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The efficient use of energy: Tracing the global flow of energy from fuel to service

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ABSTRACT

The efficient use of energy is a key component of current efforts to reduce carbon emissions. There are two factors which are important when assessing the potential gains from energy efficiency technologies: the scale of energy flow and the technical potential for improvement. However, most efficiency analyses consider only the potential gains from known efficiency technologies, while ignoring the complex flow of energy through the chains of conversion devices. In response, this paper traces the global flow of energy, from fuels through to the final services, and focuses on the technical conversion devices and passive systems in each energy chain. By mapping the scale and complexity of global energy flow, the technical areas which are likely to deliver the largest efficiency gains can be identified. The result is a more consistent basis for directing future research and policy decisions in the area of energy efficiency.

1. Introduction: the potential gains from energy efficiency

Delivering goods and services more efficiently, using less energy, is a core component of today's attempts to reduce global carbon emissions. Moreover, improving energy efficiency remains the largest and least costly strategy for realising reductions in carbon emissions, according to the International Energy Agency (IEA, 2008b, p. 4). Yet, despite its large potential for demand reduction, efficiency is often overlooked amidst the excitement surrounding renewable energy and the resurgence of nuclear power.

Finding the global improvement potential from energy efficiency measures requires 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. Eq. (1) is used to find potential energy savings for each energy conversion device or system:

$$\text{Potential for saving energy} = \text{Scale of energy flow} \times [\text{Target efficiency} - \text{Current efficiency}] \quad (1)$$

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 paper addresses the first term of Eq. (1), the scale of energy flow, by mapping the technical devices, systems, and energy chains which form the global energy network.

2. Previous work: mapping the scale of energy use

In 1971, Claude Summers in his paper entitled *The conversion of energy* stated, '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' (Summers, 1971, p. 41). Mapping the scale of energy flow through this complex machine helps identify the most important technical devices, where large potential efficiency gains are likely to be found.

The *Sankey diagram*, first used by the Irish engineer Riall Sankey in 1898 (Schmidt, 2008), has become an important graphical tool for mapping the chains 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, allowing 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, 1971, p. 150). More recent examples include the *Global energy flows* diagram produced by the IPCC (Sims et al., 2007, p. 259) and the *Navigating the Numbers, GHG diagram* by the World Resources Institute (WRI) which attributes the worldwide greenhouse gas emissions to end-use activities (Baumert et al., 2005, pp. 4–5).

Such diagrams are useful for conveying visually, the comparative scale of energy flows. However, for the purpose of estimating potential efficiency gains the current Sankey diagrams are

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incomplete, for two reasons. Firstly, it is common to 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 *Energy footprints* for the industrial sector (USDOE, 2009); however, a technically focused global diagram has yet to be published.

Secondly, current Sankey diagrams stop short of tracing the entire length of each energy chain, from fuels through to the final energy services delivered to consumers. 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 light-bulbs) and the energy systems which transform this energy into final services (e.g. vehicles, buildings, and factory systems). This distinction becomes important when calculating energy efficiency gains, because energy flows sequentially through these two steps, and therefore potential efficiency gains are multiplicative and not additive.

This idea is explained using an example from the climate change literature. In their paper on stabilisation wedges, Pacala and Socolow (2004) suggest two efficiency measures to improve the operation of the world's 2 billion cars in 2054. The first is to increase fuel economy from 30 to 60 miles per gallon (mpg), saving 1 billion tonnes of carbon (GtC). The second is to reduce annual average car travel from 10,000 to 5000 miles, also saving 1 GtC. For each option, this equates to a saving of half the carbon emissions from cars. However, achieving both targets will not result in a 2 GtC reduction (i.e. no carbon at all), instead only 1.5 GtC will be saved as the percentage reductions in efficiency must be multiplied, rather than added together.

The concept of tracing energy flow through to final services has been explored by Nakicenovic and co-authors in the early 1990s (Nakicenovic and Grubler, 1991; Nakicenovic et al., 1993, 1996; Nakicenovic, 1996). They introduce the term 'service efficiency', defined as 'the provision of a given task with less useful energy (the output from conversion devices) without loss of 'service' quality' (Nakicenovic et al., 1993, p. 422, with authors explanation). The effect is to separate out efficiency measures, for example using a more fuel-efficient car, from conservation measures, such as improving the flow of traffic. However, they are careful to focus on technical measures, excluding those behavioural and lifestyle changes which imply a degree of austerity or loss of service. A more recent report by the United Nations Development Program (UNDP) entitled *World Energy Assessment* (Goldemberg, 2000, p. 176) outlines in theory, the separation between energy conversion devices and the 'technology producing the demanded services'. They refer to building materials, window systems, and lightweight vehicles; however, they do separate out these technologies as a distinct category in their subsequent calculation of regional efficiency potentials.

Separately, work has developed aiming to measure the energy consumption per unit of final service delivered, using *physical indicators*. For example, Farla and Blok (2000) developed physical indicators for all sectors of the Dutch economy, 1980–1995, and Schenk and Moll (2007) evaluated the use of physical indicators for industrial demand scenarios in several multi-country regions. These studies are useful for identifying structural changes in energy use over several years, but do not help identify areas in which potential efficiency gains might be available. This is because the selected service categories are based on available physical data sets, which tend to mix materials (steel) with services (transport), are often normalised by confusing factors such as the household area or number of employee years, and are typically disaggregated into too many categories. Therefore, it is difficult to trace each individual energy chain completely through to a selection of comparable final services.

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. Methodology: 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 Fig. 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

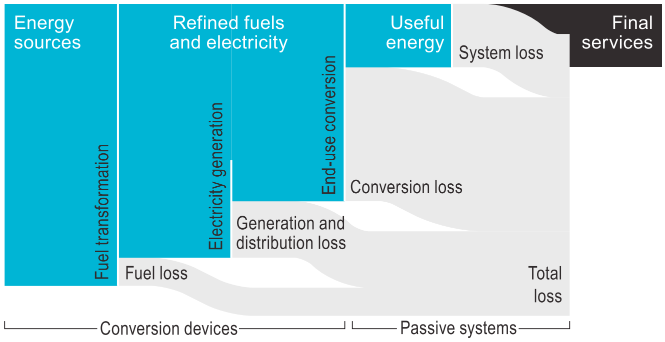

Fig. 1. The flow-path of energy.

Table 1
Energy sources and transfer mediums.

	Description
Energy sources	
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% average efficiency)
Renewable	Electricity/heat from hydro, geothermal, solar, wind, tide, and wave energy
Transfer mediums	
Electricity	From generation plants and CHP plants (elec. portion)
Heat	From utility heat plants and CHP plants (heat portion)

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 allocate primary energy supply to the individual technical components in each energy chain. 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 10) which cover the entire energy flow, for each step in the flow-path.

This paper focuses on the scale of energy flow, and thus in contrast to Fig. 1, the energy losses during conversion processes and from passive systems are not separated out from the main flow. Instead they remain embedded with the allocation of primary energy. It is through mapping the connections between these technical categories in Summer's 'complex machine', that potential opportunities for improving energy efficiency can be identified. The remainder of this section describes the process of selecting the technical components and allocating the global energy supply to conversion devices, passive systems, and final services.

3.1. Energy sources

Energy enters society from fossil fuel reserves, biomass matter, uranium deposits, and renewable sources. However, Lightfoot (2007) 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 IEA (2008a), and divided into the energy source categories listed in Table 1 (renewable energy is technically not a 'fuel' but included here for completeness). This source also provides the basis for dividing 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 combustion for 2005 are taken from the IEA *Key World Energy Statistics* (IEA, 2007a, 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 (4–11% across the sources, from Ertesvag and Mielnik, 2000, 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. End-use conversion devices

In most analyses, energy in the form of refined fuels and electricity is allocated directly to broad commercial sectors such as transport, industry, and buildings. Yet, technical advances in energy efficiency are not found in these sectors, but instead in examining conversion devices such as engines, motors, burners, and light bulbs. Therefore, Table 2 presents a list of technically distinct conversion devices, of significant scale, to be used in this analysis. The allocation of energy to each conversion device is based on the study *Regional and global energy and energy efficiencies* by Nakicenovic et al. (1996, Table 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 (2007a, p. 20).

3.3. Passive systems

The listing of passive systems in Table 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 (2000, 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 might be equally satisfied

Table 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

Table 3
Passive energy systems.

Passive system	Description
Vehicle	
Car	Light-duty vehicle: car, mini-van, SUV, pick-up
Truck	Heavy duty vehicle: urban delivery, 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	Medium temperature application: petrochemical cracker, reaction vessel, cleaning facility
Furnace	High temperature application: blast furnace, arc furnace, smelter, oven
Building	
Hot water system	Fuel and electric immersion boilers
Heated/cooled space	Residential/commercial indoor space
Appliance	Refrigerator, cooker, washer, dryer, dishwasher, electronic devices
Illuminated space	Residential/commercial indoor space, outdoor space

Table 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, quarrying, construction, non-specified

Table 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 use, household appliances
Thermal comfort	Heating and cooling of air in buildings
Communication	Digital and written communication
Illumination	Provision of light

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 4. The allocation is based upon the 2005 industrial energy data from IEA (2008b, pp. 476–477) and the conversion device breakdown from USDOE (2004, pp. 13–16), after accounting for upstream generation and fuel losses.

3.4. *Final services*

The key consideration when creating a list of final services is to select a small number of distinct but comparable categories, for which physical data is available or can be inferred. Eight final energy categories are chosen for this study as listed in Table 5. The physical values for final energy services are estimated using two methods. Where possible, bottom-up calculations from literature of the global final service in physical units are used. For example, Gantz et al. (2008) 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 (IEA, 2006b, 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, 1999, 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 (2006a, p. 427) in MJ/t 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 ($1.2\,\mathrm{kJ/m^3\,K}$) is used to infer the total volume and temperature change of air as a result of heating and cooling. This departs from the thermal comfort indicators used in literature, for example in Schipper et al. (2001), which take the housing floor area multiplied by the average temperature difference ($\mathrm{MJ/m^2}$ 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/kg K for food and 4.2 kJ/kg K 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, the allocation of materials to final services is based on regional product end-use data from: EUROFER (2008) for steel; IEA (2007b, p. 260) for chemicals; BCA (2008) for minerals; FAOSTAT (2008) for paper; and IAI (2006) for aluminium.

4. Results and discussion: What do we now know?

The energy data is presented in Sankey diagram form in Fig. 2. The global flow of primary energy is traced along each individual energy chain from left to right, and allocated to each of the four technical groupings: energy sources, end-use conversion devices, passive systems, and final services. Energy losses from devices and systems are not shown separately, but instead remain included with the primary energy flow. 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 ($EJ = 10^{18}$ J) and direct carbon emissions associated with the primary fossil fuels are shown in red circles in billion tonnes of carbon dioxide ($Gt\ CO_2 = 10^9\ t\ CO_2$).

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.

4.1. 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 in Section 2, 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 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 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 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 by any of the renewable sources 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. Large absolute efficiency

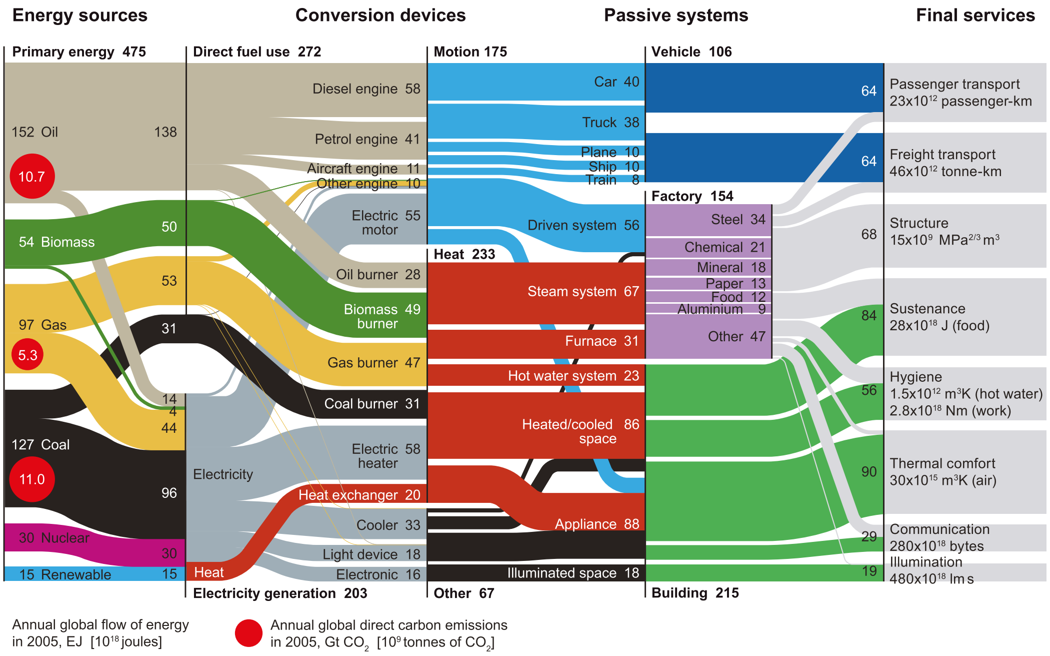

Fig. 2. From fuel to service: tracing the global flow of energy through society.

Table 6
Vertical slices with technical components ranked by the scale of primary energy use.

Energy source	EJ	Conversion device	EJ	Passive system	EJ	Final service	EJ
Oil	152	Diesel engine	58	Appliances/goods	88	Thermal comfort	90
Coal	127	Electric heater	58	Heated/cooled space	86	Sustenance	84
Gas	97	Electric motor	55	Steam system	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	Furnace	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

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 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. (2009), including improving material efficiency through substituting less energy intensive materials, light-weighting products, and designing for reuse and recycling. Improvements to 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 intensive. 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.

4.2. *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 Fig. 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%) 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 kW h/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. However, to make specific policy recommendations for alternative horizontal paths requires the assessment of both the scale of energy flow and the efficiency of each device or system in the chain. The focus of this paper is to map only the scale of energy flow—further research is required to assess the potential efficiency gains. Nevertheless, reductions in energy use for passive systems are likely to be particularly attractive, because any saving in energy is

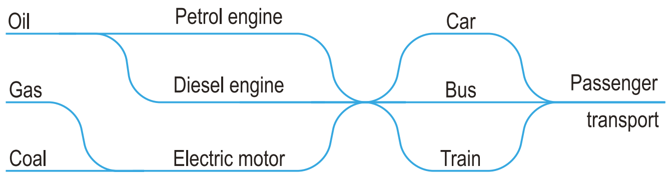

Fig. 3. Delivering passenger transport using alternative energy chains.

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.

4.3. *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 (2007), and energy institutions do no 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.

5. Conclusion

The energy map presented in Fig. 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, and
- identifying the key areas where technical innovation is likely to deliver the greatest efficiency gains.

The next stage in this research is to calculate the technical potential for energy efficiency gains in conversion devices and passive systems. Once target efficiencies for individual technical devices are known, they can be overlaid on the global map of energy flow to provide an absolute physical measure of the global improvement potential from efficiency measures. This will allow avoidable energy losses to be categorised by their engineering mechanisms, and provide a more consistent framework from which to direct research initiatives and energy policy in the area of efficiency.

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