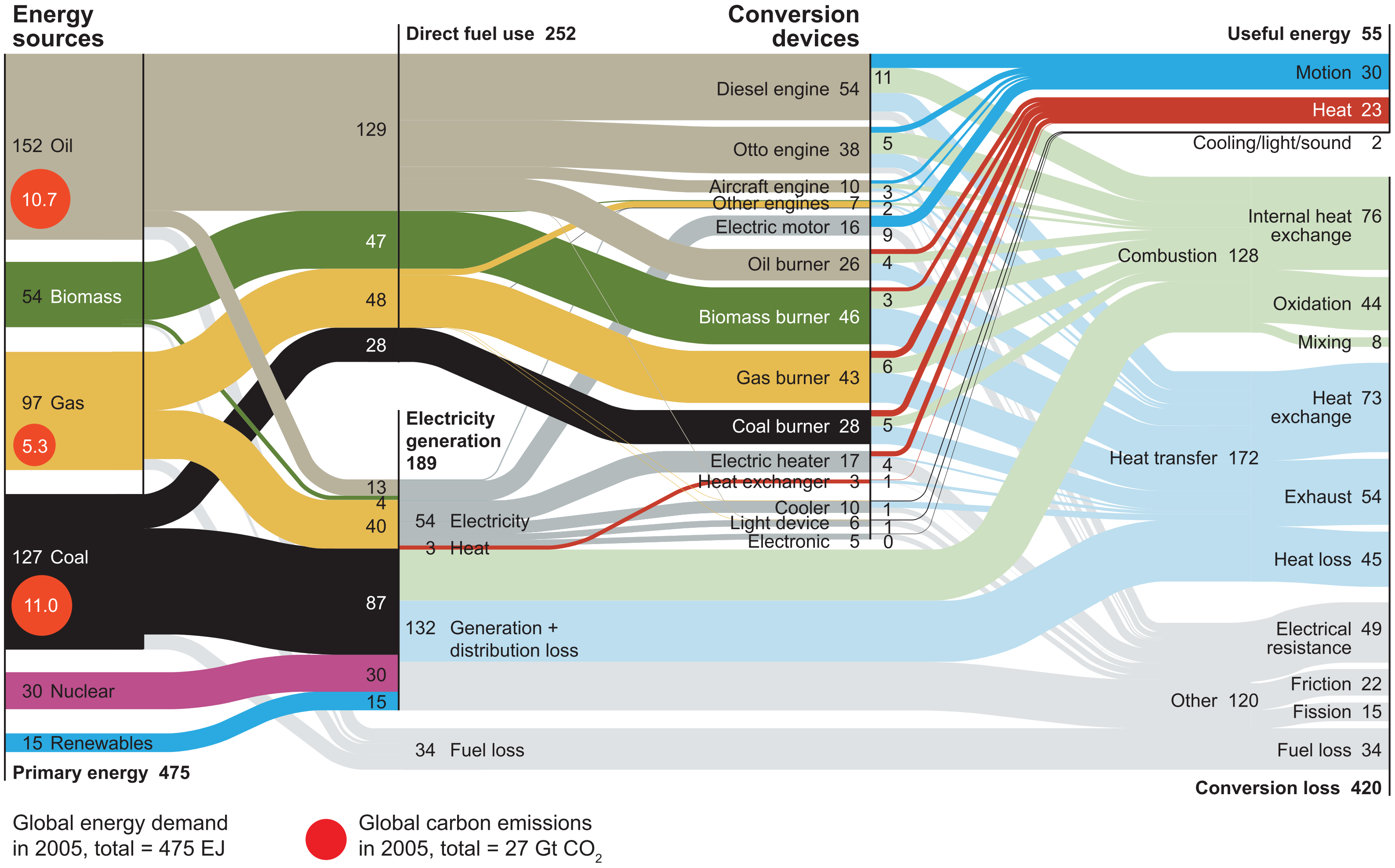

Figure 4.1 The global map of energy conversion efficiency

prioritising action in the area of energy efficiency. It is anticipated that over time new studies will provide more accurate efficiency data for energy conversion devices, which can be used to build further upon this research.

4.2 Discussion

Having mapped the theoretical efficiency limits for conversion devices onto the global energy network, what can now be inferred about the efficiency with which society uses energy? How do the efficiencies of different conversion devices compare? How can we interpret the map of energy efficiency, in order to direct priorities for researchers, designers and engineers working in the field of efficiency?

4.2.1 How efficient are current conversion devices?

Individual device efficiencies from different parts of the diagram cannot be compared directly with each other. To state that an electric motor is more efficient than a diesel engine, ignores the larger upstream energy losses from electricity generation and distribution that are linked to the electric motor. Instead, a compound efficiency (ϵ_c) can be calculated for each energy chain, by multiplying consecutive device efficiencies together along the entire chain length:

$$\epsilon_c = \epsilon_f \times \epsilon_e \times \epsilon_d \tag{4.4}$$

The subscripts used to indicate the type of conversion device are taken from the map of energy flow shown in figure 3.1: c = compound efficiency, f = fuel transformation; e = electricity generation and distribution; d = device conversion (end-use).

The resulting compound efficiencies for energy chains are shown in table 4.5, organised by the end-use conversion devices. These

Table 4.5 Comparing the efficiency of conversion devices

Energy chain	Conversion efficiencies			
	ϵ_f %	ϵ_e %	ϵ_d %	ϵ_c %
Aircraft engine	93	100	27	**25**
Diesel engine	93	100	21	**20**
Other engine	92	78	25	**18**
Electric motor	93	32	56	**17**
Petrol engine	93	100	12	**12**
Motion average	93	77	24	**17**
Coal burner	90	100	19	**17**
Oil burner	93	100	15	**14**
Gas burner	91	100	13	**12**
Electric heater	93	32	24	**7**
Biomass burner	95	100	7	**6**
Heat exchanger	93	17	13	**2**
Heat average	93	76	14	**10**
Light device	93	34	12	**4**
Cooler	93	33	7	**2**
Electronic	93	32	6	**2**
Other average	93	33	8	**2**
Overall Average	93	70	18	**11**

Notes: ϵ = exergy efficiency, with subscripts, f = fuel transformation; e = electricity generation; d = end-use device conversion; c = compound efficiency

indicate the theoretical efficiency limit for each chain, from fuel to useful energy, irrespective of any particular combination of conversion devices. The table shows that the conversion of fuels to useful energy is typically inefficient, averaging only 11% across all devices. The efficiency of conversion devices has improved only marginally over the last 15 years, when compared with the 10% calculated by Nakicenovic *et al.*.[111] This small *absolute* improvement in average device efficiency places into sharp contrast the reported and acclaimed 15% *relative* improvement in global energy efficiency between 1990 and 2005.[126] Furthermore, the compound efficiencies (ϵ_c) for energy chains in 2005 range from 2–25%

suggesting any device operating above an efficiency of 20% is converting energy in an efficient manner.

Most of the inefficiency can be traced to the poor conversion of energy in end-use conversion devices (ϵ_d), which average only 18%. Looking specifically at this column, it can be seen that engines, which deliver motion, typically operate with relatively high efficiencies (12–27%) due to intense development motivated by economic drivers to reduce the weight of both fuel and the engine in transport vehicles. This is particularly the case for aircraft engines where weight constraints have resulted in highly efficient designs. Electric motors are even more efficient (56%), because the upstream conversion losses from combustion are included in the intermediate conversion step of electricity generation (ϵ_e). In contrast, devices which combust fuels to provide heat operate at lower device efficiencies (7–19%), with the variance depending primarily on the temperature at which heat is delivered. This explains why natural gas, a high quality fuel used in many low-grade applications such as space heating, is combusted at lower efficiencies than coal, which has many higher temperature industrial applications such as steel production. Cooling, lighting and electronic applications have low efficiencies (6–12%), and additional losses result from the conversion of fuel to electricity, at an efficiency of 32%.

However, the efficiencies calculated in table 4.5 are not in themselves sufficient for ranking conversion devices. To be consistent, the analysis needs to consider both the device efficiency limit and the scale of energy flow. For example, it would be illogical to focus efforts on improving the low efficiency of steam engines (included under other engines), when this technology is no longer in common use. The resulting efficiency gains would not translate into significant reductions in energy use or carbon emissions because the application lacks scale.

Table 4.6 Theoretical energy and carbon savings

Energy Chain	$1-\epsilon_c$ %	Energy demand EJ	Energy savings EJ	Carbon emissions Gt CO_2	Carbon savings Gt CO_2
Electric heater	93	58	54	3.4	3.1
Diesel engine	80	58	47	4.1	3.3
Electric motor	83	55	46	3.2	2.6
Biomass burner	94	49	45	0.0	0.0
Gas burner	88	47	41	2.6	2.3
Petrol engine	88	41	36	2.9	2.5
Cooler	98	33	33	1.9	1.9
Coal burner	83	31	26	2.7	2.2
Oil burner	86	28	24	1.9	1.7
Heat exchanger	98	20	20	1.2	1.2
Light device	96	18	17	1.0	1.0
Electronic	98	16	15	0.9	0.9
Other engine	82	10	8	0.7	0.6
Aircraft engine	75	11	8	0.7	0.5
Heat	90	233	210	11.7	10.4
Motion	83	175	145	11.6	9.6
Other	98	67	65	3.9	3.8
Total	89	475	420	27.2	23.8

Notes: ϵ_c = compound exergy efficiency; potential for saving energy ≡ conversion losses

4.2.2 Theoretical energy and carbon savings

Theoretical energy savings can now be calculated for each complete energy chain, from fuel to useful energy. Using equation 3.1, the *target efficiency* is set to unity and the *current efficiency* equals the compound efficiency for each chain (ϵ_c), from table 4.5. The corresponding savings in carbon emissions are calculated by equating the fossil fuel energy inputs with their direct carbon emissions, and are reported in table 4.6. This allows alternative energy chains to be compared and ranked, based on the potential for energy savings, and for responses to be directed towards the conversion devices with the greatest improvement potential.

Table 4.6 shows that 85% of conversion losses can be attributed to the provision of heat and motion (10.4 and 9.6 EJ respectively, out of a total 23.8 EJ). The top half of the table is dominated by heater, burners and engines, and efforts should be focused on improving the efficiency of these devices. Lighting devices, electronics and aircraft engines together account for less than 10% of global loss. Efforts aimed at promoting Compact Fluorescent Light-bulb (CFL) and reducing electronic standby losses, present easy gains due to their relatively low efficiencies and help raise public awareness of efficiency concerns, but will not make a significant impact on energy consumption. The conversion efficiency of aircraft engines is already high (27%), suggesting that improvement in engine efficiency will be difficult to achieve, *and* the available energy savings at the global level are small. Thus few technical options remain to improve the energy efficiency of flying, so a reduction in carbon emissions from this sector can only be achieved by a reduction in the number of flights.

4.2.3 Understanding how energy is lost

The global map of energy conversion (figure 4.1) shows that only a small fraction of the available energy supply is converted to *useful energy* in conversion devices . This fraction represents the theoretical minimum amount of energy that is required to provide the same amount of final service (assuming the downstream passive system does not change). The remaining energy is ‘lost’ to the environment as non-recoverable energy in the form of low-temperature heat, and is equal to the theoretical energy savings calculated above. The breakdown of loss mechanisms presented in this chapter is the first known attempt to collate and rank global conversion losses by technical categories. Understanding how energy is lost helps to direct research priorities and technical innovation for engineers and technical designers. Therefore table 4.7 shows how the energy lost from conversion devices, shown in figure 4.1, is reallocated to ten loss mechanisms.

Table 4.7 Categorisation of energy loss by mechanism

Loss mechanism EJ	Fuel conversion	Electricity generation	Device conversion[a]	Total Loss
Internal heat exchange[b]	0	25	51	76
Heat exchange	0	24	49	73
Exhaust	0	7	47	54
Electrical resistance	0	15	34	49
Heat loss	0	19	26	45
Oxidation[b]	0	15	29	44
Fuel loss	34	0	0	34
Friction	0	10	12	22
Fission	0	15	0	15
Mixing[b]	0	2	6	8
Heat transfer	0	50	122	172
Combustion	0	42	86	128
Other[c]	34	40	46	120
Total	34	132	254	420

Notes: [a] in end-use devices; [b] in combustion processes; [c] includes friction, electrical, fission, fuel losses

Heat transfer processes are identified as the most significant source of loss (at 172 EJ, more than 40%). This stems from the irreversible nature of heat transfer across a finite temperature difference, and reflects the ill-considered use of high quality energy sources (fossil fuels and electricity) for low temperature applications. Combustion processes are a significant source of losses (128 EJ, 30%), especially from internal heat exchange when cold reactants mix with hot combusted products. The majority of combustion losses cannot be avoided without separating the reactant and product streams, suggesting that long-term technical opportunities lie in devices which convert chemical energy directly to electricity. Surprisingly, friction does not figure prominently in the analysis indicating that the research activity in the fields of lubrication and tribology, though important for preventing material wear and hence reducing equipment costs, have limited scope for reducing energy use.

4.3 Conclusion

Developing more efficient energy conversion devices is essential if efforts to reduce carbon emissions are to be successful. The global map of energy efficiency presented in this chapter allows conversion devices to be ranked according to their theoretical improvement potential. The analysis makes three novel contributions to our understanding of energy efficiency by:

- determining the average global conversion efficiency of devices along each individual energy chain, and presenting this analysis in a visually accessible format
- combining the scale of energy flow and the theoretical limits to efficiency to identify key areas where technical innovation is likely to deliver gains
- allocating, for the first time, global energy losses to engineering loss mechanisms to direct priorities

Simple options for improving device efficiency include moving the average global efficiency towards best practice and reducing excess capacity from over-design. For example, the average efficiency of energy use in light devices is 4%, still far below advanced technologies such as CFL and light emitting diodes Light Emitting Diodes (LED) with efficiencies above 20%. Similarly, electricity generation in advanced gas-turbine plants is approaching efficiencies of 60%, yet the global average is nearer to half this value. Many conversion devices are also over-designed for excess capacity so operate well away from their optimal efficiency point. This is the case with vehicle engines, which at normal cruising conditions operate well below their optimum efficiency, because of the requirement to have reserve power for acceleration. Designs which avoid or smooth out these peaks in power demand, such as hybrid power systems in vehicles, deliver much higher conversion efficiencies.

How much of the theoretical efficiency improvement could be realised in practice? Beyond the simple gains described above, it is necessary to consider the technical barriers preventing advances in energy efficiency and look for alternative technology chains to deliver useful energy. In practice, there are many technical factors that prevent designers from approaching theoretical efficiency limits. For example, combustion processes, because they convert fuel into heat, are constrained by Carnot's Law and the adiabatic flame temperature of the fuel. This means that the efficiency of power generation is unlikely to rise much above 65% and current efforts to improve efficiency—for example, increasing the heat addition temperature by using novel materials, preheating combustion reactants, extracting mechanical work from turbines prior to steam production—will give only incremental gains. To approach the thermodynamic limit would require avoiding combustion altogether, by converting the chemical energy in fuels directly into electricity (and then motion) in devices such as fuel cells.

Nevertheless, the overriding lesson from this analysis is to begin focusing research initiatives and directing efficiency policy towards the technical devices in which the greatest gains can be found. Only 11% of primary energy is converted into useful energy, thus the theoretical gains available are substantial.

5 PRACTICAL EFFICIENCY LIMITS IN PASSIVE SYSTEMS

Efforts to improve energy efficiency can be divided into two technical approaches. The first is to improve the efficiency of energy conversion devices which upgrade energy into more useful forms such as motion, heat and light. For example, efficiency improvements can be made to the internal combustion engine, which converts the fuel's chemical energy into the more useful form of vehicle motion. Finding the theoretical efficiency limits in conversion devices is described in the previous chapter 4.

The second approach, which is less often considered, requres making better use of the upgraded energy to deliver more final service (such as transport, thermal comfort and illumination). Not only can the efficiency of the engine be improved, but also the aerodynamic design of the vehicle can be adapted to deliver more transport service. However, for passive systems no conversion of energy takes place and therefore a theoretical efficiency limit cannot be calculated. For example, a perfectly insulated building would require no heat input from a space heating device to maintain thermal comfort, giving an infinite efficiency limit which is nonsensical. Instead, only a practical efficiency limit can be defined for passive systems, measuring the minimum energy required to deliver a unit of final service.

This chapter explores the practical energy savings available in passive energy systems. A practical efficiency limit is found for each type of passive system, and then multiplied by the global scale of energy flow to determine where technical efforts should be directed. This enables energy researchers and policy makers to predict where the largest gains in passive systems are to be found.

5.1 Methodology: assessing the practical energy savings

The solution proposed here is to assess the practical efficiency limits, using physical models for each passive system. This permits the energy losses from each system to be understood and realistic estimates of energy savings to be made. The challenge is to collate and simplify existing engineering models to obtain sensible values for the efficiency gains achievable, and overlay these onto the global energy flow through each passive system.

5.1.1 The utilisation ratio

To avoid confusion with the various definitions for efficiency, a new term is defined for passive systems called the utilisation ratio:

$$\text{UR} = \text{Utilisation Ratio} = \frac{\text{Energy input}}{\text{Final service output (physcial)}} \tag{5.1}$$

which is typically measured in MJ/km for transport and MJ/kg of material for steel or aluminium. A lower value of the utilisation ratio indicates the energy is being used more effectively. The practical energy savings available from a passive system can be described by:

$$\begin{array}{c}\text{Potential for}\\\text{saving energy}\end{array} = \begin{array}{c}\text{Scale of}\\\text{energy flow}\end{array} \times \left[1 - \frac{\text{Practical UR limit}}{\text{Current UR}}\right] \tag{5.2}$$

The *scale of energy flow* is found by allocating global energy supply in exajoules (EJ = 10^{18} J) to 12 passive system categories as shown in table 5.1. The term within the brackets gives a percentage measure of the practical savings available in each passive system, up to a maximum limit of 100%. The ratio is dimensionless as long as the terms are calculated using the same energy input and final service output.

5.1.2 *More final services for less energy input*

Passive energy systems are located at the end of each energy chain, and are needed to transform useful energy—in the form of motion, heat, cooling, light and sound—into final services. Although conversion devices are necessary to upgrade energy into more useable

Table 5.1 Global energy supply allocated to passive systems

Passive system	Description	EJ
Building		**215**
Appliance/equipment	Refrigerator, cooker, washer, dryer, dishwasher, electronic devices, mechanical systems	88
Heated/cooled space	Residential/commercial indoor space	86
Hot water system	Fuel and electric immersion boilers	23
Illuminated space	Residential/commercial indoor space, outdoor space	18
Factory		**154**
Furnace	Blast furnace, electric arc furnace, smelter, oven	67
Driven system	Refrigerator, air compressor, conveyor, pump	56
Steam system	Petrochemical cracker, reaction vessel, cleaning facility	31
Vehicle		**106**
Car	Light-duty vehicle: car, mini-van, SUV, pick-up	40
Truck	Heavy duty vehicle: urban delivery, long-haul, bus	38
Plane	Aircraft: jet engine, propeller	10
Ship	Ocean, lake and river craft: ship, barge, ferry	10
Train	Rail vehicle: diesel, diesel-electric, electric, steam	8
Total		**475**

Notes: passive system categories and energy data from chapter 3 forms, it is passive systems which deliver the final services that satisfy human needs and desires. It is these services, a comfortable thermal environment or the illumination of a work space which are sought, not energy itself. The value of final services derives from the loss of useful energy (high quality, low entropy) in their creation. They typically consist of some deviation of state from the surrounding environmental reference, for example, in temperature, pressure, composition or potential/kinetic energy.

The division of final services is shown in table 5.2. Eight distinct but comparable categories are chosen, for which physical data is available or can be inferred from literature. Categories such as 'recreation and leisure' or 'culture' used in alternative studies, for example Carbon Trust,[62] are avoided because the method of allocating energy to these non-physical services is somewhat arbitrary.

To improve passive systems it is necessary to ask: to what level can the energy input to the passive system be reduced, while still providing the same service? In this analysis, behavioural changes which imply a degree of austerity or service loss are avoided, but a careful examination of the final service is undertaken to identify where energy savings might be found. For example, the service provided in passenger transport is to move the mass of passengers over some distance. Theoretically, this service can be achieved using no energy, as the net energy difference between the initial and final position is zero providing there is no change in gravitational position. However, such an idealised case is not practically achievable, as all entropy production would need to be eliminated, requiring an infinitely long trip duration.

In contrast, current passenger transport in cars requires the movement of an additional 2000 kg of vehicle mass as well as spending time idling in traffic jams, which are non-essential to the provision of the service. To find the practical minimum energy required to deliver the service, which lies between today's excessive use and the idealised case, some additional judgement is required. This is achieved by modelling the passive system using scalar equations and varying the equation coefficients within practical values.

The main body of this chapter involves building or adapting physical models for each passive system to to estimate the utilisation ratios. Basic scalar engineering equations are used to describe each system and show how energy is lost. By varying the equation coefficients, within practical limits as defined in literature, the improvement potential in each passive system can be calculated. In this way, the calculated practical energy savings are based on fundamental physical laws, and can be used with confidence to direct engineering design choices. The analysis begins with buildings, followed by factories and then vehicles.

Table 5.2 Current utilisation ratio for final services

Final service	Description	Value
Passenger transport	Person-kilometres travelled by car and plane	$23{\times}10^{12}$ p km
Freight transport	Tonne-kilometres of goods by truck, train and ship	$46{\times}10^{12}$ t km
Structure	Materials used to provide structural support	$28{\times}10^{9}$ MPa$^{2/3}$ m^3
Sustenance	Preparation, storage and cooking of food	$28{\times}10^{18}$ kg K
Hygiene	Clothes washing/drying, hot water use	$1.5{\times}10^{12}$ kg K (water)
	Appliances	$2.8{\times}10^{18}$ N (work)
Thermal comfort	Heating and cooling of air in buildings	$30{\times}10^{15}$ m^3 K
Communication	Digital and written communication	$280{\times}10^{18}$ byte
Illumination	Provision of light	$480{\times}10^{12}$ lm s

5.2 Practical energy savings in buildings

Energy is used in buildings to deliver many varied final services, including warmth in winter and coolness in summer, hot and cold water, light and entertainment, and the storage, preparation and cooking of food. Or as Ford *et al.*[29 (p.5)] states, 'buildings provide an environment for the occupants'. The equivalent of 215 EJ of primary energy is lost from the passive building system as low temperature heat, in exchange for these services. Baumert *et al.*[7] calculate that buildings contribute almost 20% of energy related carbon dioxide emissions, some 6.4 billion tonnes of CO_2, with approximately two thirds coming from residential buildings and the remainder from commercial buildings.

In this section, physical models have been developed for the passive systems in buildings, using a *domestic house* as a reference for heated and cooled space, hot water systems and appliances, and an *office* for illuminated space. Heated and cooled spaces are examined first, followed by hot water systems and illuminated spaces. The appliance category is examined last, despite using the largest fraction of building energy, because of the complexity and heterogeneous nature of this grouping.

5.2.1 Heated spaces in buildings

The provision of thermal comfort in buildings uses 86 EJ of primary energy worldwide. Heating the internal air space accounts for 84% of this energy use, with the remainder used for cooling. Thermal comfort could hypothetically be provided with much less energy if only the occupants, instead of the building space, were heated. People could wear extra layers of clothing when inside, as they already do when outside in winter, or drink more cups of tea. However, such measures involve major behavioural changes which are outside the scope of this chapter. The practical compromise is to heat the occupants and the building space around them, but eliminate energy misuse such as the heating of spaces while the windows are open. The aim is to produce a well designed passive building system which delivers thermal comfort with the minimum practical energy use.

The following assessment of the practical energy savings available in heated spaces begins by building a model from scalar equations to describe the physical basis for heat flows in a typical house and defining 'thermal comfort' for the occupants. Practical limits are found for the coefficients in the model and the effects of the geographic location of the house are considered. Finally, all houses are assumed to be constructed at the practical limit for reducing heat loss and the additional heat required to maintain thermal comfort is calculated for each geographical climate zone. Figure 5.1 shows the heat inputs and outputs for a typical heated building space. The heat inputs and heat outputs can be balanced and expressed as:

$$Q_H + Q_Z + Q_I = Q_S + Q_V + Q_T \tag{5.3}$$

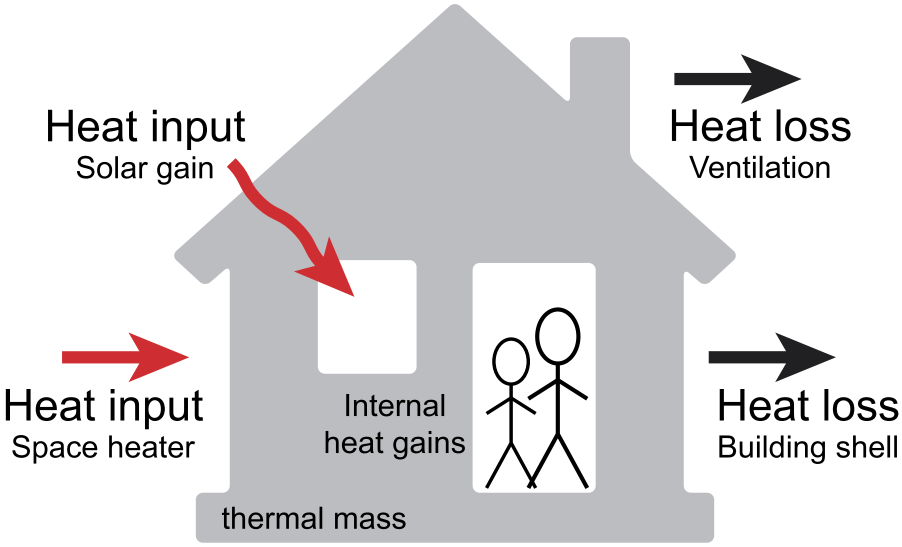

Figure 5.1 Balancing heat loads in a heated building space

where Q are the heat transfer rates (kW) with the subscripts for the heat inputs: H = heater, Z = solar and I = internal, and for the heat losses: S = shell, V = ventilation and T = thermal mass. Scalar equations have been derived for each of the heat losses and gains in equation 5.3.

Shell loss occurs whenever the interior space of a building is warmer than the outside environment. Heat is conducted through the building shell (walls, roof, floor, windows and doors), according to the equation:

$$Q_S = \sum_i (U_i A_i)(T_{inside} - T_{outside}) \tag{5.4}$$

where U is the overall heat transfer coefficient ($\mathrm{W/m^2K}$) of a given building shell section (i.e. wall), A is the external surface area of the section ($\mathrm{m^2}$), and T is the temperature. The U-value is the inverse of the thermal resistance through the shell section, and is calculated for a typical wall by summing the inverse of the surface resistances (R), and the thermal resistance of each material in the wall:

$$U_{wall} = \frac{1}{R_{inside}} + \frac{k_{plaster}}{w_{plaster}} + \frac{k_{insulation}}{w_{insulation}} + \frac{k_{brick}}{w_{brick}} + \frac{1}{R_{outside}} \tag{5.5}$$

where k is the thermal conductivity (W/mK) of the material component and w the component thickness (m). Thus heat transfer through the building shell can be described using only the physical dimensions and material properties of the shell components, and the inside-outside temperature difference.

Ventilation is required to prevent the build-up of carbon dioxide, toxic gases and odours in the interior building space. Fresh air can be provided passively by opening windows or through leaks in the building shell, or actively using a mechanical ventilation system. The temperature of the incoming cold air must be raised to the inside temperature, and the required heat load can be calculated using:

$$Q_V = q\,\rho\,C_p(T_{inside} - T_{outside})(1 - R) \tag{5.6}$$

where q is the air flowrate (m^3/s), ρ is the air density (kg/m^3), C_p is the specific heat capacity of air (kJ/kgK), and R is the fraction of heat recovered in a heat exchanger (%).

Thermal mass measures the ability of the building to store energy or act as a buffer against temperature changes. It represents a heat loss, when the average building temperature is increasing, or a heat gain when the building temperature is falling. It is calculated using:

$$Q_T = m\,C_p\frac{dT}{dt} \tag{5.7}$$

where m is the building system mass (g), with a specific heat capacity C_p (J/gK) and subject to a change in temperature T with time t. For a house, the aim is to maintain the indoor temperature within a comfortable range. Although energy is required to heat the thermal mass initially, once the desired temperature is reached no additional heat is required. The temperature of the thermal mass will fluctuate around some equilibrium and the heat absorbed and released during each cycle will cancel. Designing buildings with large internal thermal mass helps to even out temperature fluctuations.

Solar heat gains result from the radiant heat of the sun passing through the transparent components of the building shell (mainly windows) and heating the building interior. The irradiation reaching a surface at an angle (H_θ in Wh/m^2) is estimated for geographic locations, taking into account the average cloud cover, hours of daylight and incident angle of the sun. The solar heat gain coefficient (C_S) is used to estimate the proportion of the radiant heat that passes through the windows (glazing area A_w in m^2) to the building interior. Thus:

$$Q_Z = A_w C_S H_\theta \tag{5.8}$$

Interior heat gains come from the building occupants, each producing approximately 90 W at rest, and the waste heat from various conversion devices, including lights, refrigerators, cookers and electronics. The heat input from the *space heater* (gas boiler, stove, open fire or electrical heater) is characterised by the mass flowrate and specific heat of the combustion fuel, or by the demand for electricity. The heat input from the space heater, and to some degree the solar heat gain, are varied in a typical house to balance the heat loss and maintain the internal temperature at a comfortable level.

Occupant comfort: The minimum inside temperature to maintain thermal comfort is defined using the European Standard for indoor building environments EN15251[143] and the discussion papers on this standard by Nicol and Humphreys[144] and by Olesen.[145] The central equation used to define a comfortable occupant temperature (T_{comf} in °C) for buildings without mechanical cooling, is:

$$T_{comf} = 0.33 T_{rm} + 18.8 \tag{5.9}$$

where T_{rm} is the running mean of daily outside temperature, for $10\,°\mathrm{C} \leq T_{rm} \leq 30\,°\mathrm{C}$. This equation incorporates the latest research in adaptive comfort theory which models how occupants modify their behaviour in response to temperature changes. Nicol and Humphreys[144] explain that in buildings without HVAC systems (heating, ventilating and air conditioning) the range of acceptable temperatures is much greater, because people respond ‘adaptively’ to temperature change by making clothing changes or opening windows. The occupants’ expectation of a tightly controlled thermal environment is also relaxed.

For the occupant to feel comfortable, the occupant temperature ($T_{occupant}$) must lie within some variation from the comfort temperature. The variance allowed on this comfort temperature is given as ±3 K for a ‘normal’ expectation in new build and renovations (used for this analysis), and ±4 K for a ‘moderate’ expectation in existing buildings. However, the occupant temperature is affected by both the air temperature and the average radiant temperature of the surrounding surfaces. If indoor air speeds are below 0.1 m/s and the air moisture content ignored, then the contribution from the air and surfaces can be assumed equal. Thus the occupant temperature can be expressed as the average of the air and surface temperatures.

For an outside temperature of 10 °C and a normal expectation of comfort (±3 K), the minimum acceptable inside temperature is calculated as 19.1 °C using equation 5.9. This is a lower temperature than would normally be specified in a heated space, because of the adaptive comfort assumptions. The aim of the practical minimum house design is to trap solar and internal heat gains within the building enclosure, and therefore bridge the difference of 9.1 °C between the inside and outside temperatures. If the outdoor temperature falls below 10 °C then equation 5.9 no longer applies, and the minimum indoor temperature is taken as 19.1 °C.

Equations 5.3–5.9 are used to estimate the practical energy savings available in heated spaces. This involves three steps: (1) defining the physical parameters for the model house which operates at the practical design limit; (2) categorising building locations by climatic zone to quantify the effects of solar heat gains and outdoor temperature; (3) performing a heat balance by climatic zone to determine the additional heat requirements for the model house.

Model house: A typical two-storey detached house is used as a basis for modelling the heated space. The house measures 6.5 m wide by 7.0 m long with the overall height of both floors measuring 6.0 m, and has 6.0 m^2 of vertical windows facing the sun. The sample house is occupied by 3 people, each producing approximately 90 kW at rest. The selected practical limits for the equation coefficients are based on the PassivHaus design,[146] and are given in table 5.3.

More than 7000 buildings across Europe have reached the PassivHaus standard, each with an annual space heating and cooling load below 15 kWh/m^2 (54 MJ/m^2). Low energy requirements are achieved by specifying high levels of thermal insulation, making use of solar and internal gains, and providing excellent airtightness using mechanical ventilation systems with heat recovery. Typical wall and roof constructions use more than 300 mm of cavity insulation with minimal thermal bridging, and triple-glazed windows are standard. For this analysis, the only adjustment made to the PassivHaus standard is to reduce the design U-value for the exterior shell components (roof, wall and floor). The standard recommends a maximum U-value of 0.15 W/m^{2}K but in practice a U-value of 0.10 W/m^{2}K can be achieved.

Table 5.3 Typical and practical limit constants for heated spaces

Description	Symbol	Typical	Practical limit[1]	Units
U-values				
Roof	U_{roof}	0.4–2	0.10	W/m^{2}K
Walls	U_{wall}	0.5–2	0.10	W/m^{2}K
Floor	U_{floor}	0.4–2	0.10	W/m^{2}K
Windows	U_{window}	3–5	0.80	W/m^{2}K
Ventilation rate	q	10–50	7	l/s/person
Solar heat gain	C_S	0.4–0.6	0.5	
Heat recovery	R	0	0.8	

Notes: [1] based on Passivhaus design standard.[146]

Table 5.4 Climatic data for temperate and cold geographical zones

City		Oct	Nov	Dec	Jan	Feb	Mar	Year
Barcelona, Spain (temperate zone)								
H_{90°	kWh/m^2	3.72	3.21	3.17	3.26	3.33	3.68	3.19
$T_{outside}$	°C	18.0	12.6	9.6	9.2	9.7	12.0	16.2
Cambridge, England (temperate zone)								
H_{90°	kWh/m^2	2.26	1.57	0.94	1.39	1.97	2.25	2.19
$T_{outside}$	°C	11.7	7.5	4.9	4.7	5.4	6.8	10.7
Oslo, Norway (cold zone)								
H_{90°	kWh/m^2	1.57	0.88	0.58	0.64	1.46	2.15	2.03
$T_{outside}$	°C	6.8	1.7	-2.4	-3.2	-2.6	-0.3	6.2
St Petersburg, Russia (cold zone)								
H_{90°	kWh/m^2	1.64	0.65	0.36	0.76	2.10	3.18	3.08
$T_{outside}$	°C	6.1	-0.2	-4.4	-5.7	-6.2	-2.5	5.5

Notes: H_{90° = daily solar irradiation for a surface at 90°, $T_{outside}$ = 24 hour average outside temperature

Climatic data: the solar conditions and outside temperatures vary according to geographic location. Therefore, the world population is divided into four climatic zones—tropical (24%), desert (17%), temperate (44%), cold (14%)—using country level data from the CIESIN database.[147] Solar irradiation levels (H_{90°) and outside temperatures ($T_{outside}$) are taken from the database managed by PVGIS,[148] for two representative cities in each of the colder zones. The 24 hour average outside temperature is used in place of the running mean temperature suggested in equation 5.9. Olesen[145] comments that little separates these two measures, but that on average the running mean gives slightly wider fluctuations in temperature. However, it is assumed that the model house has sufficient thermal mass to even out any daily fluctuations in temperature above or below the average. Table 5.4 collates this climatic data for each city in the winter months.

Heat balance: the model house parameters and climatic data

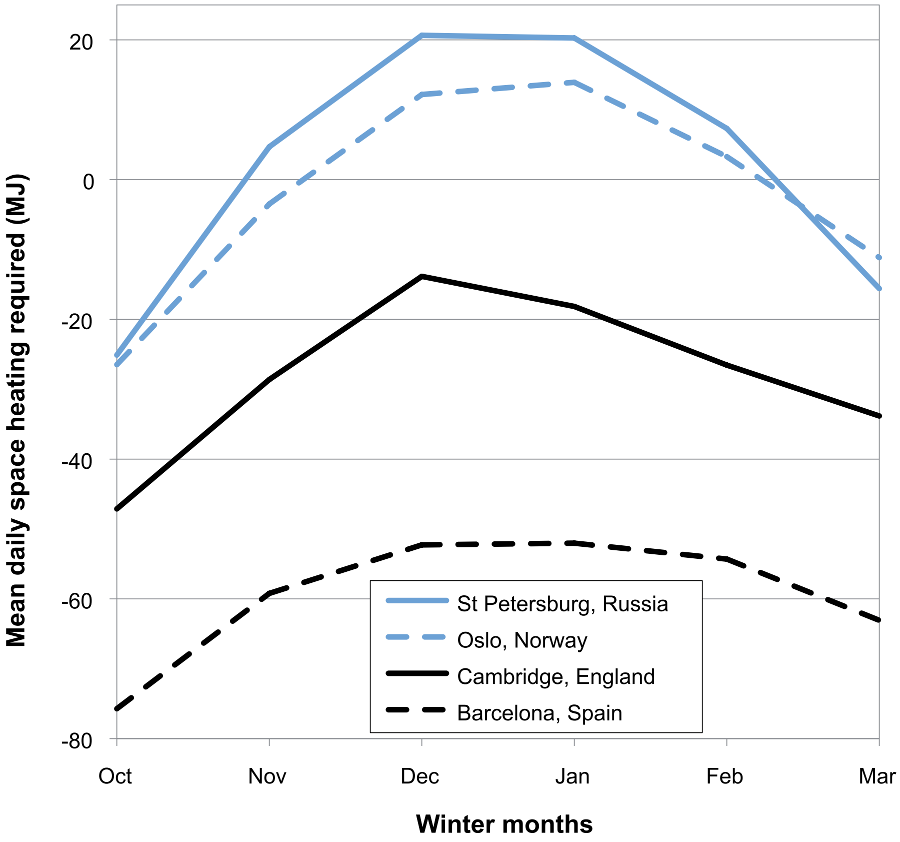

Figure 5.2 Heat requirement in temperate and cold climatic zones

are used in equations 5.3–5.9 to assess the additional space heating requirements. The comfort temperature variation in equation 5.9 is assumed to be ±3 K, a normal expectation for a new build or renovation. The results are shown in figure 5.2, with a mean daily heat requirement (MJ) greater than zero, indicating that additional heat input is required.

The graph shows that for a model house located in a temperate zone (for example, Barcelona or Cambridge) the solar and internal heats gains are sufficient to maintain thermal comfort throughout the winter months. In fact the windows may need to be opened on occasion to prevent overheating. For a model house located in St Petersburg the maximum daily heat from the space heater is about 20 MJ. This equates to 1.6 GJ of additional energy over the year to maintain thermal comfort (the area between the curve and zero), which is less than 5 kWh/m^2 (18 MJ/m^2) per year.

Currently 14% of the world's population, some 850 million people, live in the cold climatic zone[147] for which additional heating of the model house is needed. Angel *et al.*[149] reports the global mean floor area per person as 18 m^2 with a range from 4–69 m^2, which makes the model house floor area of 30 m^2 per person conservative. Although this floor area does not include commercial buildings it is assumed that when people are working in offices they occupy an equivalent floor area, and that as the same time their home space is unheated. Thus, if all houses were constructed equal to the model house, the global requirement for space heating equals:

$$Q_H = 850\times10^6 \times 18\,\mathrm{MJ/m^2} \times 30\,\mathrm{m^2} = 0.5\,\mathrm{EJ}. \tag{5.10}$$

which can be compared to the current global energy used for space heating of 28 EJ (at a weighted first law conversion efficiency of 40% from primary energy to delivered heat). The conclusion is that if all buildings were designed at their practical limit, the energy required for space heating would be reduced by 98%.

5.2.2 *Cooled spaces in buildings*

The strategy in cooler climates is to minimise heat loss from buildings by insulating and controlling ventilation, so that solar and internal heat gains are trapped to maintain a comfortable temperature. In hot climates, this strategy is reversed. Solar heat gains are minimised by providing shading—in the form of an extended roof overhang, shutters and deciduous trees—and insulating the building exterior to keep heat out. Ventilation rates are increased by opening windows and doors to remove the now unwanted internal gains from devices and from the occupants. Thermal mass can

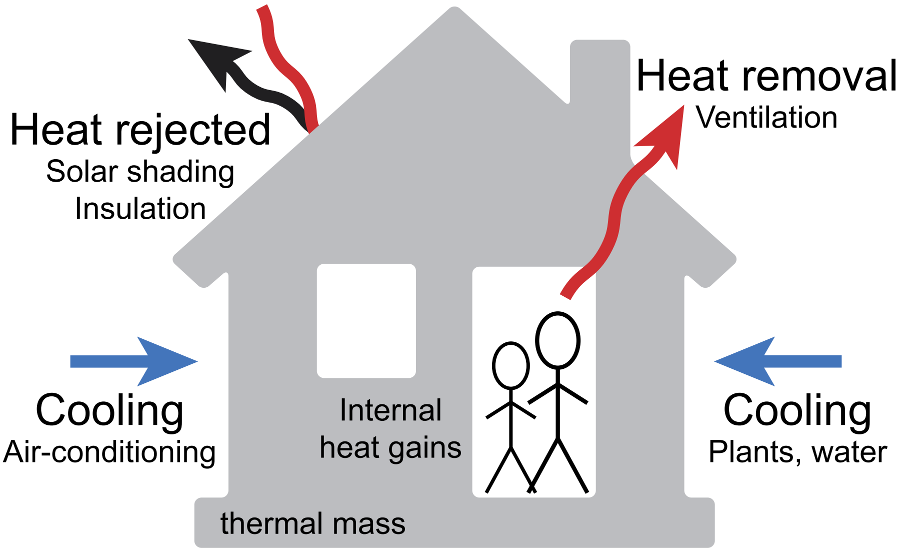

Figure 5.3 Balancing heat and cooling loads in a cooled building space

be used to even out temperature fluctuations, preventing the building from heating up too quickly, and water features and plants can provide additional evaporative cooling. Additional space cooling is provided by air-conditioning equipment which currently is responsible for 14 EJ of primary energy use worldwide. An overview of these heating and cooling flows is shown in figure 5.3.

Modelling the cooled space is much simpler than the heated space. The maximum inside temperature that is comfortable for the occupants is calculated as 31.7 °C using using equation 5.9. The upper range limit for the outdoor temperature is taken as T_{rm} =30 °C, and a normal expectation of variance from the comfort temperature (±3 K) is assumed. In a well designed building solar heat gains are reduced to zero and internal gains can be removed by increased ventilation. Therefore, it can be assumed that the inside temperature is always less than the outside temperature, and that the occupants will be comfortable when the running mean outside temperature remains below 31.7 °C.

Table 5.5 shows the average outside temperatures for the two representative cities in each of the warmer climatic zones, from

PVGIS[148] and Hoare.[150] The maximum recorded temperature is 27.7 °C, which is 4 °C less than the limit for occupant comfort. This suggests that if all houses were designed at the practical limit and the specification for thermal comfort was relaxed, air-conditioning would never be required, even in the hottest climates. Thus 100% of the energy used to cool building spaces could, in practice, be saved. Once again, it is assumed that the 24 hour average temperature and the running mean temperature are interchangeable, and that the model house has sufficient thermal mass to even out the daily fluctuations in temperature. Additional cooling provided by water features and plants has not been considered.

5.2.3 *Hot water systems*

The provision of hot water in buildings accounts for 23 EJ of primary energy consumption. The IPCC[151] report lists six options for reducing the energy used to heat water: (i) water efficient fixtures and appliances; (ii) more efficient and better insulated water heaters; (iii) tankless 'point-of-use' water heaters; (iv) heat recovery from waste water; (v) air-source heat pumps; (vi) solar water heaters, and estimate the combined effect of all these measures to approach 90% energy savings. However, the purpose of the passive hot-water system is not to heat the water, but rather to store and

Table 5.5 Climatic data for tropical and desert zones

City	$T_{outside}$ (°C)						
Tropical	Oct	Nov	Dec	Jan	Feb	Mar	Year
Singapore	27.2	26.8	26.3	26.9	27.3	27.7	27.1
Accra, Ghana	26.0	26.9	27.1	27.4	27.6	27.6	26.3
Desert	May	Jun	Jul	Aug	Sep	Oct	Year
Tunisi, Tunisia	18.3	22.6	25.5	26.3	23.9	19.5	17.7
Rabat, Morocco	17.3	20.1	22.3	22.6	22.1	19.4	17.6

Notes: $T_{outside}$ = 24 hour average outside temperature distribute hot water to the point of use. Therefore several options can be eliminated such as improving the combustion efficiency of the water heater, switching to a solar or heat pump options, or upgrading the appliances which use hot water. Demand reduction measures, such as installing low-flow shower heads and faucets, are not assessed as they are considered behavioural changes. Better insulation is a valid option for systems which store hot water, but greater gains are available by removing the cylinder altogether and installing point-of-use water heaters. Therefore, only the practical energy savings from tankless hot water systems and heat recovery are assessed.

The heat balance for the hot water system can be modelled using:

$$Q_H = m\, C_p(T_{out} - T_{in}) + Q_L \tag{5.11}$$

where the heat transfer rate Q_H (kW) must be sufficient to heat the water—where m is the mass flowrate of water (kg/s), C_p is the specific heat capacity of water (J/gK), and T_{out} and T_{in} the hot water outlet and cold water inlet temperatures (°C)—and to balance Q_L, the loss of heat during storage and distribution of hot water from the cylinders, fixtures and distribution pipes. There are two benefits from using a tankless point-of-use system which dispenses with the storage and distribution of hot water: Q_L can be reduced to zero and the outlet water temperature can be reduced.

The heat loss from water cylinders can be calculated using equation 5.4. For example, a typical 210 l cylinder at 65 °C and with 2.5 cm thick insulation (U =1.1 W/m^{2}K) loses about 110 W. The same cylinder stores approximately 40 MJ of energy, relative to an inside building temperature of 20 °C, giving a typical storage time of 120 h. The rate of heat loss is relatively slow allowing the water to be heated intermittently. Hot water in distribution pipes cools more quickly due to the higher surface area to volume ratio, however the overall heat loss is less than for the cylinder because of the small volume of hot water stored in the pipes. The USDOE[152] website states that insulating pipes can raise the water temperature by 1–2 °C at the point of use. Ford *et al.*[29] estimate that about 30% of the energy used in a storage system is lost from the cylinder, fittings and piping. For a point-of-use hot water system losses can be ignored, leading to a practical energy saving of 30%.

Hot water storage systems are typically required to maintain a minimum temperature of 60 °C throughout the system to prevent the growth of legionella bacteria. This means water heaters typically have a set temperature of 65 °C. Yet, the dishwasher is the only household application which requires a water temperature above 50 °C and is often fitted with a built-in heating coil to boost temperature. Mixing hot water with cold water to obtain the correct temperature makes little sense from a thermodynamic viewpoint as entropy is increased. Fortunately, a temperature of 50 °C is sufficient to avoid bacteria growth if the water is used immediately after heating. Reducing the hot water temperature T_h in equation 5.11 from 65 °C to 50 °C, saves a further 19% of the water heater energy.

Further gains are available using a drain-water heat recovery system, as shown in figure 5.4. In recovery systems, heat from the waste water is captured and used to preheat the cold water, reducing the heat requirements of the water heater. Storage of the heat is needed for applications where hot water is used in batches rather than continuously, for example, in bathtubs, sinks and clothes washers. According to the USDOE[152] 80–90% of the energy used to heat the water is lost down the drain. The proportion of energy recovered can be estimated using a simple countercurrent heat exchanger model.

If it is assumed that no heat is lost to the surrounding environment, then the heat balance for the the exchanger can be written

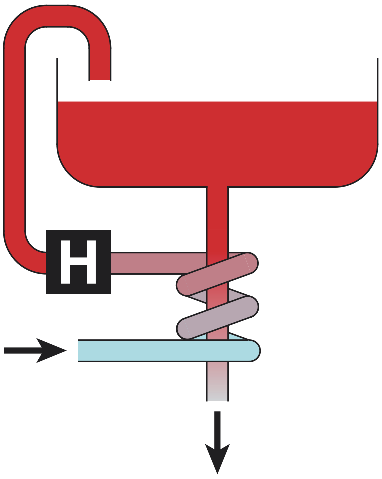

Figure 5.4 On-demand hot water and heat recovery from waste water

as:

$$Q_h = m_h\,C_p(T_{in,h} - T_{out,h}) = Q_c = m_c\,C_p(T_{in,c} - T_{out,c}) \quad (5.12)$$

where the subscripts h and c denote the hot and cold fluids. For the heat recovery system, the mass flowrate (m) and the specific heat capacity (C_p) are assumed equal. Under these conditions the temperature drop in the hot water ($\triangle T_h$) must equal the temperature rise in the cold water ($\triangle T_c$).

The heat exchanger equation is defined as:

$$Q_X = fUA\triangle T_{LM}(= Q_h = Q_c) \quad (5.13)$$

where f is a temperature correction factor based on the heat exchanger design, U is the overall heat transfer coefficient ($\mathrm{W/m^2K}$), A is the heat transfer area (m^2) and T_{LM} is the log-mean temperature difference (°C), measuring the average temperature difference between the hot and cold fluids.

The proposed heat recovery system is assumed to be purely counter-flow, allowing f to be set to unity. Typical U-values for water to water heat exchangers range from 800–1500 W/m^{2}K, so the upper limit is selected. The general aim is to minimise the temperature difference T_{LM} so that the outlet temperature of the cold water ($T_{out,c}$), is as close as possible to the inlet temperature of the hot water ($T_{in,h}$). Temperature approaches as low as 1 °C are possible with advanced heat exchanger designs, with fine channels giving very large heat transfer areas, however these are only suitable for non-fouling applications.

A more conservative temperature difference of 10 °C is chosen for the heat recovery system to avoid fouling from the hot waste water, giving a heat transfer area of 3.1 m^2. If a compact plate heat exchanger is selected with a typical surface area density of 400 m^2/m^3,[153] then the unit would fit in a cube of side length 0.2 m, which is credible.

The reduced heat requirement of the point-of-use water heater, with heat recovery installed, can now be calculated. Hot water is supplied from the water heater at 50 °C. Average losses during the use of the water (15%) reduce the drain-water temperature to 44 °C, which is used as the exchanger inlet temperature ($T_{in,h}$). A temperature difference of 10 °C in the exchanger gives a cold water outlet temperature ($T_{out,c}$) equal to 34 °C. Thus the water heater only needs to raise the temperature 16 °C, bringing the overall practical savings to 80% for the passive hot water system, as summarised in table 5.6. This agrees well with the range heat recovery rates, 50–80%, given for hot water heat transfer applications in USDOE.[90(p.126)]

5.2.4 *Illuminated space*

Artificial lighting is responsible for 18 EJ of primary energy use, with 99% of lighting devices connected to the electrical grid. The potential for saving energy in lighting applications is large, ranging from 25 to 80% in case studies reported in the International Energy Agency (IEA) 'Light's labour lost' report,[117] however most solutions focus on improving the efficiency of the lighting device. Less attention is given to improving the passive system surrounding the light device, from which significant gains can also be achieved.

The key variable for the passive lighting system is *luminous flux*, which measures the *perceived* light emitted from a light source, in lumens (lm). It is found by calculating the total light 'power' (or radiant flux) from a light source and adjusting for the sensitivity of the human eye to different light wavelengths. The aim is to minimise the lumens required (and therefore the energy) from the light device, without compromising the illumination service.

Illuminance (E) measures the final service delivered by the lighting system. It is the amount of light (or luminous flux) incident on a plane per unit area, expressed in units of lux (lx = $\mathrm{lm/m^2}$). Minimum illuminance levels are specified in lighting codes for different building spaces, ranging from 54 lx for hallways and utility rooms to 430 lx for office lighting, in IEA.[117] The human eye is designed to cope with a wide range of lighting levels—the illuminance for an overcast day is typically 50,000 lx, which is 100 times greater than a typical office space.

The practical energy savings for the passive lighting system can

Table 5.6 Practical energy savings in hot water systems

System configuration	T_{in} °C	T_{out} °C	Savings[1] %
Storage water heater	10	65	
Point-of-use, no storage	10	65	30
Point-of-use, lower temp.	10	50	49
Point-of-use, heat recovery	34	50	80
		Practical energy savings available	**80%**

Notes: [1] cumulative savings from reference case (storage water heater) be found by minimising the luminous flux from the light device (LF_{device} or source-lumens) while still maintaining a specified level of illuminance, using the equation:

$$LF_{device} = \frac{E \times A}{UF \times LLF} \tag{5.14}$$

where E is the average illuminance, UF is the light utilisation factor, and A is the horizontal illuminated area which is assumed to be constant for a given lighting application.

LLF is the light loss factor, which accounts for the degraded performance of the lighting system with time under real conditions, in comparison to laboratory tests. It can be divided into non-recoverable components, such as the physical degradation of the lamp, fixture and room reflectance over time, and recoverable components, such as cleaning and maintenance. Although some technical improvement in LLF is possible, for example by using materials that do not 'yellow' or designing self cleaning systems, the largest gains are found in the organisation of maintenance practices. For this reason the light loss factor is also kept constant in the model. This leaves three strategies for improving the passive lighting system: avoiding over-capacity in light design, focusing light on the task area (both which reduce the average luminance level (E)) and increasing the utilisation factor (UF).

Firstly, illuminance levels in real applications are frequently specified much higher than the application requires. This results from an historical trend in lighting design to specify ever brighter working spaces, and the need to provide extra capacity to cover variable light distribution and future degradation of illuminance levels. IEA[117 (tab 4.6)] estimates the average illuminance levels in commercial offices to be 775 lx for Organisation for Economic Co-operation and Development (OECD) countries, whereas the Illuminating Engineers Society of North America (IESNA) recommends a level of 430 lx. Thus commercial lighting applications

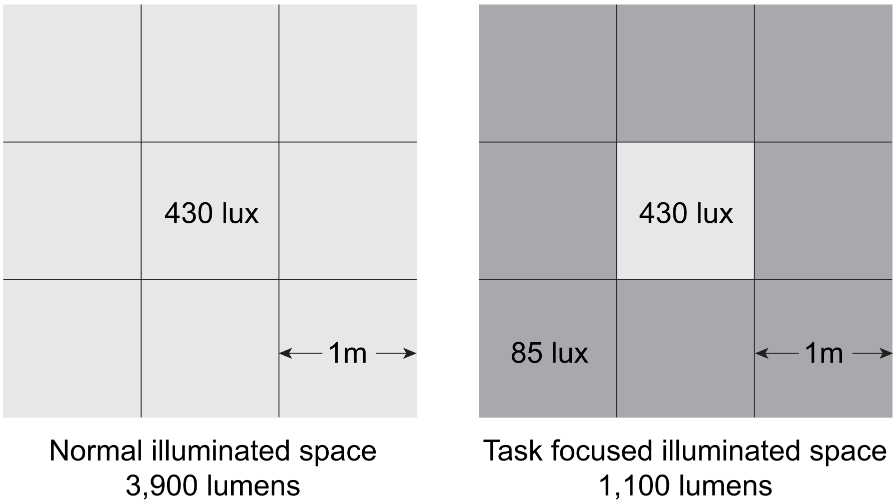

Figure 5.5 Reduction in luminous flux from using task lighting

are currently 44% over-designed.

Secondly, a uniform level of light is not required over the entire floor area, if light is instead focused where the task occurs. This is illustrated using the simple model shown in figure 5.5, which is based around the hypothetical example given in IEA.[117(tab 4.6)]

For the reference office it is assumed that a person occupies a floor area of $9\,\mathrm{m}^2$, at a uniform illuminance of 430 lx. For an office designed at the practical limit, only $1\,\mathrm{m}^2$ is illuminated at the task level, with the light level in the surrounding area reduced by 80%. Although the specified minimum uniformity factors (the variance of illuminance levels across a space) in lighting codes range from 0.33 to 0.8, a factor of 0.2 is considered the practical limit for occupant comfort. In comparison, Ford *et al.*[29] have calculated that humans are comfortable with natural light levels that can vary by more than 7 orders of magnitude. This redistribution of light results in a practical saving of more than 70%.

Thirdly, modifications can be made to the luminaire (or light housing) and the room to improve the utilisation factor (UF). Ford *et al.*[29] estimate that only half of the light from a typical device reaches the horizontal surface, whereas the IEA[117] believe

Table 5.7 Practical energy savings in passive lighting systems

Configuration	E Wm^2	UF lm/W	Efficacy[1] $\mathrm{lm/m}^2$	LPD	Savings[2] %
Reference[3]	775	0.3	50	15.5	
Correct E limit	430	0.3	50	8.6	44
Task lighting	125	0.3	50	2.5	84
Improved UF	125	0.9	150	0.8	95
				Practical energy savings available	**95%**

Notes: LPD = average lighting power density, E = illuminance $\mathrm{lm/m}^2$ [1] Overall lighting system efficacy [2] cumulative savings from reference office. [3] based on estimated data for commercial buildings in the OCED 2000, from IEA.[117(tab 4.6)]

the figure is much lower at 30%. The remaining light is trapped in the luminaire or lost to the ceiling and walls where it is not needed. The luminaire output ratio (LOR) accounts for losses in the luminaire and ranges from 0.3 for uncleaned painted surfaces to 0.96 for mirrored surfaces. Minimum LOR of 0.7 in commercial lighting and 0.5 in residential lighting are recommended for new installations, and the current average LOR is likely to be less than 0.5. Thus, a two-fold improvement in LOR is realistic if the most advanced light housings are used.

The other contributions to the utilisation factor are the dimensions of the room, reflectance of the ceilings and walls, position of the light fixtures and height of the task surface. In the absence of statistical data to quantify these contributions, an overall UF of 0.9 is assumed for the practical limit.

Table 5.7 presents the results of minimising the illuminance levels (E) and the utilisation factor (UF), giving an overall practical energy saving of 95%. The model is based on commercial office lighting, which according to the IEA [117] accounts for 43% of global energy use in lighting. Although the illuminance levels for residential (31%), industrial (18%) and outdoor (8%) lighting are generally lower, this is counteracted by typically larger illuminated floor areas and lower utilisation factors. Therefore, the percentage gains for commercial lighting are applied across all lighting applications. The reference is based on commercial lighting in OCED countries, which is likely to give conservative energy savings in comparison to offices in the developing world.

Efficacy is the ratio of light produced to electrical power consumed, in lumens per watt (lm/W). It is specified here for the overall lighting system, and therefore reflects the change in the UF. However, the efficacy of the lighting conversion device and the efficiency of the upstream electricity generation is left unchanged in the model, so that only the energy savings from the passive system are assessed. The IEA[117] states that daylighting (from the sun) might already be offsetting 25% of artificial lighting needs in commercial buildings and reported savings in daylighting case studies range from 15–80% for offices. However, these potential gains have not been included in the analysis.

5.2.5 Appliances

The appliance category uses a larger fraction of primary energy than any other building category, some 88 EJ. This energy is consumed in the delivery of three broad services: sustenance (55 EJ), hygiene (17 EJ) and communication (16 EJ). Nevertheless, the appliance category is the last building category to be analysed for three reasons. Firstly, the grouping covers a wide range of different applications including cooking, washing, cooling, drying and processing information. Secondly, there is more variety of technical designs within each application, in comparison to other passive systems. For example, food can be cooked using a wood fuelled open fire, a gas oven, or a microwave. Thirdly, energy data for appliances in literature is not easily divided between the conversion device and the passive system. This makes it time-consuming to develop a single model for each appliance.

Table 5.8 Practical energy savings in appliance systems

Appliance	Elec EJ	Fuel EJ	Primary energy EJ	 %	Savings[1] %
Cooker	8	27[2]	35	40	80
Refrigerator/freezer	15	0	15	17	88
Consumer electronic	11	0	11	13	0
Washing machine	4	0	4	4	91
Dishwasher	2	0	2	2	91
Clothes dryer	2	0	2	2	65
Other	11	8	19	22	59
Total	53	35	88	100	67
				Practical energy savings available	**67%**

Notes: Data from Nakicenovic *et al.*[111] and Jäger-Waldau.[154] [1]Percentage energy savings available in each appliance. [2]Includes 18 EJ of biomass

Table 5.8 shows a breakdown of global energy used in appliances and the practical energy savings available in each type of appliance. To follow is a description of how the practical savings are calculated for each appliance type.

Cookers: The global energy required for cooking food (35 EJ) is comparable to the energy used in the transportation of goods by truck. Cooking food changes its flavour, texture, appearance, and nutritional properties, and according to Warwick and Doig[155] is required to make 95% of staple foods edible. More than half the global energy used for cooking comes from biomass sources (such as wood, dung, crop), another quarter from electricity, one fifth from gas, and the remaining few percent from oil and coal. Significant energy savings are available from improving the combustion efficiency and the heat transfer between the heat source and the vessel, but are not considered here as they relate to the conversion device. Only the passive system, the container or vessel in which the food is cooked is analysed.

Food is typically heated by one or some combination of the following heat transfer mechanisms:

Conduction where the food is in direct contact with the vessel, for example when frying

Convection where heat is transferred to the food by the movement of the fluid (air, water or oil) surrounding the food, for example when boiling

Radiation involving the direct transfer of heat or microwave radiation to the food, for example when grilling or using the microwave

Heat loss occurs through the shell of the vessel, when the heating fluid (air or steam) leaks from the vessel and when the heat stored in the thermal mass of the system is not recovered. Thus the heat required (Q in kW) to cook the food can be written as:

$$Q = Q_S + Q_V + Q_T \tag{5.15}$$

Q_S is the heat loss through the shell of the vessel, Q_V results from the venting of cooking fluid and Q_T is the heat required to change the temperature (T) of the thermal mass of the food, cooking fluid and vessel. Normally the thermal mass term would act as a buffer to changes in temperature, absorbing and releasing heat. However, for the model it is considered a loss, because the absorbed heat is typically lost after the cooking is finished, as the cooking vessel cools down and the fluid escapes or is discarded.

Three models have been created to estimate the practical savings available in passive cooking systems: a pot on a stove top, a conventional oven and a microwave oven. The breakdown of heat losses, into the shell, ventilation and thermal mass components is inferred from literature or estimated, due to the lack of complete energy studies of cooking in literature.

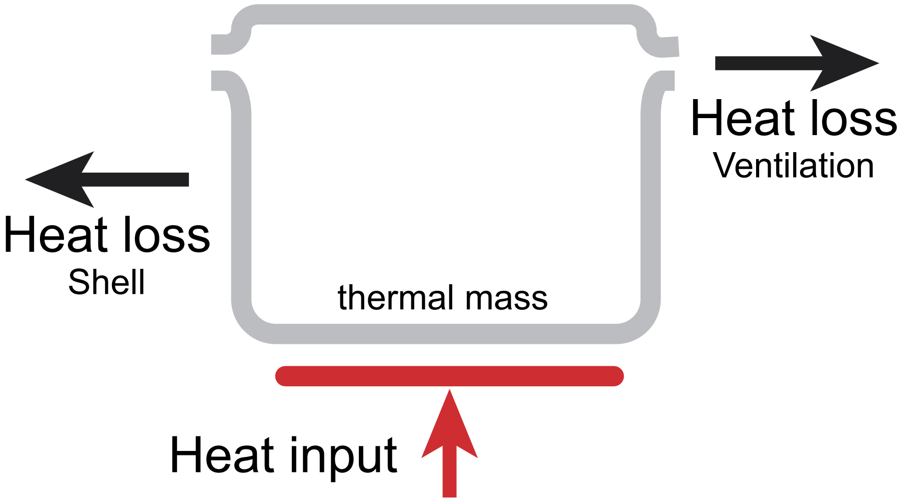

Figure 5.6 Heat balance for cooking vessel (pot)

Table 5.9 Enthalpy change for heating and boiling a litre of water

Stage	Temperature	Enthalpy change	
	°C	kJ/kg	%
Heating	20 to 100	335	13
Evaporation (latent heat)	100	2,270	87
Total (water to steam)	20 to 100	2,605	100

Notes: Enthalpies at standard conditions. Density of water equals 1000 kg/m^3. Specific heat capacity of water equals 4.187 kJ/kgK.

The *stove-top* model describes cooking on a gas, electric or biomass stove (or hob) using a container such as a pan or pot as shown in figure 5.6. Cooking food in a pot of simmering water allows heat to be transferred quickly to the food due to high heat transfer rates (conduction from metal container to water, and water to food) and the convection currents present when heating water. The drawback is that significant heat is required to heat the water to boiling temperature and then evaporate the water during boiling, as shown in table 5.9. Therefore, preventing the loss of water vapour (Q_V) from the cooking vessel is a priority.

Brundrett and Poultney[156] have shown that when boiling water without a lid, 80% of the heat from the stove is used for evaporating the water. The simple action of using a lid, reduces the steam losses by a factor of 100 (practically zero), and eliminates the heat loss due to escaping steam (Q_V). The energy used to evaporate the water is recovered when the vapour re-condenses on the walls and lid of the pot. In the absence of empirical data about the use of lids when cooking, it is assumed that pot lids are used for only half the time when cooking. Thus in the stove top model, two-thirds of the heat is used for ventilation. Other stove top cooking methods such as grilling or frying are not analysed but are likely to be even less efficient due to the heat loss to the surrounding air.

The remaining heat input (one-third) is required to overcome the shell and thermal mass heat losses. Heat loss from the shell is calculated using equation 5.4, with the pot surface area equal to $0.05\,\mathrm{m}^2$, and a temperature difference of 80 °C. The heat transfer is limited by the interface between the bare metal exterior surface and surrounding air, with a typical surface resistance value (R) of $40\,\mathrm{W/m^2K}$ in natural air currents, resulting in a heat flux of 160 W. The food, perhaps a staple such as rice or potato, is assumed to be cooked in 1 L of simmering water for 15 minutes, giving an overall shell heat loss of 144 kJ. This is about 30% of the one off heat input of 335 kJ to raise the water to boiling temperature. Thus the estimated heat loss fractions for the average stove top pot are: 67% ventilation, 23% thermal mass and 10% shell.

Three changes are made to the stove-top model to assess the practical limit. Firstly, it is assumed that the pot is sealed with a lid, eliminating all ventilation heat loss. Secondly, the walls and lid of the pot are insulated with 30 mm thick fibreglass with a thermal conductivity (k) of 0.03 W/mK. This lowers the average shell U-value from 40 to $1\,\mathrm{W/m^2K}$, reducing the shell heat losses 98%. Thirdly, the thermal mass of the system is reduced by 50%, based on an assumption that half of the thermal mass is retained in the cooked food, primarily as absorbed water. This can be practically achieved by using heat resistant materials instead of metal for the inside of the pot and reducing the quantity of water for boiling.

The *oven* model is based on a typical 50 l electric or gas oven operating at 200 °C with a cooking time of 60 minutes. Food takes longer to cook in an oven than in boiling water due to the lower heat transfer rates through air. Goorskey *et al.*[157] report that only 6% of the heat input to a oven is absorbed by the food. Current oven designs have a double-skin cavity, filled with loosely packed fibreglass insulation to prevent the oven exterior from reaching high temperatures. The shell heat loss is calculated to be 150 W, assuming 50 mm of fibreglass insulation ($k = 0.05\,\mathrm{W/mK}$) which gives an overall U-value of $1\,\mathrm{W/m^2K}$. Heat is lost when hot air is vented or escapes from the oven. The ventilation heat loss is found using equation 5.6 assuming the air inside the oven is replaced every 10 minutes during the cooking time. This gives a ventilation heat loss of 15 W, a factor of 10 less than the shell heat loss.

Yet, these heat losses are small in comparison to the loss from thermal mass. This is because the typical oven contains 15–20 kg of steel, which requires approximately 1.5 MJ of energy to heat to 200 °C. This energy, averaged over the 60 minute cooking time, gives a heat loss of 415 W. Thus the estimated heat loss fractions for the current oven are: 72% thermal mass, 26% shell and 2% ventilation, which differ remarkably from the stove-top model.

To assess the practical limit for the oven model three modifications are made. Firstly, the oven is sealed throughout the cooking time, reducing the ventilation heat loss to zero. Secondly, the oven fibreglass insulation is packed tightly ($k = 0.04\,\mathrm{W/mK}$) and increased in thickness from 50 to 100 mm, reducing overall heat transfer coefficient (U) to $0.4\,\mathrm{W/m^2K}$ and preventing 60% of the shell heat loss. In theory, there is no limit to the thickness of the insulation and negligible shell heat losses can be attained. A insulation thickness of 1 m would result in a 95% reduction in shell heat loss, but would be difficult to use in a normal kitchen. Therefore, for oven model (and also the stove top model) the volume of insulation has been limited to 2.5 times the volume of the cooking vessel. Thirdly, the thermal mass of the oven is reduced by removing the steel, leaving only a thin non-conducting barrier to protect the thermal insulation. The thermal mass heat loss is reduced to 6%, which is the energy absorbed by the food.

Microwave ovens differ significantly, because the microwave radiation heats the food directly and not the air surrounding the food. Heat loss through the oven shell and from ventilation occurs indirectly as a result of the cooking food—these losses are assumed negligible in the model. LBNL[158] have calculated the overall efficiency for a typical microwave oven to be 56%, with the majority of energy loss occurring in the magnetron (the conversion device). The practical energy savings in the microwave oven (passive system) are negligible.

A summary of the practical energy savings for cooking is given in table 5.10. The heat losses for each cooker type have been normalised so that the sum of the loss components (shell, ventilation and thermal mass) for the current model, add to equal one.

Refrigerators and freezers: Domestic refrigerators and freezers consume 15 EJ of primary energy every year, for the purpose of chilling or freezing of food and drinks. Food is kept cold for two reasons: to keep the food fresh over an extended period of time, and because it is preferable to eat some foods at a cold temperature.

To calculate the practical energy savings available in refrigerators requires an estimate of the current energy use per unit volume for the average global refrigerator (the current utilisation ratio). Rosenfeld[159] shows the average annual energy consumption of new refrigerators in the US has fallen from 1,800 kWh in 1974 to 450 kWh in 2001, driven largely by changes in the federal standards. The fall in energy consumption is approximately linear during this period. The average size of a new refrigerator is also

Table 5.10 Practical energy savings in passive cooking systems

System (f_i)	w mm	k W/mK	U W/m^{2}K	Q_S %	Q_V %	Q_T %	Q %
Stove top (76%)							
Current	0	0	40	10	67	23	100
Practical	30	0.03	1	0	0	12	12
		Practical energy savings available **88%**					
Oven (16%)							
Current	50	0.05	1	26	2	72	100
Practical	100	0.04	0.4	11	0	6	17
		Practical energy savings available **83%**					
Microwave (8%)		Practical energy savings available **0%**					
Overall (100%)[2]		Practical energy savings available **80%**					

Notes: [1]includes biomass stoves, [2]weighted average, by distribution of energy use (f_i). Q_S= shell, Q_V= ventilation, Q_T= thermal mass, Q = total heat loss from passive system

shown to have stabilised at 0.6 m^3 since about 1980.

The average age of a refrigerator in Norway is calculated by Strandbakken[160] to be 7.9 years old. This is rounded up to 10 years (a 1995 refrigerator as the energy data is collected for 2005) to compensate for the older stock of refrigerators in other countries. The average energy consumption in 1995 for a new refrigerator, from the chart by Rosenfeld, is 700 kWh per year (equal to an average use of 80 W). For an initial comparison, a similar sized RF19 refrigerator from Sun Frost (who claim to manufacture the most efficient refrigerators in the world) consumes just 120 kWh per year (14 W).[161] This 80% improvement in efficiency comes from modifications to both the conversion device and the passive system, such as:

- the compressor is mounted at the top of the refrigerator, instead of the bottom, which shifts the heat generated by the compressor away from the condenser coils, improving the cooling efficiency

- for refrigerator/freezer models, two independent compartments with separate cooling systems and temperature controls are used, allowing the refrigerator section to be cooled by a higher than normal evaporator temperature
- the refrigerator box is insulated with 50–100 mm thick polyurethane foam insulation
- defrosting is achieved without using heating coils

Models have been created for the refrigerator and freezer to separate out just the efficiency contributions from the passive system. These give even greater energy savings than the Solar Plus refrigerator because there is no economic constraint placed on the model. The models are based on the equation developed for the cooking passive system (equation 5.15), which divides the heat loss from the passive system into contributions from shell (Q_S), ventilation (Q_V) and thermal mass (Q_T). The key difference is that instead of adding heat to balance the system heat loss, the refrigerator and freezer produce cooling to balance the system heat gain. Improving the passive system requires eliminating or reducing these heat gains. A summary of the practical energy savings in refrigerators and freezers is provided in table 5.11.

The cooling input to the refrigerator box (Q) is calculated as 34 W, using the Rosenfeld example and assuming a typical refrigeration conversion device efficiency of 50% and a smaller refrigerator volume of 0.5 m^3. An equal sized freezer will typically consume twice the energy of a refrigerator, thus the cooling input to the freezer is calculated as 67 W. Overall refrigeration energy use is divided evenly between refrigerators and freezers, assuming chilled space accounts for twice the volume of freezer space.

Heat gains through the refrigerator shell have been calculated using the standard expression for heat conduction (equation 5.4).

Table 5.11 Practical energy savings in refrigerators and freezers

System (f_i)	w	k	U	Q_S	Q_V	Q_T	Q
	mm	W/mK	W/m^{2}K	W	W	W	W
Refrigerator (50%)							
Current	15	0.05	2.9	29	1	4	34
Practical	200	0.03	0.15	2	0	4	6
	Practical energy savings available **83%**						
Freezer (50%)							
Current	20	0.05	2.2	56	1	10	67
Practical	200	0.03	0.15	4	0	1[1]	5
	Practical energy savings available **92%**						
Overall (100%)[2]	Practical energy savings available **88%**						

Notes: [1]net cooling required for frozen goods defrosted in refrigerator [2]weighted average, by distribution of energy use (f_i). Q_S= shell, Q_V= ventilation, Q_T= thermal mass, Q = total heat gain to passive system.

Both the refrigerator and the freezer are assumed to have a volume of 0.5 m^3 giving a heat conduction surface area (A) of 0.63 m^2 based on a cube shape. The refrigerator holds the chilled food at a constant temperature of 4 °C, while the freezer maintains the frozen food at -20 °C, with an average ambient temperature of 20 °C. The surface area and temperature differences are kept constant in the model. The overall heat transfer coefficient (U) is dominated by the thermal resistance of the insulation material. Values for the thermal conductivity (k), insulation thickness (w) and corresponding U-value, for the current and practical limit cases, are shown in table 5.11. The insulation thickness for the practical limit is restricted to 200 ml to remain below a practical maximum ratio of 2.5 for the insulation volume to cooled space volume (assumed for the cooking vessel models). The percentage reduction in shell heat gain in both models exceeds a factor of ten.

Ventilation heat gains resulting from hot air leaking into the refrigerator box must be cooled down. However, they are relatively insignificant (less than 1% of the passive system loss) due to the low volumetric heat capacity of air and because only a fraction of the refrigerator volume (the air, but not the food) escapes when the door is opened. To calculate Q_V, it is assumed that $2.5\,\mathrm{m}^3$ of warm air infiltrates the refrigerator every day, equivalent to opening the door 20 times when the refrigerator is three-quarters full. In the practical model, ventilation heat gains are reduced to zero. This can be achieved by compartmentalising the cooled space, sealing each compartment, and using horizontal drawers or a chest type refrigeration unit to prevent the cool air leaking downwards when accessing food.

Cooling is required to lower the thermal mass of the food that is deposited in the refrigerator or freezer. Table 5.12 gives the change in enthalpy required to cool and freeze a litre of water, used as a proxy for food. The thermal mass components in table 5.11 are found by closing the heat balance, using equation 5.15. For the refrigerator, the value of 4 W is the equivalent of chilling 6 litres of water per day. The thermal mass component is higher in the freezer model, 10 W, but due to the greater enthalpy change, is equal to freezing 2 l of water. Both these values appear credible in light of typical refrigerator and freezer use. The thermal mass

Table 5.12 Enthalpy change for cooling and freezing a litre of water

Stage	Temperature	Enthalpy change	
	°C	kJ/kg	%
Cooling (refrigerator)	20 to 4	67	15
Cooling (freezer)	4 to 0	17	4
Freezing (latent heat)	0	333	73
Cooling (freezer)	0 to -20	41	9
Total (water to ice)	20 to -20	458	100

Notes: Enthalpies at standard conditions. Density of water equals $1000\,\mathrm{kg/m^3}$. Specific heat capacity of water equals 4.187 kJ/kgK, and of ice equals 2.05 kJ/kgK.

of the refrigerator and freezer is ignored because once cooled it remains at constant temperature in operation.

The thermal mass of the food in the refrigerator remains unchanged for the practical limit calculation. However, it is reduced for the freezer model. Domestic freezers maintain food at approximately -20 °C, well below the freezing temperature, extending the shelf life of food products to between 2 and 12 months. Only a small fraction of food products are consumed at this cold temperature, for example ice cream. The majority of foods are defrosted and frequently cooked before consumption. Thus food enters the freezer at room temperature and is consumed at or above room temperature, suggesting there is potential to recover the energy used for freezing the food. In the practical model it has been assumed that all frozen food is defrosted in the refrigerator, resulting in a net cooling requirement equal to refrigeration (instead of freezing).

Washing machines, dishwashers and dryers: So called *wet* appliances use approximately 8 EJ of primary energy to deliver clean and dry clothes and crockery. For washing machines and dishwashers approximately 85% of this energy is used for heating water, according to Goorskey *et al.*.[162] Heated water is normally supplied from the house hot-water system, however some dishwashers have in-built booster heaters to deliver the higher temperatures required for killing germs and softening fatty deposits.

Practical savings in energy use result from three strategies: lowering the water temperature, recovering energy from the hot waste water, and using less hot water. The wash temperature for clothes can be reduced for most loads to 20 °C with the use of ‘cold’ water detergents. This reduces the energy required for heating the hot water by about 80%. For clothes washers and dishwashers, which require hot water, similar practical savings can be attained by recovering the heat from waste water, using the model developed for hot water systems in section 5.2.3. Using a counter-flow heat exchanger, with a temperature gap of 10 °C and a waste water temperature 60 °C, gives an equivalent 80% potential savings in energy.

Traditional vertical axis washing machines require significantly more water than horizontal axis machines, because the clothes must be completely submerged during washing. Horizontal axis washing machines also have faster spin speeds, reducing the energy required for drying. Goorskey *et al.*[162] state that advanced washing machines and dishwashers can use 30–60% less water than conventional models. Therefore, it has been assumed for the practical limit that water usage in washing machines and dishwashers can be reduced by a further 50%.

The practical utilisation limit is found for washing machines and dishwashers by multiplying together the hot water savings (80%) and water usage savings (50%), and overlaying these onto the fraction of energy used in these appliances for heating water.

$$\text{Practical UR limit} = (1 - 0.8) \times (1 - 0.5) \times 0.85\% = 9\% \quad (5.16)$$

Therefore, the practical energy savings available in these appliances equals 91%.

Clothes dryers work by passing warm air through the clothes as they are rotated in a drum. The warm air evaporates and absorbs moisture from the clothes before it is vented outdoors or passed through a heat exchanger where the water vapour condenses. The reason for condensing the water vapour is not to save energy, but to avoid the need for a hole through the external wall of the building. It is more convenient, especially in apartments to discard the extracted water down the drain. In both options the enthalpy in the water vapour is lost.

Using a heat exchanger, the latent heat of vaporisation for water (see table 5.9) could be recovered. Possible options for recovery include: preheating the cool drying air, mechanically re-compressing the vapour for drying, preheating water in a hot-water system, or converting the energy to electricity using a heat pump. Palandre and Clodic[163] report energy savings of 50% for a mechanical vapour re-compression system with a temperature approach of 20 °C, in comparison to conventional condensation drying. In comparison, USDOE[90(p.126)] give an upper limit of heat recovery in steam systems of 60% and domestic condensing boilers are reported as recovering up to 75% of the water vapour energy from the boiler exhaust gases. Therefore, a practical energy saving of 60% is assumed for clothes dryers.

Consumer electronics: The use of consumer electronic devices, such as televisions, DVD players, radios, computers, printers, mobile phones and office equipment, accounts for 13% of the primary energy demand for buildings. Some ambiguity exists over the service they provide—some options include entertainment, data processing, communication, and record archiving—and the separation of the conversion device from the passive system is challenging. In this analysis, electronics have been treated in much the same way as the light bulb. The various flows of energy and conversion processes are of little use until the point where the information is displayed on the screen or projected audibly through speakers. It is the output of the electronic device, as light or sound, that interests the user and can be measured. The more subtle functions of storing data are more difficult to quantify.

Consequently, the passive system is defined as the space into which the information, as light or sound, is delivered. This is akin to the illuminated space for artificial light. However, the three strategies used for improving the utilisation of light—task lighting, reducing over-design and improving the luminaire—are difficult to apply to electronic devices. The light and sound from consumer electronics is normally focused toward the user so task lighting principles do not apply. Brightness and volume are easily adjusted by the user to the correct level and in battery operated devices there is a natural driver to avoid over-design. Reflecting the light off the surrounding surfaces does not make a computer screen easy to read. Reflecting sound causes echoes which can render speech unintelligible. Therefore, it is concluded that there are no practical energy savings available in the passive systems of consumer electronics.

Other appliances and equipment: This category contains many diverse types of appliances and other equipment used in domestic and commercial buildings. Most energy use is attributed to mechanical energy systems, including: water pumps, ventilation systems and generators used in commercial buildings; and motor-mowers, chain saws and other small petrol driven engines used in workshops and gardening. Without any specific breakdown of appliances and equipment, it is impossible to attribute practical energy savings within any accuracy. Instead practical energy savings of 59% are applied based on the analysis of industrial driven systems in section 5.3.3.

Combining the practical energy savings from each appliance group as a weighted average by energy use leads to an overall potential reduction of 67% for appliances as shown previously in table 5.8 on page 114.

5.3 Practical energy saving in factories

The manufacture of materials and products in factories uses 154 EJ, almost a third of the world's primary energy. The energy used to make products contributes to all the final service catergories: structure (68.4), sustenance (28.0), hygiene (17.1), communication (13.2), freight transport (11.2), passenger transport (10.6), thermal comfort (4.3) and illumination (1.2). The modelling of practical energy savings in industry is challenging due to the complex and varied use of energy, the wide range of manufactured products, and the embedded energy content of materials. This sections starts with a discussion of the influence of embedded energy, before developing engineering models for furnaces, steam systems and driven systems. The potential gains from material efficiency strategies—reducing material scrap in processing (yield gain), extending the service life of products, and recovering waste material—have not been included in this assessment of practical limits.

5.3.1 Embedded energy

Materials and products differ from the services provided by vehicles and buildings. Whereas light, heat and motion last only for a brief time, the energy input to materials can remain embedded for many years. This energy is carried with the product, as embedded energy, and accounts for the chemical and physical changes made to the product material during processing. Chemical changes to the composition of the material account for most of the embedded energy—materials processes such as mixing, separating, crushing and deforming, require comparatively smaller quantities. For example, the enthalpy of reaction (ΔH_r) for the reduction of iron ore (in the form of hematite Fe_2O_3) to iron (Fe) equals 7.4 MJ/kgFe. This energy is embedded in the steel, and could theoretically be recovered from the steel at a later stage. The enthalpy of reaction is also, from an energy perspective, the theoretical minimum energy required to make the steel.

Embedded energy is not to be confused with the term *embodied energy* (as Ashby[164] explains) which includes all the energy inputs to a product, including the ore, feed-stock, fuel and electricity consumed in making a material. This remaining energy—the energy input to the process less the enthalpy of reaction—is lost as heat from processing equipment (for example, furnaces, pumps and steam systems) during the manufacture of the product. It is this wasted energy which is targeted for reduction.

The difference in energy between the reactants and products defines the theoretical energy requirement for a chemical reaction (ΔH_r). Endothermic reactions (ΔH_r<0) require an energy input and thus the theoretical energy requirement is positive, whereas exothermic reactions (ΔH_r>0) have a negative theoretical energy requirement. This is important because some material production processes are exothermic, and should release energy, yet in practice they still consume process energy. In these cases, the potential savings in energy may be greater than the fuel and electricity input to the process.

Table 5.13 gives a breakdown of global energy use in industry, with the five most energy intensive materials shown. Moving across the columns from left to right, the total primary energy (T) has been allocated to the three main passive systems in industry—furnaces (F), driven systems (D) and steam systems(S). The total primary energy has been divided by global material production figures to give the energy intensity in units of MJ/kg This is contrasted with the theoretical energy requirements per unit mass, taken from literature.

The theoretical minimum energy value for steel is a weighted average of 60% primary production with ΔH_r=7.4 MJ/kgFe,[165] and 40% secondary production with no enthalpy change. It is noted that for secondary production of steel from scrap no reaction takes place, and theoretically the steel does not need to be melted to be formed into a new product (the deformation energy is assumed negligible). Similarly, for aluminium the minimum energy is a weighted average of 50% primary production with ΔH_r=31 MJ/kgAl,[166] and 50% secondary production with no enthalpy change.

For chemicals, Neelis *et al.*[167] have calculated the average reaction enthalpy change from a survey of 68 chemical processes, covering 63% of the primary energy use in the chemical industry. The energy minimum is negative due to the many exothermic chem-

Table 5.13 Energy use in industry

Industry	Primary energy[1]				Global	Energy	Theoretical	
	T	F	D	S	prod.	intensity	minimum	
	EJ	EJ	EJ	EJ	Mt	MJ/kg	MJ/kg	EJ
Steel[2]	36	26	8	2	1100	32	4	5
Chemical	24	10	5	10	500	47	-31	-15
Cement	13	10	3	0	2400	6	2	4
Paper	11	0	2	9	380	29	3	1
Aluminium[3]	6	5	1	1	40	155	16	1
Other	64	17	38	9				
Top 5	90	50	19	21	4420	20		-4
Total	154	67	56	31				

Notes: [1]Primary energy: T = Total, F = Furnace, D = Driven system, S = Steam system. Breakdown by industry and passive system from USDOE[90] with non-combusted energy excluded. [2]Steel production: 60% primary, 40% secondary. [3]Aluminium production: 50% primary, 50% secondary.

ical reactions especially in the petrochemicals industry. Taylor *et al.*[168] report the thermodynamic minimum energy requirement for the calcification reaction to produce cement as 1.8 MJ/kg of clinker.

Kinstrey and White[169] calculate a theoretical minimum for pulping and paper making of 15.7 MJ/kg. However, this value includes contributions from items such as 'powerhouse losses' from the cogeneration of electricity and the evaporation of the water in paper-making—the value is not a true theoretical minimum as it is constrained by today's known technology. In contrast, de Beer *et al.*[170] states the theoretical energy to make a flat sheet of paper from pulp is almost negligible as the only energy needed is for aligning and bonding the fibres. Therefore, only the minimum energy for pulping (lime kiln and liquor evaporation) from Kinstrey and White[169] has been included in the table.

In the last column of table 5.13 the absolute theoretical minimum energy has been calculated for each of the top five materials, representing nearly 60% of global industrial energy use. The total of this column shows net embedded energy in materials of minus 4 EJ; the energy released from the exothermic reactions to produce chemicals is greater than the energy input to the endothermic reactions for metals, cement and paper. Assuming that this conclusion holds for the remaining processes in the *other* category, then the waste energy lost from factories is at least equal to, if not slightly more than the total inputs of fuel and electricity. Therefore, in the engineering models developed in the next section, the embedded energy in materials is ignored.

5.3.2 Furnace

Furnaces account for 44% of industrial energy use worldwide and are used to deliver medium and high temperature heat, either directly or indirectly. The furnace category includes fired heating systems (including furnaces, dryers, calciners, reactors and evaporators) which combust fuel, electrical furnaces, and electrochemical cells (where electricity instead of heat is used to drive a chemical reaction). Engineering models of furnaces typically include the combustion of fuel in the conversion device, the losses from the heated space and the distribution and transfer of heat. For the passive system analysis only the heated space or vessel is considered. Many of the principles governing heat loss from the passive furnace system have already been developed in the previous section on buildings, for example the domestic oven.

According to the first law of thermodynamics, the heat delivered to the furnace system must be balanced by the sum of the heat losses:

$$Q = Q_S + Q_V + Q_T \tag{5.17}$$

Q_S is the heat loss from the shell (walls and roof) of the furnace and is calculated using the standard heat transfer equation (see equation 5.4). The magnitude of heat loss depends primarily on the thickness (w) and thermal conductivity (k) of the insulation material, from equation 5.5. Q_V results from the leakage of hot air primarily when the doors are opened to charge or discharge material from the furnace. It depends upon the volume and temperature of the lost air, according to equation 5.6, but is a comparatively small heat loss due to the low heat capacity of air.

Q_T is the energy required to heat the furnace shell and raise the temperature of the product material (the thermal mass of air is ignored). Ashby[164] explains that the for small batch furnaces, with frequent cycles of heating and cooling, significant energy is used to heat the furnace shell to the operating temperature. The heat input can be found using the average temperature of the shell:

$$Q_{T,\text{shell}} = m\, C_p\, (\frac{T_{out} - T_{in}}{2}) \qquad (5.18)$$

where m is the mass of the shell and C_P the specific heat capacity. An optimum shell thickness can be found which minimises heat loss, by trading off a thick well-insulated shell (Q_S) against a thin shell of lower thermal mass ($Q_{T,\text{shell}}$). Ashby shows that this optimum wall thickness is found when $(kC_p\rho)^{\frac{1}{2}}$ is minimised.

When a furnace is operated continuously, as is the case for most larger furnaces, the heat absorbed by the shell can be ignored. In this case, the heat input to the furnace equals the heat loss, with no accumulation of heat within the system. Thus, heating the thermal mass of the product material is the only contribution to Q_T.

The prediction of current energy use in furnaces is based on a study of two 250 t/h reheating furnaces in a Taiwanese hot strip steel mill, performed by Chen *et al.*.[171] Each furnace is designed to reheat steel slabs (1250 mm wide and gauge 250 mm) from 25 °C

Table 5.14 Practical energy savings in the furnace

Furnace	w	k	U	Q_S	Q_V	Q_T	Q
	mm	W/mK	W/m^{2}K	%	%	%	%
Current	100	1.0	10	25	31	43	100
Practical	250	0.5	2	4	6	28	38
						Practical energy savings available	**62%**

Notes: Q_S= shell, Q_V= ventilation, Q_T= thermal mass, Q = total heat loss from passive system

to 1250 °C prior to being rolled into steel coil. The furnace is oil fired with a rectangular insulated shell of effective dimensions of 40 m long by 10 m wide by 0.25 m high, and a door at each end to allow continuous operation.

Chen *et al.* have published a breakdown of the heat losses covering both the conversion device and passive system components of the furnace.

- 17.7% for heat losses from the furnace shell (Q_S) and the opening of the doors when slabs are charged and discharged (ignored)
- 42.3% as enthalpy in the discharged steel slab (Q_T)
- 31.4% in the exhausted flue gas (Q_V)
- 7.7% in the water used to cool the furnace and equipment (Q_S)
- 0.9% as enthalpy in the removed oxidation scale (Q_T)

This distribution has been used to find the heat loss terms from equation 5.17 (as indicated), leading to the current energy use breakdown shown in table 5.14. No specific details are provided about the insulation of the furnace shell, although refractory bricks typically have thermal conductivities ranging from 0.5 to 1.5 WmK at 800 °C.[172] An average value of 1 WmK has been used in the current model.

For the practical limit model, three modifications have been made. Firstly, the insulation thickness (w) is assumed to have increased by 150 mm and the thermal conductivity (k) is lowered from the average to the lowest value for Zircoa[172] refractory brick. This results in an 83% reduction in shell heat loss. Secondly, heat is recovered from the exhaust flue gas at an efficiency of 80%, based on the energy recovery rates given in USDOE.[90]

Thirdly, some of the enthalpy contained in the hot discharged slab (900 kJ/kg at 1250 °C) is recovered as steam. de Beer *et al.*[42] give an example of direct transfer to steam in a boiler where the slab enters the boiler at 900 °C and exits at 300 °C. The boiler produces 40 bar steam at 450 °C, recovering 320 kJ/kg in the steam at a recovery rate of 36%.

This recovery efficiency is lower than for liquid or gas heat exchangers, because transferring heat from solids restricts the range of available heat exchangers and the maximum working temperature of steam is much lower than the slab discharge temperature. In the practical limit model a recovery rate of 36% is used, giving an overall practical energy saving of 55%, which is applied across all types of furnaces.

5.3.3 *Driven systems*

Motor driven systems consume 55 EJ of primary energy and account for approximately one third of global electricity use. The category includes all industrial use of: pumps, fans, material processing and handling equipment, compressors and refirgeration. The majority of motor systems are powered by electrical motors (90%), with natural gas being the second most used energy source (5%).

A generic pumping model has been developed to calculate the practical energy savings in motor driven systems. Although each driven system is likely to have distinct characteristics which differ from the pumping application, the lack of specific data on energy losses in these systems has necessitated the use of a more general model. This pumping model is described first, followed by a description of the the specific adaptions or exceptions to match the model to the other categories of driven systems.

Pumping applications can be divided into two categories depending on the service they deliver. The first application aims to transport a fluid (liquid, gas or slurry) over some distance or change in height, through some distribution system (piping, ducting or channels), to the point of use. The distribution of potable water from a source to the residents in a city is a common example. Material handling systems such as conveyors belts achieve the same aim for solids. The purpose of the second application, is to raise the pressure of the liquid to provide mechanical work—for example, the propulsive force of a water jet or hydraulic pressure in a piston—or to deliver the liquid into a high pressure vessel. Compressed air and material processing systems (grinders, crushers and mixers) operate in a similar fashion.

The liquid pressures in the pumping system can be calculated using the *mechanical energy equation*, sometime referred to as the extended Bernoulli equation:

$$P_{in}+\frac{\rho\nu_{in}^2}{2}+\rho g z_{in}+\rho W_{shaft}=P_{out}+\frac{\rho\nu_{out}^2}{2}+\rho g z_{out}+\rho W_{loss} \quad (5.19)$$

where P is the static pressure (inlet and outlet), ρ is the fluid density, ν is the fluid velocity, g is the acceleration due to gravity, z is the elevation height, W_{shaft} is the net shaft energy per unit mass of fluid, and W_{loss} is the loss due to friction. For pumping systems, the fluid velocity terms can be cancelled out if a constant volumetric flow rate and pipe diameter are assumed. The height terms balance if no net change in height is required—this is a valid assumption for most pumping applications.

For pumping liquids over a distance (transport applications) the pressure terms cancel out as the fluid enters and exist at atmospheric pressure. The increase in pressure imparted by the pump is eventually lost due to friction in the piping and fittings, and the all the shaft energy is lost as friction, $W_{shaft} = W_{loss}$. If a higher pressure is required at the outlet then the required shaft work is $W_{shaft} = W_{loss} + P_{out} - P_{in}$.

The term W_{loss} includes contributions from friction losses in the pump (suction, impeller and discharge), valves (throttle and control), piping, and fittings. Friction losses in the pump and throttle valve are normally grouped together with the electric motor and drive coupling losses, to calculate the conversion device efficiency. The USDOE[90] estimates these losses to be 40% of the electrical input to the electric motor. Passive system friction losses result from the fluid flowing through the pipes and fittings. This delineation between conversion device and passive system is logical, given that the fluid is not in a useful form (at the correct pressure) until after it has been conditioned by the throttling valve. This separation is also consistent with the common practice of replacing the throttling valve with a variable speed drive (VSD) on the pump motor, to save energy in the conversion device.

The pressure loss in piping and fittings due to friction is calculated using the DarcyWeisbach equation:

$$\Delta P_{piping} = \rho W_{loss} = f \frac{L}{D} \frac{\eta^2}{2g} \tag{5.20}$$

where f is the dimensionless Darcy friction factor, L is the effective pipe length (which includes the equivalent length of piping for fittings) and D is hydraulic diameter of the pipe (which equals the diameter for circular pipe). Substituting the volumetric flow (q) per unit cross-sectional wetted area for the fluid velocity η, gives:

$$\Delta P_{piping} = f \frac{L}{D} \frac{1}{2g} \left(\frac{4q}{\pi D^2} \right)^2 = \frac{8fLq^2}{\pi g D^5} \tag{5.21}$$

The variables f, L and D can be adjusted to reduce the piping pressure loss (and pumping energy), but the greatest gains are achieved by increasing the pipe diameter. For example, doubling the pipe diameter will decrease the pressure by $1 - \frac{1}{2}^{5}$ or 97%. However, this must be balanced against the additional piping cost and greater floor area.

For the practical limit a 25% increase in the pipe diameter has been assumed, giving a 67% reduction in pumping energy. This agrees well with industrial case studies reported by Lovins[173] where the redesign of piping systems reduced the friction loss by a between 67% and 83%. A similar example provided by the IEA[1] shows the piping efficiency increasing from 60% to 90%, equating to a two-thirds reduction in piping losses. The calculated 67% energy reduction from increasing the pipe diameter is applied to the motor driven systems which transport materials: fan system, material handling systems and pump systems (the fraction of energy used for transporting fluids is assumed to be 80% as no value could be found in literature).

The practical energy saving in refrigeration systems (88%) have been based on the domestic refrigerator and freezer model described in section 5.2.5. The remaining motor driven systems are used to provide direct mechanical energy: compressed air systems, material processing systems and 20% of pumps. The practical limits for these devices are sourced from the United States Department of Energy (USDOE) report *Energy use, loss and opportunities analysis*,[90] which provides a breakdown of the delivered usable work versus the energy lost for these applications. It is assumed that 50% of the energy lost in these mechanical processes can be practically avoided. The resulting practical savings in energy use are shown in table 5.15.

Table 5.15 Energy use in driven systems

System	Primary energy EJ	%	Savings %
Pump	14	25	62[1]
Material processing	12	22	45
Compressed air	9	16	40
Fan	8	14	67
Material handling	7	12	67
Refrigeration	4	7	88
Other	2	4	67
Total	56	100	59
		Practical energy savings available	**59%**

Notes: [1]weighted average of transportation and mechanical energy applications

5.3.4 *Steam*

Steam systems consume 31 EJ of primary energy every year, delivering heat at lower temperatures (150–550 °C) than furnaces. Conceptually, steam systems differ from furnaces because the heat is not transferred directly to the heated space. Instead, steam acts as a heat transfer medium and is typically distributed from a centralised boiler, via a piping network, to the place of application. The indirect heat transfer also means that further heat cannot be recovered from the combustion flue gas.

To calculate the practical energy savings from the steam system, the ventilation term Q_V in equation 5.17 has been replaced by a distribution term Q_D. According to the USDOE[90] steam distribution accounts for 15% of the overall fuel input to the boiler, which equates to 29% of the overall heat loss (after taking into account the conversion efficiency of the boiler). Table 5.16 shows the modified distribution of heat loss components for the current energy use.

For the practical limit, the shell (Q_S) and thermal (Q_T) heat

Table 5.16 Practical energy savings in steam systems

Steam system	Q_S %	Q_D %	Q_T %	Q %
Current	27	28	45	100
Practical	4	0	29	33
			Practical energy savings available	**66%**

Notes: Q_S= shell, Q_D= distribution, Q_T= thermal mass, Q = total heat loss from passive system

losses are reduced by the same percentage as for the furnace model. Although, the absolute energy savings are much lower for the steam system, because of the reduced operating temperature, it is credible that the percentage reductions will be similar. The distribution heat losses are completely eliminated using the same arguement that was developed for point-of-use hot water heaters in section 5.2.3. The resulting practical energy savings for the steam systems are marginally higher than for the furnace, at 66%.

5.4 Practical energy savings in vehicles

Transporting people and goods in vehicles results in 106 EJ of primary energy use. This energy is ultimately lost from the vehicle passive system as low temperature heat to the surrounding environment, in exchange for the final service of transport. Half of the energy is used to move goods (freight transport) and the other half to move people (passenger transport). Improving the utilisation of energy in the vehicle passive system requires reducing the resistive forces where energy is lost.

Figure 5.7 shows the generic forces which act on a vehicle, in this case a car. The same schematic can be used for trucks, ships and airplanes, with some minor adjustments. The resistive drag forces, and therefore efficiency, are highly dependent on velocity, as illustrated in the seminal paper by Gabrielli and von Kármán[174] using a graph of specific resistance (resistive force divided by weight) versus velocity. The Kármán-Gabrielli line was plotted on this graph as practical efficiency limit for vehicles, irrespective of the transport mode. However, it has since been demonstrated that large ships and freight trains have passed through this barrier, as reported by Yong *et al.*.[175] Practical velocity ranges for different vehicles can by classified by the type of force supporting the vehicle: buoyancy force for ships (<50 km/h), reaction force for cars, trucks (<200 km/h) and trains (<350 km/h), and lift force for airplanes (<800 km/h). As a consequence, the drag forces and utilisation ratio increase as the vehicle changes from ships, to cars and trucks, to trains, to planes.

Although the models presented below include velocity as a variable, for the comparisons between current utilisation and the practical limit the average velocity for each class of vehicle has been held constant, to avoid unnecessary changes to delivered final transport service. In the section to follow the model for the passenger car is explained followed by a summary of the specific differences for the other transport modes.

5.4.1 Cars

The use of passenger cars to transport people and goods results in 40 EJ of primary energy consumption. The car engine and drive system (both conversion devices) convert fuel energy to vehicle

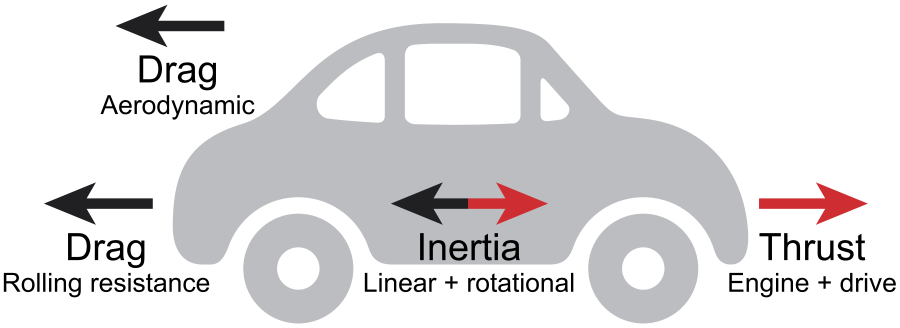

Figure 5.7 Forces on a car

motion (passive system). The thrust force provided by the engine is resisted by two drag forces, rolling resistance (mechanical) and aerodynamic drag. According to Newton's law, when the thrust and drag forces are balanced the car moves at constant speed. However in practice additional thrust is required to overcome inertia and accelerate the car. Conversely, reducing the engine thrust, or braking, produces a negative force which causes the vehicle to decelerate.

Equation 5.22 describes these forces as a scalar equation for a car. Forces are measured in Newtons (N), or in joules per metre (J/m or kJ/km) which conveniently are the same units as for the utilisation ratios described in equations 5.1 and 5.2. At constant speed, the thrust force (F) is counteracted by the mechanical drag (F_M), aerodynamic drag (F_A) of the car, and during acceleration, inertia (F_I). Thus, energy is finally dissipated as low temperature heat to the road, air and braking system.

$$F = F_M + F_A + F_I = \mu mg + \frac{1}{2}\rho\nu^2 C_D A_f + m\frac{d\nu}{dt} \tag{5.22}$$

Mechanical drag in the car is almost entirely due to rolling resistance, as energy dissipated during deformation of the tyre. (Mechanical friction in the engine, drive-train and wheel bearings is considered part of the conversion device.) Ford *et al.*[29] explains that tyre rubber is visco-elastic, resulting in one-fifth of the energy needed to flex the tyre being converted into heat by internal hysteresis. Losses are primarily dependent on the vehicle weight (mg), although some models include minor contributions from velocity terms. Micro-slippage between the tyre and road and the aerodynamic fan effects of the rotating wheel make up the remaining resistance (less than 10%). For a typical car tyre the friction coefficient $\mu \approx 0.015$.

Aerodynamic drag results from shear stresses created as air flows around the car body, in both laminar and turbulent flow conditions. Santin *et al.*[176] describes the complex aerodynamic system as having two principle mechanisms: 1) frictional drag, which is proportional to the wetted area of the vehicle; and 2) pressure drag, caused by flow separation around blunt vehicles, the generation of lift and the boundary layer pressure loss. Aerodynamic drag is modelled adequately by the classical fluid-drag equation, where ρ is the mass density of air ($1.225\,\mathrm{kg/m^3}$), ν is the average car velocity (m/s), A_f is the car's projected frontal area ($\mathrm{m^2}$), and C_D is the dimensionless drag coefficient, which ranges from 0.2 to 0.6 for cars.

Inertia, the resistance of mass, must be overcome to accelerate the car. Vehicle engines are therefore designed with significant reserve power to accelerate the car, causing the engine to operate at lower efficiencies during normal load. The energy expended during acceleration dominates during urban driving, where the car is forced to brake and accelerate in frequent cycles, and when climbing gradients. However, inertia energy is ideally recovered by decelerating without braking (coasting) or by using a regenerative braking system.

On a gradient, the force of inertia due to gravity is described by:

$$F_I = mg\,\sin\theta \cong mg\theta \tag{5.23}$$

where mg is the weight of the car and θ is the grade angle. For the car acceleration, both the linear and rotational inertia are combined to give:

$$F_I = m'a = \left[m + \frac{4I_w}{r_w^2}\right]\frac{d\nu}{dt} \tag{5.24}$$

where the effective mass (m') includes both the car mass, the rotational inertia of the engine and wheel assemblies, and the acceleration is found by differentiating the changes in velocity profile for the driving pattern, with respect to time. The wheel assembly inertia is typically small, but Ford *et al.*[29] claims that the engine inertia, in the lowest gear ratio, can be more than 1.5 times the vehicle mass. However, under cruising conditions the rotational inertia is typically less than 5% of the inertia force.[177] It is common practice to simplify the above inertia terms into a single multiplying factor based on surveyed driving patterns.

Significant opportunity exists to reduce the resistive forces in cars, preventing the dissipation of valuable energy. The amount of energy which can be saved is practically constrained by the limitations of engineering materials and the available design options. Practical limits are therefore governed by the possible range of variables and coefficients in scalar equations. For example, drag coefficients (C_D) range from 1.05 for a cube, to the ideal limit of 0.04 for an elongated 'teardrop' shape—the practical limit for a car is bounded by these two extremes. A value of 0.10 is selected here for the practical limit, which is marginally higher than 0.09 for a 'half-teardrop' shape.

By varying the coefficients in equation 5.22 within realistic literature values, the practical energy savings available can be quantified. Table 5.17 shows that practical improvements to the car's passive system can reduce energy use for cars by 91%.

The current utilisation ratio is calculated using data from Zachariadis and Samaras[178] and Hickman[179] which assesses the performance of vehicle types across 15 European Union countries in 2000. Equation 5.22 is used to calculate the mechanical resistance (from rolling) (F_M) and aerodynamic drag (F_A) for each design of car. Scaling factors are taken from Zachariadis and Samaras[178] to account for the inertia term. These estimate the fraction of power consumed for acceleration in passenger cars—40% for urban driving, 30% for rural driving and 20% for highway driving—and are multiplied by the sum of the other two drag forces, to calculate (F_I). The resulting forces for the 7 different car designs are averaged to find the 'current utilisation limit', using the percentage distribution of total distance travelled in Europe (f_i for i types of car).

For the practical utilisation limit, the variables and coefficients are reduced based on the ranges found in literature for real examples. The most significant gain comes from reducing the car mass to 300 kg. The 'world's most fuel efficient vehicle', the PAC-Car II developed by Santin *et al.*[176] weighs only 29 kg when empty, with the body being constructed from two layers of carbon reinforcement with a combined mass of 390 g/m^2. For safety reasons this is considered unrealistically low. In contrast, the Rocky Mountain Institute's '2000 Revolution Hypercar'[180] is a sport utility vehicle (SUV) weighing only 857 kg. By reducing the vehicle size it

Table 5.17 Practical savings available in cars

Design[1]	m	ν	μ	C_D	A	f_i	F_M	F_A	F_I	F
	t	m/s			m^2	%	N	N	N	N
Gasoline										
<1.4 l	1.0	19	0.015	0.40	1.9	36	147	163	130	440
1.4–2.0 l	1.2	20	0.015	0.40	2.0	28	177	201	155	533
>2.0 l	1.4	21	0.015	0.40	2.1	6	206	232	178	616
LDV[2]	2.1	17	0.015	0.50	2.2	3	309	199	223	731
Diesel										
<2.0 l	1.3	19	0.015	0.40	2.0	11	191	174	156	521
>20.0 l	1.5	19	0.015	0.40	2.1	7	221	193	174	588
LDV[2]	2.1	16	0.015	0.50	2.2	8	309	165	219	693
Current[3]	1.3	19	0.015	0.41	2.0	100	188	183	157	528
Practical	0.3	19	0.001	0.10	1.5	100	3	33	13	49
Practical energy savings available **91%**										

Notes: [1] by fuel type and engine size in litres, [2] LDV = light duty vehicle, [3] weighted average, by the distribution of total distance travelled (f_i). m = mass, ν = average velocity, μ = friction coefficient, C_D = drag coefficient, A_f = frontal area, F = force, with subscripts $_M$ mechanical, $_A$ aerodynamic and $_I$ inertia is expected that the empty car mass could be reduced to 200 kg, with an extra 100 kg for the average passenger loading. Such a reduction in mass makes energy recovery from the braking system marginal, given the inertia forces are much lower, and the additional equipment mass which would be required to store the recovered energy.

For the tyre rolling resistance coefficient (μ), Santin *et al.*[176] quotes the 45-75R16 radial ply tubeless Michelin tyre as having $\mu \approx 0.00082$—chosen as the practical limit—which is only fractionally higher than train wheels, which make direct steel-on-steel contact, for which $\mu \approx 0.00073$. Some cars on the road today already have a drag coefficient (C_D) as low as 0.2, and the PAC-Car II was measured in wind tunnels as $C_D = 0.075$, leading to a practical limit of $C_D = 0.1$ being selected. However, large reductions in the car's projected frontal area (A_f) are unlikely, due to the requirement to carry passengers, resulting in a practical limit of $A = 1.5\,\mathrm{m}^2$.

Figure 5.8 shows the current and practical limit for the urban, rural and highway driving cycles. At the average speed, the practical energy savings are highest for the urban driving, equal to 96%, compared with 90% and 87% for rural and highway driving respectively. This demonstrates that reduction in the vehicle mass is particularly beneficial when the driving cycle involves frequent acceleration and braking. In contrast, for the highway driving cycle the car velocity dominates through aerodynamic drag. Reducing the car's maximum speed is an operational rather tha technical change, and therefore is not considered in this study. However, it is noted that reducing the car velocity from 120 to 100 km/h results in a 30% reduction in the propulsive thrust needed from the engine.

These results do not include any efficiency gains from design changes such as: improvements to the engine, gearbox or drive train; recovering energy in the braking system or switching off the engine during idling; or reducing energy use in electrical ac-

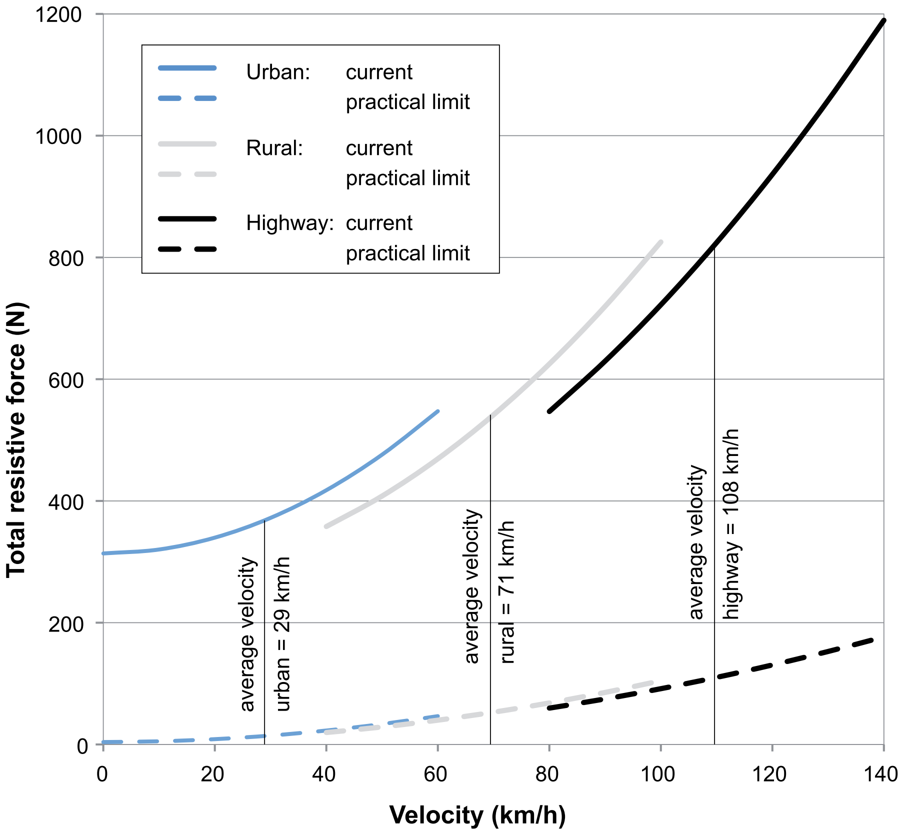

Figure 5.8 Resistive force versus velocity for the car

cessories, such as the air-conditioner, alternator, power steering or water pump. The following operational parameters have also been kept constant: the driving cycles, including the maximum speed, acceleration and time between stops; and the driving conditions, such as the number of passengers, the direction of travel relative to the wind and the gradient of hills. Yet, a ten-fold saving is available for the passive car system across all driving cycles.

5.4.2 Trucks

The transportation of goods by truck uses 38 EJ of global primary energy. The loss of energy from the truck passive system is modelled in a similar way to the car, with the results in table 5.18

Table 5.18 Practical savings available in trucks

Design[1]	m	ν	μ	c_d	A_f	f_i	F_M	F_A	F_I	F
	t	m/s			m^2	%	kN	kN	kN	kN
Diesel										
3.5–7.5 t	5.5	16	0.012	0.8	7.0	31	0.6	0.9	0.6	2.1
7.6–16 t	11.8	17	0.012	0.9	7.0	20	1.4	1.0	1.3	3.7
16–32 t	24.0	19	0.012	1.2	7.0	34	2.8	1.9	2.7	7.4
>32 t	36.0	19	0.012	1.2	7.0	2	4.2	1.9	3.9	10.0
Coach	10.0	15	0.012	0.6	7.0	12	1.2	0.6	0 .9	2.7
Current[2]	14.1	18	0.012	0.95	7.0	100	1.7	1.3	1.5	4.5
Practical	12.7	18	0.0052	0.31	7.0	100	0.7	0.4	1.4	2.4
Practical energy savings available **54%**										

Notes: [1] by gross vehicle tonnage (GVT), [2] weighted average, by the distribution of total distance travelled (f_i)

showing that energy use can be practically reduced by 54%. The current utilisation ratio is calculated using averaged data from Hickman[179] and Zachariadis and Samaras[178] covering 5 'heavy duty vehicle' categories, including trucks, buses and coaches. For the practical utilisation limit, reductions in the coefficients are more conservative, than for the car. The light-weighting strategy used for the car (75% reduction in mass) is limited for trucks because the transported goods make up a much larger proportion of the total vehicle mass—typically 60% in trucks versus 5–10% in cars. Furthermore, the mass of the empty truck performs the essential function of supporting the goods during travel. Therefore, only a 25% reduction in the unladen mass of the truck is assumed practical.

Reductions in the projected frontal area (7.0 m^2) are not deemed practical, as most truck payloads are limited by volume rather the weight, meaning truck designs tend to expand to the maximum permitted dimensions in their class. The modest gains in rolling resistance and drag coefficient are based on design values for Class

8 tractor-trailer vehicles in the United States, provided by Ogburn *et al.*.[181] As trucks are mainly driven on highways, the fraction of energy use for acceleration is lower, leading to only minor savings in the intertia force from mass reduction.

5.4.3 Planes

Travel by aircraft was responsible for 10 EJ of primary energy use in 2005, approximately 10% of direct transport energy use. The mechanisms for energy loss from the plane passive system are more complex than for land-based forms of transport for two reasons. Firstly, once in the air there is no mechanical drag force acting on the plane, thus μ and F_M from equation 5.22 can be set to zero. Instead, the lift needed to support the weight of the plane is included in the aerodynamic drag F_A term. Secondly, the mass of fuel forms a large proportion of the aircraft mass, so average energy use over the entire trip is a function of this changing mass of fuel, and thus is proportional to the journey distance. Decher[182] explains that over short distances, the energy required for taxiing and climbing to cruise altitude dominates, leading to high average energy use per kilometre. For long distances the average energy also increases, as more energy is needed to carry the extra fuel over the entire journey. In between is an optimum range for each plane design, where the energy required per kilometre is minimised.

The *Air travel - greener by design* technology report by Green *et al.*[183] describes in detail the underlying physics of air travel, which is used for the aircraft model. For steady state level flight (cruising) the range of an aircraft R (km) can be calculated using the Breguet equation:

$$R = X \ln\left(\frac{W_1}{W_2}\right) \tag{5.25}$$

where W_1 and W_2 are the initial and final weight of the aircraft (mg in Newtons) and X is the key performance parameter in kilometres, defined as:

$$X = H\eta\frac{L}{D} \tag{5.26}$$

where H is the fuel heating value (J/N or km), η is the overall propulsion efficiency, and L/D is the lift/drag ratio (dimensionless).

The Breguet equation must be divided into those terms which relate to the conversion device efficiency (excluded from this analysis) and those which affect the passive system utilisation. The overall propulsion efficiency (η) is the product of thermal efficiency (η_E), which together with H are attributed to the conversion device, and the propulsive efficiency or Froude efficiency (η_P), which measures the efficiency of transferring rotational energy in the fan blades to thrust in the air stream. This is analogous to the slippage of car tyres on the road, or the propeller losses in a ship, so is included in the passive system calculation. Further passive systems gains result from structural optimisation of the aircraft frame and engine to reduce the weight of the plane, W_1 and W_2, and aerodynamic improvements which affect the L/D ratio.

The propulsive efficiency (η_P) of today's ducted fan engines lies between 80 and 85%[183] and is close to the practical design limit. Further increase to the engine bypass ratio would improve the propulsive efficiency, but at the expense of an increase in fan diameter and therefore the weight of the engine and nacelle. However, using a pair of counter-rotating unducted propellers, which are not constrained in this way, could deliver significant gains in propulsive efficiency and acceptable cruising speeds (Mach 0.8) for long-range journeys.

The lift/drag ratio is optimised by reducing the drag force (F_D) on the aircraft, for a given lift (L), which is the weight of the plane (mg) at cruising conditions. Two drag components (D) act on the aircraft:

Profile drag results from skin friction, pressure drag and wave drag, and is represented by the coefficient C_{DO}

Vortex drag is caused directly by the generation of lift

Overall drag force is minimised when these components are equal, which leads to an expression for the maximum lift/drag ratio:

$$\left(\frac{L}{D}\right)_{max} = \sqrt{\frac{\pi A}{4kC_{DO}}} \tag{5.27}$$

where A is the wing aspect ratio (= span^2/area), k is the vortex drag factor (= unity for an elliptically loaded wing), and C_{DO} is the profile drag coefficient (= drag calculated at zero lift). Together, these three dimensionless constants define the maximum aerodynamic efficiency of the airframe. In practice, most planes operate at a cruise point where profile and vortex drag are not exactly equal. This is corrected by multiplying the maximum L/D ratio by a constant typically equal to 0.98.

Rearrangement of the Breguet equation gives equations for the weight of fuel consumed during the journey (W_F) and the payload weight (W_P) as functions of range (R), the key performance factor (X) and two structural constants (c_1 and c_2) related to the maximum take-off weight and payload, respectively. These are combined to give the specific fuel burn (SFB), which measures the weight of fuel consumed during the entire journey (W_F) divided by the payload weight (W_P) times the range (R), in units of kg/kgm. The specific fuel burn is used as the utilisation ratio, and is defined by:

$$SFB = \frac{W_F}{W_P R} = \left(\frac{c_2}{X}\right)\left[\frac{(1 - 0.978e^{-Z})}{Z\,(0.978e^{-Z} - c_1)}\right] \tag{5.28}$$

where $Z = R/X$. The value 0.978 results from the provision of 2.2% additional take-off weight to account for the non-cruising fuel required for taxiing, acceleration and climb.

Figure 5.9 shows specific fuel burn plotted against range for a typical modern Swept Winged Aircraft (SWA) and for the advanced laminar flying wing Laminar Flying Wing (LFW) aircraft, with Unducted Fan (UDF) propellers, calculated using data from Green *et al.*.[183] For these curves, the aircraft design range is assumed equal to the specific journey range, thus all aircraft fly at their optimum design range. This is not true in practice, given the small number of commercial aircraft designs and requirement for route flexibility, leading to slightly optimistic curves especially for the swept-wing aircraft. The LFW–UDF aircraft flies at a lower speed (0.80 versus 0.85 Mach) and altitude (9,000 versus 10,000 m)

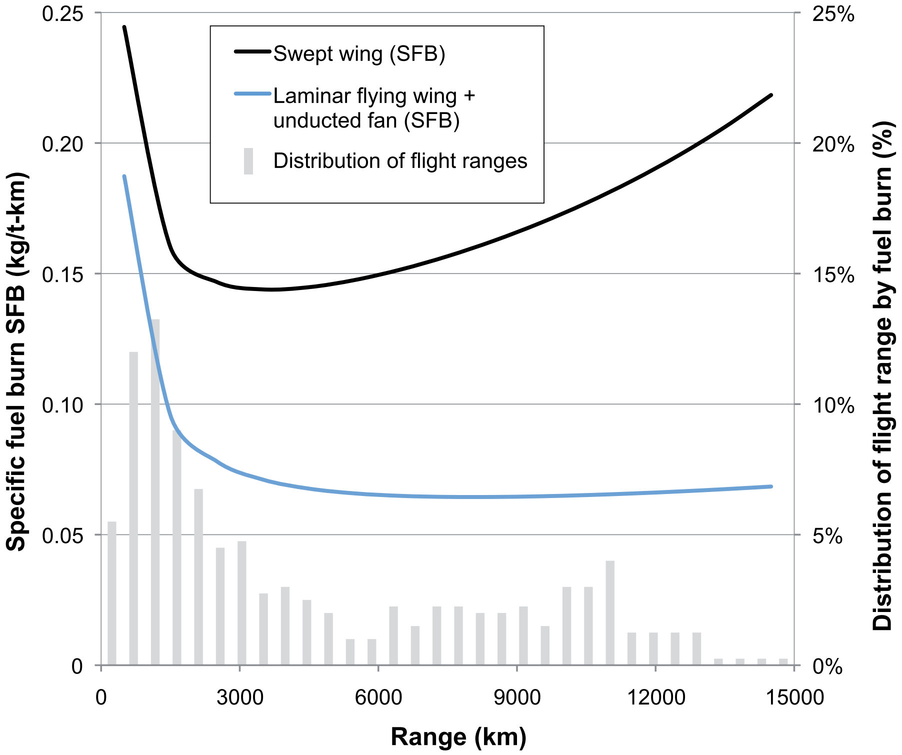

Figure 5.9 Specific fuel burn versus range for aircraft

due to design limitations. The figure also gives the distribution of fuel burn by journey range, taken from Green *et al.*,[183(fig.70)] which is used to calculate the practical savings available of 46% in the plane passive system, as shown in table 5.19.

The SWA has remained the dominant airframe design for more than 50 years, and is therefore used as the base configuration for the current utilisation ratio. The LFW with UDF is used as the practical limit. Figure 5.10 shows the radically different shape of the dominant SWA wing design and the proposed LFW design. This design concept, employing boundary layer suction to maintain laminar flow over the entire airframe, and the design pa-

Table 5.19 Practical savings available in planes

Design	η_P %	c_1	c_2	A	k	C_{DO}	L/D	R_D km	SFB kg/t km
SW	81	0.315	2.0	10	1.2	0.0211	17.6	5000	0.176
LFW+UDF	95	0.375	1.9	5	1.1	0.0026	37.1	9000	0.096
									Practical energy savings available **46%**

Notes: constant values for both ratios: $H = 4350\,\text{km}$, $\eta = 0.3$, n = 0.98. R_D is the aircraft design range

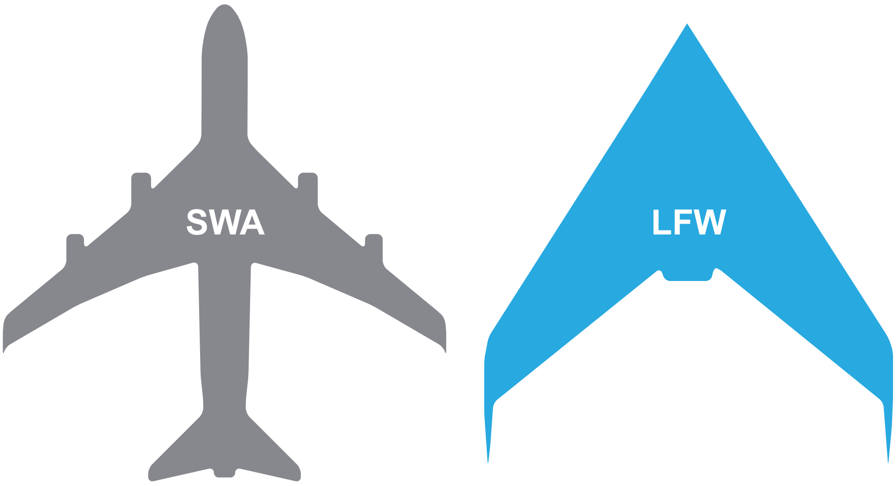

Figure 5.10 Swept Winged Aircraft versus Laminar Flying Wing

rameters are based on test flights of the NASA F-94 aircraft, fitted with a full-chord suction glove on the wing surface. Forty years of research has shown that a LFW passenger aircraft could be practically built, despite the design being commercially risky. Using the UDF engine design lowers the plane velocity from 0.85 to 0.80 Mach, and is likely to incur additional costs for noise reduction measures and maintenance. However, the increased propulsive efficiency of the UDF engine from 81% to 95%, in combination with the LFW, make this option the most 'economical large civil aircraft that is feasible' using kerosene fuel, according to Green *et al.*.[183(p.47)] The effects of changing the aircraft velocity, flight path or propulsion are not included in the analsysis.

5.4.4 Ships

More than 90% of world trade by weight is carried by ships IPCC,[151] yet due to their comparatively high efficiency per tonne transported, they consume less than 10% of primary energy for transport (10 EJ). Ships are supported by the buoyancy force created by the difference in average density between the ship and the water. This allows very large and heavy loads to be transported, but limits the upper velocity of travel due to rapid increase in resistive drag at high speeds. The utilisation ratio for ships is influenced primarily by the design of the propeller and the shape of the hull, the mechanics of which are discussed below.

Ships are most commonly driven by 'simple' screw propellers. Thrust is provided as the propeller blades turn through the water, creating localised lift in the same way a wing creates lift in a plane. An efficient propeller design creates this lift with minimum drag. However Bertram[184] explains that the relative shortness of propeller blades complicates the modelling of propeller performance. He describes five different modelling techniques used by today's marine engineers.

The simplest of these propeller model, momentum theory, assumes the propeller is an actuator disk that accelerates the flow in the axial direction by creating a pressure jump in the propeller plane. The flow of water into the propeller is given by $\rho\nu_{in}A_{in}$, where ρ is the water density, ν_{in} is the velocity and A_{in} is the cross-sectional area of the propeller plane. The action of the propeller increases the velocity of the water flow (ν_{out}), but contracts the cross-sectional area of the flow 'tube' (A_{out}). The change in momentum is the thrust delivered by the propeller.

Thus, the ideal efficiency for the propeller can be written as:

$$\eta = \frac{2\nu_{in}}{\nu_{out} + \nu_{in}} \tag{5.29}$$

which predicts high efficiencies for propellers that deliver only a small change in velocity. Practically, this means increasing the propellor diameter so that thrust is delivered at lower revolutions per minute (rpm). Further efficiency improvements result from limiting the frictional drag on the hull downstream of the propeller, which is caused by the increased velocity and lower pressure of the flow; reducing interference from the ship's wake; and avoiding cavitation, caused by the rapid formation and collapse of vapour bubbles in regions of low pressure near the blades.

The resistive drag forces acting on the ship's hull in calm water can be divided into three main components:

Friction resistance is caused by water particles adhering to the wetted area of the hull and being dragged along with the ship. The friction force is related to the shear stresses within the boundary layer which forms.

Viscous pressure resistance results from variations in localised flow velocities, vortices and separation of the flow, caused by the shape of the hull, which increase the average overall shear stress in the boundary layer. It can be minimised by designing long slender hulls, allowing for practical limitations such as stability.

Wave resistance is related to the wave system created by the ship as it travels through the water (not the ship travelling through waves). No satisfactory equation has been found to quantify this effect, instead it is typically found experimentally.

Other less important resistance forces result from: aerodynamic drag (which is significant in high-speed vessels); drag from underwater appendages (such as the rudder and keel); wind, waves and current; shallow water; and the cleanness of the hull.

The total resistive force (F) can be represented in the single term:

$$F = \frac{1}{2}\rho\nu^2(C_T) \tag{5.30}$$

where ρ is the water density and C_T is the total resistance coefficient. Bertram[184] describes several methods for determining experimentally the forces acting on the hull, each with a separate definition for C_T. However, the components of C_T typically include a frictional coefficient C_F, which depends on the Reynolds number, and residual coefficient C_R, which includes the wave resistance amongst other factors, and depends on the Froude number. These factors depend critically on the velocity of the ship and favour large ships.

The resulting set of equations are non-linear and can only be solved using complex fluid dynamic modelling or by testing scale models experimentally in 'towing tanks'. This makes the formation of a simple generic model for ships impossible. Instead, design parameters from a comprehensive survey of experimentally tested hull designs are used to determine the practical savings available of 63%, shown in table 5.20.

The final report to the International Maritime Organization, entitled *Study of greenhouse gas emissions from ships*[185] is used as the principal source for calculating the practical energy savings. This report finds the technical advances in the efficiency of ships,

Table 5.20 Practical savings available in ships

Type	m	ν	f_i	Percentage reductions			
				Prop	Hull	Speed	Total
	kt	m/s	%	%	%	%	%
Oil tanker	275	7	29	5	35	18	58
Bulk carrier	70	7	23	5	28	23	56
Container	36	10	15	10	31	22	63
General cargo	12	8	19	5	43	25	73
Other[1]		8	14	5	43	25	73
Practical[2]		7	100	6	35	22	63
			Practical energy savings available **63%**				

Notes: [1]estimated based on general cargo, [2]weighted average, by the distribution of carbon emissions (f_i)

and then reduces this potential based on the economic barriers to implementation. For this analysis, the economic constraint is removed and the most aggressive technologies chosen. Improvements to three components relating to the passive system are examined: the propeller design, the hull and the ship's velocity.

For the propeller design, Henningsen compared several technical advances from literature and estimated their influence on overall efficiency. Four options in particular are recommended for consideration when designing new propellers: low RPM large diameter propellers, pre- and post-swirl devices, ducted propellers (for high thrust low speed vessels such as tankers) and twin counter rotating propellers (for container vessels). They conclude that the practical energy savings relating to the choice of propeller range from 5–10%, depending on the type of ship.

The practical savings for the hull are based on MARINTEK's substantial database of model test results, also reported in Henningsen.[185] The model data for each type of ship—oil tanker, bulk carrier, container and general cargo—is normalised back to the typical case ship size and plotted on a power versus speed graph to find the worst, average and best case curves. The hull designs show a significant spread, up to plus or minus 30%. The difference between the average and best case curves is calculated at the specific ship velocity to find the percentage energy savings.

Henningsen considers the effect of decreasing the ship speed by 10%. This is accepted for ships, although not for other forms of transport, because the journey time is not as critical. The calculation includes an adjustment to increase the entire shipping fleet by 10% to maintain the same global transport capacity. Yet, even with this correction, the energy savings from reducing speed are large and the most easily implemented.

5.4.5 Trains

Trains are used to provide both freight transport and passenger transport, using 5.6 EJ and 2.2 EJ of global primary energy respectively. Transporting goods and people by rail is typically more efficient than by road due to 'convoy effects', whereby the resistive forces do not increase significantly with length. Raghunathan *et al.*[186] comments that although train speeds have reached over 300 km/h, in contrast to airplanes, the flow physics around trains is not well understood and is complicated by the length of the train, different wagon shapes and interaction with the fixed track, structures, tunnels and platforms.

The drag forces acting on a moving train are typically modelled using a second order polynomial with respect to velocity, of the form:

$$F = A + B\nu + C\nu^2 \tag{5.31}$$

where A, B and C are constants found experimentally. There is some debate about the underlying physical mechanism for each coefficient. Term A is normally attributed to mechanical drag and depends on the axle loading, roller bearing resistance, deflection of the track and the wheel to rail friction contact. Term A scales with the weight of the train (mg), and is thus analogous to μ in equation 5.22. Term C relates to the aerodynamic drag and, when found experimentally over drive cycles, includes the inertia force.

According to Raghunathan *et al.*[186] it can be expressed as:

$$C\nu^2 = \frac{1}{2}\rho A_f \left(C_D + \frac{\lambda}{d} l \right) \nu^2 \tag{5.32}$$

where the additional terms to equation 5.22 are: d hydraulic diameter of train (m), l train length (m) and λ hydraulic friction coefficient (to account for the connecting parts between wagons and the structures under the train).

Term B is traditionally expressed as a function of mass, for example in Gawthorpe,[187] but a recent study by Lukaszewicz[188] covering modern higher speed trains shows that term B relates only to the train length. Depending on the exact definition, it is likely there are contributions from both the mechanical drag and the energy required to accelerate the intake air for combustion and ventilation, to the velocity of the train.

Without a definitive model of the physical contributions to resistance in trains, it is more difficult to accurately predict the practical utilisation limit. Furthermore, national energy use data for trains is rarely broken down beyond the high level freight and passenger categories, and does not correlate with the case studies for which empirical coefficients are available. Nevertheless, Lukaszewicz presents general train data (for example, configuration, mass, length) and resistance coefficients (A, B and C) for 5 configuration of 'loco-hauled passenger trains', 3 'high-speed trains' and 7 'freight trains' operating in Sweden. These were compared with studies by Gawthorpe,[187] Hickman,[179] Raghunathan *et al.*[186] and Kemp[189] to validate the data.

Table 5.21, shows the practical energy savings that can be achieved in freight trains (62%) and passenger trains (43%). The

Table 5.21 Practical savings available in trains

Design	m t	ν m/s	A N	B Ns/m	C Ns^2/m^2	F kN	Ratio kJ/t km
Freight							
Current[1]	395	28	5,600	160	21	26.0	66
Practical	398	28	2,300	58	8	9.9	25
						Practical energy savings available	**62%**
Passenger							
Current[2]	300	42	3,300	28	11	23.2	77
Practical	398	42	2,300	58	8	18.1	46
						Practical energy savings available	**41%**
High-speed[3]	398	56	2,300	58	8	29.4	74

Notes: [1] typical freight train has locomotive plus 24 wagons, [2] typical passenger train has locomotive plus 5 wagons, [3] high-speed passenger train used as a reference for the practical limit ratios

current utilisation ratios are calculated using poor performing configurations from the Lukaszewicz[188] study, to correct for the technology differences between Swedish and global average trains. The selected values are not as high (inefficient) as some configurations in the literature, which may be due to the test method excluding inertia forces, but a cautious approach is taken to avoid overestimating the energy savings.

The Swedish X2 high-speed passenger train, with speeds approaching 250 km/h and a utilisation ratio of 74–80 kJ/t km, is selected as the basis for the practical utilisation limit for both freight and passenger trains. Comparison with the French TGV and the Japanese Shinkansen (300 km/h, 67–82 kJ/t km) high-speed trains show remarkably similar performance. These trains are highly optimised, making use of light-weight materials and streamlined body design to reduce aerodynamic and mechanical drag, and are thought to be approaching practical design limits. The aim of such advanced designs is to counteract the increase in fuel consumption at high speeds.

Two corrections are made to the high-speed train model to allow comparison. Firstly, the average speed is reduced from 56 m/s (200 km/h) to: 28 m/s (100 km/h) for freight train, and 42 m/s (150 km/h) for the passenger train. This approximates the effect of using the best available design at the current average train speed, and reduces the practical utilisation limit. The second, is to use the mass of the high-speed train (not the freight or passenger train) in the calculation. This avoids a correction to the terms A, and perhaps B, to account for the change in mass. However, the difference in mass is cancelled out when the utilisation ratios are normalised by mass. It is assumed that the use of coasting and regenerative braking will make the energy to overcome inertia almost negligible. Improvements to the engine or drive-train are not considered.

5.5 Results and discussion

The practical energy savings in passive systems can now be calculated using equation 5.2, in which the primary energy use values from table 5.1 are multiplied with the percentage gains available from each model. Using primary energy values has the effect of compounding the energy savings in the passive system back up through the entire energy conversion chain, and allows the reduction in carbon emissions to be inferred.

Table 5.22 summarises the practical energy and carbon savings for the passive energy systems. It shows that the greatest absolute energy savings (column 4) are found in buildings, and in particular heated spaces and appliance systems. As with the ranking of conversion devices in the previous chapter (see table 4.6), aircraft are prioritised lowest, demonstrating that the aircraft engine (device) and the aircraft (system) are comparatively well optimised. In addition, the low ranking for aircraft confirms that scale of energy flow through the system is a reasonable indicator of the absolute

Table 5.22 Practical energy and carbon savings

Passive System	Practical savings %	Energy demand EJ	**Energy savings EJ**	Carbon emissions Gt CO_2	**Carbon savings Gt CO_2**
Heated space	98	72	**71**	3.3	**3.3**
Appliance	67	88	**59**	4.1	**2.8**
Furnace	62	67	**42**	4.0	**2.5**
Car	91	40	**37**	2.8	**2.6**
Driven system	59	56	**33**	3.3	**1.9**
Truck	54	38	**20**	2.6	**1.4**
Steam system	66	31	**20**	2.0	**1.3**
Hot water system	80	23	**18**	1.1	**0.9**
Illuminated space	95	18	**17**	1.1	**1.0**
Cooled space	100	14	**14**	0.8	**0.8**
Ship	63	10	**6**	0.7	**0.4**
Train	74	8	**6**	0.5	**0.4**
Plane	46	11	**5**	0.8	**0.3**
Building	83	215	**179**	10.5	**8.8**
Factory	62	154	**95**	9.3	**5.7**
Vehicle	70	106	**74**	7.3	**5.1**
Total	73	475	**348**	27.1	**19.6**

energy savings available.

The analysis presented in this chapter demonstrates that an average global energy saving of 73% is practically achievable in passive energy systems. It is the first time that the practical energy savings in passive systems have been assessed separately from those in conversion devices. Representative global energy data was often unavailable across the range of technology options, making the accurate assessment of current energy use in passive systems challenging. The allocation of energy use between the conversion device and the passive system also proved difficult in some cases.

Nevertheless, basing the practical limit on fundamental engineering principles has removed much of the uncertainty from the analysis. Current energy use is forever changing, but at least the practical target by definition will remain stable. Furthermore, technology options and efficiencies are surprisingly uniform across the world's geographic and economic zones. There are clear exceptions, such as wood fired stoves in the developing world, but in many cases economic status determines whether or not you own an energy consuming technology, not the efficiency of the technology. Therefore, it is hoped that this research proves useful for understanding the function and utilisation of energy in passive systems, and becomes a basis for setting future priorities for action in the field of energy efficiency.

6 DISCUSSION AND CONCLUSIONS

Having determined the efficiency limits for all energy conversion devices (theoretical limit) and passive energy systems (practical limit), it is now possible to identify efficiency options from across the entire global energy network.

6.1 What new conclusions can now be made?

If all conversion devices and passive systems could be operated at their efficiency limit, then substantial reductions in primary energy use and carbon emissions would result. Today's conversion devices are inefficient, converting on average only 11% of primary energy input into a useful energy output. Passive systems use only 27% of the useful energy input to deliver final services. The remaining energy is currently lost as low temperature heat to the environment. Multiplying these efficiency limits together gives an overall efficiency for the entire network of 3% suggesting more than a 30-fold improvement in efficiency is technically possible.

Table 6.1 shows the potential energy savings in conversion devices and passive systems. The largest potential saving across all devices and systems is found in the passive system of the heated space. This is due to both the scale of energy use for heating building spaces and the possibility of thermally insulating the buildings in most parts of the world, such that no artificial heat input is required to keep the occupants comfortable.

Clearly, the potential savings in energy cannot be all achieved at the same time. Efficiency gains in the conversion devices cannot be simply added to the gains in the passive systems (as stressed

Table 6.1 Efficiency limits, energy savings and carbon savings

Conversion device	Primary energy	Percent savings	Energy savings	Carbon savings	Passive system	Primary energy	Percent savings	Energy savings	Carbon savings
	EJ	%	EJ	Gt CO_2		EJ	%	EJ	Gt CO_2
Electric heater	58	93	54	3.1	Heated space	72	98	71	3.3
Diesel engine	58	80	47	3.3	Appliance	88	67	59	2.8
Electric motor	55	83	46	2.6	Furnace	67	62	41	2.5
Biomass burner	49	94	45	0.0	Car	40	91	37	2.6
Gas burner	47	88	41	2.3	Driven system	56	59	33	1.9
Petrol engine	41	88	36	2.5	Truck	38	54	20	1.4
Cooler	33	98	33	1.9	Steam system	31	66	20	1.3
Coal burner	31	83	26	2.2	Hot water system	23	80	19	0.9
Oil burner	28	86	24	1.7	Illuminated space	18	95	17	1.0
Heat exchanger	20	98	20	1.2	Cooled space	14	100	14	0.8
Light device	18	96	17	1.0	Train	8	74	6	0.4
Electronic	16	98	15	0.9	Ship	10	63	6	0.4
Other engine	10	82	8	0.6	Plane	10	46	5	0.3
Aircraft engine	11	75	8	0.5					
Heat	233	90	210	10.4	Building	215	83	179	8.8
Motion	175	83	145	9.6	Factory	154	62	95	5.7
Other	67	98	65	3.8	Vehicle	106	70	74	5.1
Total	475	89	420	23.8	Total	475	73	348	19.6

several times in this thesis) without saving more energy than is consumed.

6.1.1 Where are efficiency gains most likely?

The analysis has shown that conversion devices on average operate at only 11% of their theoretical potential. Yet, given the sizeable effort already in progress to improve device efficiency, it is unlikely that this ideal—a factor 10 improvement—will be approached in the near future. Where should action and responses be focused? Is it better to prioritise efforts on improving coal fired power stations or diesel engines? This is difficult to answer because the theoretical saving in both energy and carbon emissions depends not only on the efficiency of the individual device, but also on the upstream efficiencies of all devices in the energy chain. A solution to this question can be found by performing a sensitivity analysis to assess the energy savings that would be achieved from a small independent change in efficiency for each type of conversion device.

Applying an absolute efficiency change (for instance, increasing each value of ϵ by 1%) to each device might be misleading, as achieving an equivalent gain in an already efficient device is likely to be more difficult than for a less efficient device. Instead, the conversion loss (which equals the theoretical energy saving) for each device is reduced by 1%, and a modified device efficiency is calculated using:

$$\epsilon' = \epsilon + (1 - \epsilon) \times 1\% = 0.99\epsilon + 0.01 \tag{6.1}$$

The efficiency of each device in turn was changed to the modified value (ϵ') and the resulting total global energy input required to deliver the same useful energy was calculated. This leads to a sensitivity analysis of energy savings for the same relative level of improvement in each device, and provides a more equitable way to compare and rank individual conversion devices, irrespective of the location of the device in the energy network. This sensitivity analysis is performed for individual conversion devices, as opposed to energy chains, and the results are shown in figure 6.1. The chart shows the reduction in energy and carbon emissions resulting from a 1% reduction in the energy loss from each conversion device.

Efforts to improve the efficiency of coal-fired power stations will deliver the most savings in the upstream fuel conversion and electricity generation processes, because coal dominates electricity generation. However, greater energy savings are available from focusing individually on: biomass burners, coolers, gas burners and petrol engines. Collectively, prioritising efficiency measures for end-use conversion devices over fuel transformation and electricity generation delivers more than five times the potential gain (28 EJ versus 5 EJ). This is a surprising result, given the emphasis placed on improving the efficiency of electricity generation, for example in the International Energy Agency (IEA) report, *Energy technology perspectives 2008*.[1]

Biomass burners emerge as the single most important conversion device and where the largest energy savings can be achieved from an incremental improvement in efficiency. These burners are predominantly open fires, which burn wood, dung, crop waste, coal and charcoal, to meet the energy needs of people living in the developing world. The reason biomass burners top the sensitivity list is due to the scale of use—used by half the world's population and burning more than 10% of global energy supply—and the inefficiency of the burners, averaging only 7%. In this analysis, biomass burners do not contribute to carbon emissions, because it is assumed that the carbon dioxide (CO_2) released during combustion is equivalent to the CO_2 absorbed when growing the biomass. However, if the biomass is not replaced, for example in areas where deforestation is a problem, then net carbon emissions to the atmosphere result. Improving the efficiency of biomass burning stoves is technically very easy, and has the added benefit of reducing res-

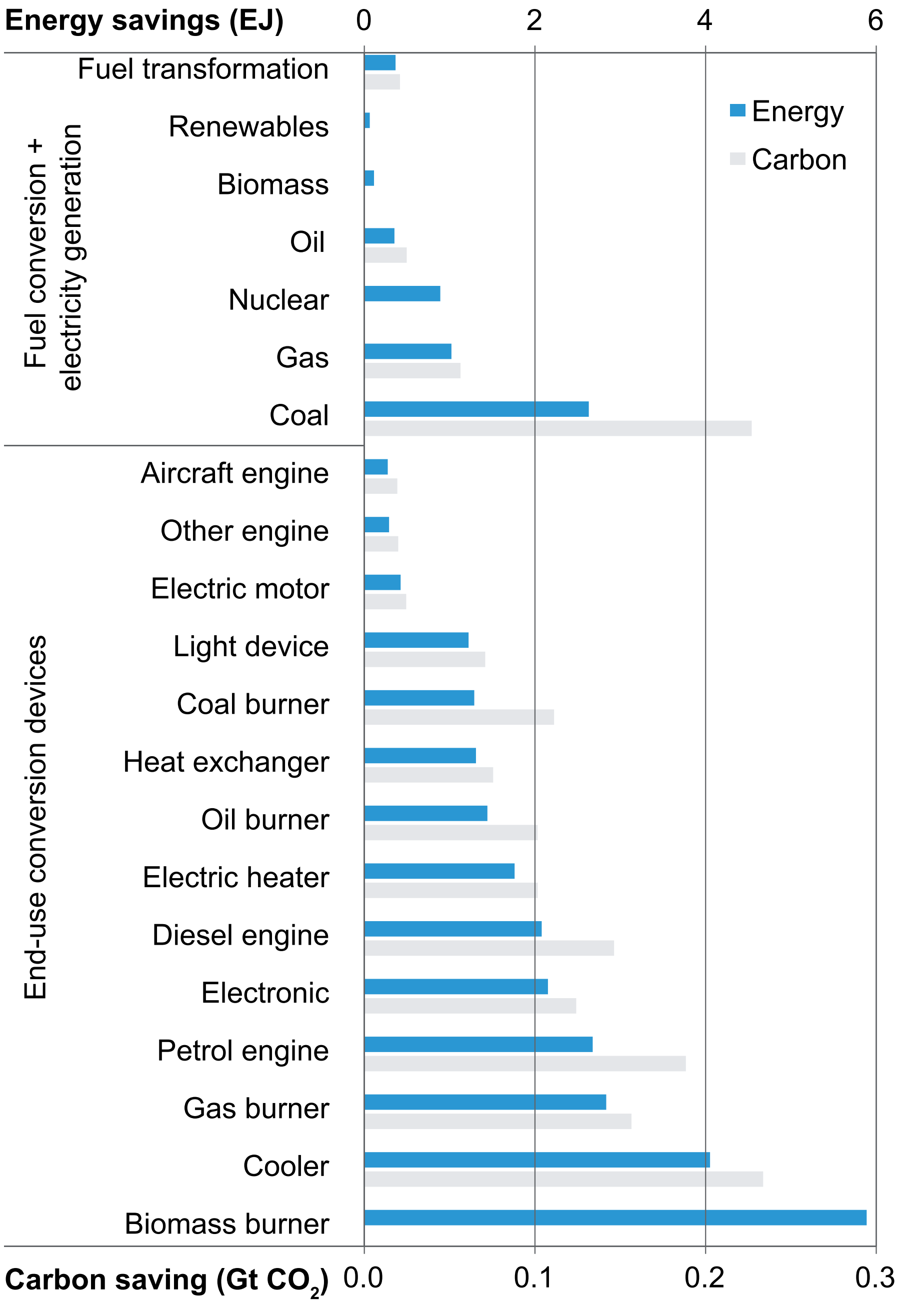

Figure 6.1 Sensitivity ranking of individual conversion devices

piratory illness from the inhalation of smoke, which is 'the single biggest killer of children under five years of age'.[190(p.24)] However, wide-scale dissemination of improved stove technology is held back by insufficient international political backing, limited funding and the enormous number of open fires in use.

6.1.2 Application of this research

The results of this research demonstrate that significant energy savings are technically possible in conversion devices and passive systems. Yet such gains are not necessarily achievable, and history has shown that technical efficiency potentials are typically under-realised. The use of theoretical and practical efficiency limits presents an ideal, an ideal which may not be realised because of economic or behavioural constraints. This work makes no attempt to assess the economic costs of developing and deploying advanced efficiency measures. Neither does it consider the many socio-economic barriers to the uptake of new technologies. Therefore, one must be careful to avoid claiming that the calculated efficiency targets will or even should be attained.

Economists tend to assume that change can be brought about by the choice of appropriately constructed policies. Such thinking can neglect questions of the fundamental physical and engineering laws, which place limits on the energy that can be saved. By providing an overview of the entire energy network and assessing the potential impact of energy efficiency measures, this thesis contributes to the field of policy-making by demonstrating both the potential reach and the limits of energy efficiency. If technical solutions can be found, and are supported by well designed policy measures, then large reductions in energy use and carbon emissions are possible.

Further research is required to evaluate the effect that efficiency gains have on the embodied energy in the device or system. It is possible that some of the potential energy savings may be eroded by the additional embodied energy required to manufacture the improved conversion devices and passive system. Thus, a fraction of the saved energy from transport or buildings may reappear as an increase in factories for the production of materials and goods. However, the common assumption that more efficient devices are always more energy intensive to build, does not always hold. Three practical examples are given to illustrate this point:

1. It is possible to design a super-insulated and air-tight building, which does not require artificial external heating or cooling, *and therefore also* dispenses with the need for energy intensive capital equipment such as boilers and air-conditioning units.
2. Light-weight streamlined cars deliver higher fuel efficiency *as well as* reductions in the size of the engine, drive train, braking system and structural components of the vehicle.
3. In many cases it is more cost effective for power utility companies to give away efficient light-bulbs and appliances than increase generation capacity by building new power stations.

Such win/win options that reduce both operational energy use *and* the energy embodied in capital equipment, should be prioritised.

The scope of this thesis is wide-ranging, covering a large body of literature and drawing heavily on statistical energy data and previous efficiency studies. The intricacies of specific energy processes are only examined to the level of detail necessary to determine the limits to efficiency. The accuracy of the analysis could, with more time, be improved. Despite best efforts to find representative global data for current device and system use, in many cases only regional or country specific data could be found. Allocating energy flows and losses between the conversion devices and passive systems proved difficult in some cases. It is hoped that other energy researchers will contribute understanding from their specific areas of expertise, to improve, correct and validate the research. Nevertheless, even in its current form, the results of this work are useful for directing future research priorities and setting energy policy in the field of efficieincy.

6.2 Outline of future research

Several deserving project ideas have emerged out of this research into energy efficiency. The general intention is to take the thesis material, divide and reformat it into more accessible forms, and present this in a wide range of written and public settings. It is hoped that this fundamental approach to energy efficiency will not only gain traction among engineers and technical researchers, but in addition, will be an influence on energy policy and be integrated into the wider public debate on climate change. In the immediate future, it is planned to pursue the following activities to promote this goal.

6.2.1 Journal papers

In addition to the five published or pending journal papers listed in the front matter (page iii), three further journal papers are planned:

The first paper, extends the theoretical analysis of conversion devices (chapter 4), by asking what are practical limits of energy efficiency. Simple engineering models are created for each device to understand how energy is lost during energy conversion. An estimate of the practical energy savings available can then be calculated by varying the coefficients in the model scalar equations, within physical limits from literature.

The second paper, examines the efficiency limits for materials. Allwood, Cullen and Milford[125] have explored the concept of material efficiency, identifying several innovative routes for achieving a 50% cut in industrial carbon emissions. However, their estimate of potential material efficiency gains in 2050 was based on surveys of known recycling techniques and yield improvements. This proposed paper would add to this research by completing a fundamental study of material efficiency, based on physical limits for reducing, conserving and recovering material during the product life-cycle.

The third paper, will present a summary of the entire body of work, from the scale of energy flow, to the efficiency limits in conversion devices and passive systems. This will be published in a journal with a wide technical readership—such as the *Philosophical Transactions of the Royal Society A*, or *Environmental Science & Technology*—to provide a single reference point for the research.

6.2.2 Energy efficiency guide book

The wide ranging top-down approach taken to energy efficiency in this research appears to have broad appeal amongst not just engineers, but also scientists, economists, business people, policy makers and the general public. Therefore it is proposed to convert the thesis material into a guide book for energy efficiency. The intention is to use simple language and frequent illustrations to make energy efficiency options understandable and give the non-academic reader practical efficiency options to reduce carbon emissions. There is much experience to be gained from the successful launch of MacKay's book *Sustainable energy - without the hot air* and the popular engineering texts published by Ashby, for example, *Materials and the environment.*[164] The book is expected to be well received and will hopefully lead to further opportunities to speak about energy efficiency to a diverse range of audiences.

6.2.3 Matlab model of global energy efficiency

The aim of this project is to transfer the data model from Microsoft Office Excel™ to a matrix form in MATLAB® to allow multiple data sets to be created and maintained. MATLAB® also has the capability to draw the Sankey diagrams automatically, replacing the laborious manual drawing process using Adobe® Illustrator®. This added flexibility will allow:

- the energy maps to be easily translated into equivalent carbon maps, giving greater accessibility for policy makers and the public

- future energy scenarios to be explored, such as increased renewable or nuclear energy, or a switch in transport designs from conventional to hybrid or electrical
- the energy source and device efficiency to be updated for historical and subsequent years, permitting time-series trend analysis
- the construction of similar regional, country or company based energy maps

6.2.4 WellMet: steel, aluminium and the carbon targets 2010–2050

As the research into energy efficiency progressed, it was identified that significant efficiency gains in the production of material goods would be more difficult to achieve. For buildings and transportation, technical solutions such as insulation and light-weighting, are already accepted, understood and likely to deliver significant efficiency gains. In contrast, many of the simplest technologies have already been exploited in industry, and the long capital cycles and inertia of dominant technical solutions can prevent new ideas from reaching the market.

In response Allwood, Cullen and Milford[125] completed an original study into industrial carbon emissions from the five most energy intensive materials: steel, cement, plastic, paper and aluminium. This analysis shows that industry efforts to increase energy efficiency and recycling rates will not be sufficient to meet a 60% cut in carbon emissions by 2050, against a doubling of demand for materials. Based on this research work, Dr Julian Allwood applied for and was awarded a five-year Engineering and Physical Sciences Research Council (EPSRC) Leadership Fellowship project (RG50904), entitled WellMet: steel, aluminium and the carbon targets 2010–2050. The author will be part of the leadership team for this project.

WellMet, aims to identify and validate all means to halve, by 2050, global carbon emissions from the production of steel and aluminium goods, against a projected doubling of demand. The project has received funding of £1.5 million, comprises a team of seven researchers, and is backed by a consortium of 20 global companies. The research will firstly, evaluate all existing options for carbon emissions reduction, ranging from low carbon energy supplies (renewables, nuclear and Carbon Capture and Storage (CCS) to energy and material efficiency. Secondly, radical new options will be explored—such as non-destructive recycling (the reuse of materials without remelting), light-weighting, and single-step heat processing—to deliver much greater carbon reductions. The work will combine physical and economic modelling, development and demonstration of new technologies, and ongoing interaction with industry built around a portfolio of fact sheets, case studies and workshops on wider themes. Two key publications will be released over the five year project: a mid-term project report that will be widely distributed to stakeholders, and a final book to be used as a reference guide for future work in this area.

6.3 Two promising ideas

Two additional ideas have emerged from the efficiency research, and given no constraints on time, would be explored further. They are noted here to enable other researchers to perhaps investigate them in the future.

6.3.1 Conversion devices: an energy conversion matrix

Imagine that the global energy map (figure 3.2) is printed onto a A4 rubber sheet. Possible future changes to the energy network could then be visualised by stretching the rubber sheet. For instance, if in a future scenario renewable energy sources are doubled, then the renewable energy line on the Sankey diagram would be stretched to be twice the width. If electric vehicles were to replace half the existing petrol engines, then the petrol engine line would halve, a new line for electrical drives in vehicles would appear, and some of the upstream oil supply would be displaced by electricity generation. Thus, the rubber sheet would become a tool for exploring alternative energy supply options and different technology pathways—for assessing large-scale changes to the energy network, rather than just improvements.

During the last century, abundant supplies of inexpensive fossil fuels have proved significant in shaping and driving the global economy. For this reason, the conversion of chemical energy to heat using combustion is the dominant conversion process, being present in 90% of energy conversion pathways. It is not surprising therefore that much of the current energy efficiency research is focused on around improving combustion processes. Although alternative conversion pathways are available—for example electromagnetic radiation to electricity (in solar panels), nuclear energy to heat (in fission reactors), and kinetic energy to electricity (in hydro and wind turbines)—these technologies play only a minor role in energy conversion.

In contrast to the dominance of fossil fuels, concerns over climate change and energy use reduction are still relatively new. Yet, at some point in the future, perhaps in 100 to 200 years, the dominance of fossil fuels energy supplies will likely end (due to excessive environmental damage or because the fossil fuel supplies dwindle) making alternative options more cost effective. During this transition, alternative conversion processes will become increasingly important.

Energy can be divided into 6 different forms: radiation, chemical, nuclear, thermal, mechanical, and electrical. This gives 36 possible energy transformations for a single conversion process. In 1969, Zwicky[191] proposed creating a matrix of all possible energy conversions, which he called the ‘Morphological Box of Energy Transformations’. The idea was to identify and explore alternative pathways for converting energy, however the work was not completed. The concept of an energy conversion matrix has been revisited several times, but only in outline form, for example Summers,[82(pp.150–1)] Smil[40(p.14)] and Ashby.[164(p.21)]

With the current pressures on fossil fuel supplies, it seems an opportune time to revive Zwicky's idea, quantify the current energy conversions using an input-ouput framework and begin a comprehensive and fundamental search for alternative energy conversion routes. This would begin by reviewing all known technologies for converting energy, whether used in practice or still in the conceptual stage. Then using the morphological approach, a structured search of potentially new conversion pathways could be explored. Based on future projections of the fossil fuel availability and public acceptance, scenarios could be developed and a roadmap described for large-scale changes to the energy network.

6.3.2 Passive systems: reduce, conserve and recover

The analysis of passive energy systems separate from conversion devices, has led to a new perspective on saving energy. This new view originates from the concept of material efficiency, where the demand for materials can be decreased by: reducing the material in the product (reduce), extending the service-life of products (conserve) or recycling and reusing products (recover). It is proposed to apply these concepts to useful energy—motion, heat, light, cooling and sound—in passive energy systems.

The 'reduce' approach aims to deliver the same amount of final service, using less useful energy. This includes measures such as: increasing the passenger loading in cars, turning off light bulbs when not in use, and ensuring electric motors and drives are matched with the required load. The underlying aim is to eliminate over-deisgn and use systems to their full capacity. (Energy savings in passive system, should not be confused with reductions in energy use through efficiency gains in conversion devices.)

The 'conserve' approach involves modifying passive systems to extend the lifetime over which useful energy is applied. Examples include: insulating and sealing buildings to conserve heat; reducing vehicle aerodynamic drag and tyre-to-road friction to maintain momentum; designing electronic displays that require no power to maintain text on the screen.

The 'recover' approach requires improving the design of passive systems to recover useful energy following its application. Motion in vehicles can be recovered using regenerative braking, a technique already commonly used in electric motor systems. A possible alternative is the transfer of momentum to another moveable body, as is observed in a Newton's cradle. Interestingly, if a significant proportion of motion in vehicles could be recovered, it would negate the need to light-weight vehicles.

The recovery of heat follows the same principle as down-cycling of materials in products. Currently, most of the thermodynamic availability of fossil fuels is wasted because it is used for low temperature applications, such as heating air and water. However, waste heat from an application is not lost (conservation law), instead only its quality is degraded. Thus if the waste heat from a high-temperature application can be used at a slightly lower temperature, and so on, then a cascade of reducing heat quality is formed. This concept is not new and is employed in industry, using optimisation tools such as the 'pinch analysis' methodology developed by Linnhoff and Hindmarsh.[192] However, the theoretical potential to cascade heat at a national or global level has only briefly been explored (see Lovins[37] and Nakicenovic and John[193]), and is an area that warrants further investigation.

Table 6.2 gives examples of reduce, conserve and recover for the passive energy systems. The time scales for useful energy in passive systems are typically short. Light will be absorbed within less than a second, sound over a few seconds, kinetic energy perhaps lasts a few minutes, whereas heat or cooling is available for hours. In contrast, the long service life time for materials in products—from days to centuries—makes them an ideal area to pursue the strategies of reduce, conserve and recover. Allwood, Cullen and Milford[125] have discussed such ideas under the topic of material

Table 6.2 Examples of reduce, conserve and recover in passive systems

Service	Reduce	Conserve	Recover
Transport	full passenger load	aerodynamic design	regenerative braking
	engine matched to vehicle	improved traffic control	momentum transfer
Structure	low energy materials	service life extension	modular design
	light-weighting	re-configurable design	reuse/recycle
Sustenance	less supply-chain waste	advanced packaging	nutrient recovery?
	less consumer waste	long-life products	
Hygiene	tankless hot water	insulate equipment	waste-water heat recovery
Thermal comfort	heat/cool only people	insulate air-tightness	ventilation heat recovery
	use solar heat gain	reduce air leakage	thermal mass
Communication	print less on paper	static image displays	un-photocopying
Illumination	improved luminaire design	reflective surfaces?	photovoltaic surfaces?
	illuminate only task area		

efficiency for the five most energy intensive materials: steel, concrete, paper, plastics and aluminium. However, the reduce, conserve and recover strategies are yet to be examined in detail.

Having ascertained in this research that large opportunities exist for reducing energy use in passive systems, the next step required is to identify the specific technical breakthroughs required to deliver these gains. The field of energy efficiency would benefit from a structured analysis which explores this potential using the three different approaches: reduce, conserve and recover.

6.4 Conclusions

This thesis began with the questions: where should engineers focus their efforts? Are the greatest efficiency gains to be found in light bulbs or diesel engines, insulating houses or improving coal-fired power stations? What are the limits to energy efficiency? How should future research priorities be directed?

Approaching this problem from a technical perspective, based on physical and engineering laws, has resulted in a consistent framework for comparing efficiency options. Now, future efficiency research and energy policy can be directed towards the actions that will make the most difference.

The following original contributions are documented in this thesis:

1. For the first time the global flow of energy is traced from fuels through to the final services, focusing on the technical conversion devices and passive systems in each energy chain. By mapping the scale and complexity of global energy flow in Sankey diagram form, the technical areas which are likely to deliver the largest efficiency gains, can be quickly identified.

2. A novel distinction is made between conversion devices, which upgrade energy into more useable forms, and passive systems, from

which energy is lost as low temperature heat in exchange for final services. Devices and system need to be separated so that potential efficiency gains can be multiplied, instead of added, avoiding a common double counting problem.

3. Theoretical efficiency limits are calculated for global conversion devices using exergy analysis, and show a 89% potential reduction in energy use. Such an analysis has not been performed since 1990. The breakdown of conversion loss by engineering loss mechanisms is the first known attempt to collate and rank global conversion losses by technical categories.

4. Practical efficiency limits are calculated for global passive systems based on engineering models, and demonstrate energy savings of 73% are achievable. No previous study has assessed the practical energy savings in passive systems separately from conversion devices. Significant percentage gains are found in technical solutions that increase the thermal resistance of building fabrics and reduce the mass of vehicles.

5. For the first time the relative energy and carbon savings from fuel transformation, electricity generation, end-use conversion devices are compared on an equal basis using sensitivity analysis. It is revealed that improvements in end-use conversion devices—for example, engines, heaters and light bulbs—will collectively deliver five times more energy savings than the same relative improvements in upstream electricity generation and distribution. For individual devices, efforts should be focused on improving the efficiency of, in relative order: biomass burners, refrigeration systems, gas burners and petrol engines. For passive systems the priorities are insulating buildings and furnaces, and reducing the mass of vehicles.

It is certain, that over time the numbers in this thesis will be updated, the categories will be regrouped in more logical ways, and further insight will be drawn from the Sankey diagrams. Such modifications and challenges will be welcomed, because rather than devalue the research they will serve to validate the energy efficiency framework presented here. For it is this framework—this rational basis for assessing all future energy efficiency options—that is the unique contribution of this thesis.

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NOMENCLATURE

CH_4	methane
CO_2	carbon dioxide
N_2O	nitrous oxide
BAT	Best Available Technologies
BTU	British Thermal Unit
CCS	Carbon Capture and Storage
CIESIN	Center for International Earth Science Information Network
CFL	Compact Fluorescent Light-bulb
CHP	Combined Heat and Power
COP	Coefficient of Performance
DTI	Department of Trade and Industry
EDP	Electronic Data Processing
EIA	Energy Information Administration
EPSRC	Engineering and Physical Sciences Research Council
EU	European Union
GDP	Gross Domestic Product
GHG	greenhouse gas
IEA	International Energy Agency
IESNA	Illuminating Engineers Society of North America
IFS	International Financial Statistics
IMF	International Monetary Fund
IPCC	Intergovernmental Panel on Climate Change
ITP	Industrial Technologies Program
LCA	Life Cycle Analysis
LED	Light Emitting Diodes
LFW	Laminar Flying Wing
NASA	National Aeronautics and Space Administration
OECD	Organisation for Economic Co-operation and Development
PVGIS	Photovoltaic Geographical Information System
PPP	Purchasing Power Parities

SEC	Specific Energy Consumption
SWA	Swept Winged Aircraft
UDF	Unducted Fan
UK	United Kingdom
UN	United Nations
UNDP	Untied Nations Development Programme
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America
USDOE	United States Department of Energy
WEC	World Energy Council
WRI	World Resources Institute