

Physical, Chemical and Mathematical Sciences Committee Opinion Paper



A Common Scale for Our Common Future:
Exergy, a Thermodynamic Metric for Energy

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Executive Summary

A major challenge in striving for energy efficiency is the selection of technological systems, particularly given the need to consider multiple environmental, economic and social concerns. In addition, the general public, policy makers and experts alike misunderstand the physical nature of energy and hence its efficient use. After decades of fragmented agreements, regulations, treaties, strategies, indicators, targets, directives and communications, the European Union (EU) in its Energy Union strategy needs to take the lead in restoring the energy debate to firm foundations: those of thermodynamics, the science of energy.

Driven by the predicted shortfall in delivering the EU's 2020 energy efficiency target, and coincident with concerns over energy supply security in the midst of an economic crisis, there has been a rethink in the recently-launched Energy Union on how to deliver secure, affordable and sustainable energy. The most secure, most affordable, most sustainable energy is that which is never used. This realisation has promoted consideration of energy efficiency as a 'first fuel'. It is, however, not energy per se that needs to be secure, affordable and sustainable but rather exergy.

Exergy is the resource of value, the energy available for work; a measure of both the quality and quantity of available energy. Exergy analysis not only tells the truth about energy efficiency, but, in an extended perspective, potentially leads to resource accounting on a global scale: a common scale for our common future.

In this Opinion Paper, the Science Europe Physical, Chemical and Mathematical Sciences Committee builds on a recent peer-reviewed publication, 'A Thermodynamic Metric for Assessing Sustainable Use of Natural Resources', to reach out to policy makers.¹ Most importantly, the Committee calls for the formation of an international exergy panel to:

- bridge the gap between the science of energy and energy policy, leading to the systematic use of the concept of exergy where appropriate;
- provide an evidence base for interrelated energy, climate change and economic policies;
- drive interdisciplinary research and development on the causes of exergy destruction and how we can minimise this destruction, from the molecular to the global scale;
- guide the establishment of exergy destruction footprints for commodities and services; and
- collaborate with the intergovernmental panel on climate change.

Background

With the creation of the European Coal and Steel Community in 1952 and the European Atomic Energy Community (Euratom) in 1957, energy policy provided an early impetus for integration. It has, however, played a paradoxical role, essentially limited to a state-centred, sector-based perspective. Energy deregulation has been the exception.

In the 1990s, a series of market liberalisation packages created an internal market, effectively unbundling electricity and gas energy production and supply. In fact, the founding Treaties of the EU did not include a specific provision in the field of energy until 2007 when the Treaty of Lisbon Article 194 introduced the legal basis for the establishment and functioning of the internal market while promoting the interconnection of energy networks and ensuring supply security. It also recognised the need to promote energy efficiency and energy saving and develop new and renewable forms of energy to preserve and improve the environment. Still, such measures did not affect a Member State's right to determine the conditions for exploiting their energy resources, mix or general supply structure.

Since 2010, the EU has pursued its Europe 2020 'smart, sustainable, inclusive growth' strategy with climate and energy policies – enacted in the 2009 climate and energy package – focused on reducing emissions of greenhouse gases (GHG) by 20% (compared to 1990 levels), developing a 20% market share for renewable energy sources, and improving energy efficiency by 20%. These so-called '20-20-20' targets have so far had heterogeneous results. Despite substantial variations from one Member State to another, on average, GHG and renewables will likely deliver on target. In contrast, energy efficiency improvement, driven by the 2012 Energy Efficiency Directive (EED), is predicted to underachieve. The Directive was established to help the EU reach its energy efficiency target for 2020, requiring all EU countries to use energy more efficiently at all stages of the energy chain – from its production to its final consumption. However, Member States set their own indicative national targets and had until 2014 to submit action plans, implement the Directive and insert its provisions into their national laws. Hence it may take some time to see the EED's full effects.

As far back as in 2009, the EU's long-term objective was agreed, to reduce GHG emissions by 80–95% by 2050. In order to bridge the gap between short- and long-term objectives, in early 2014 the European Commission (EC) proposed that an integrated policy framework for the period up to 2030 was needed, with binding targets of 40% and 27% for GHG reduction and market share of renewable energy sources respectively, but without an energy efficiency target. The European Parliament (EP) resolution went one step further, demanding a binding energy efficiency target of 40%. Eventually, the European Council endorsed a reduction in GHG emissions of at least 40%, a 27% target for renewable energy sources and a non-binding target of 27% improvement in energy efficiency. It also requested a review of the EED and the development of an energy efficiency framework with the aim of a new policy to be prepared well in advance of the international climate negotiations at the 21st session of the 2015 Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC).

Arguably, the most relevant background to this Opinion Paper is the global context of the eurozone economic crisis enhanced by a shale gas revolution in the US, coincident with threats to the EU and its neighbours' energy supply security. The need for unification on EU energy policy has never been

more pressing, so the new EP and the EC (with 2014–2019 mandates) have had little alternative except to finally embark on a genuine effort to create an energy union. In the words of the EP committee on Industry, Research and Energy (ITRE), when presenting their priority areas, “perhaps most importantly, exploiting the full potential of EU’s common energy policy will be a fundamental priority for us. Only with secure energy can we make our economy globally competitive and avoid economic decline.”²

The Energy Union

In 2014, during the Ukrainian crisis, the move beyond a European internal energy market towards an energy union gained momentum, with particular focus on the security of gas supply. Against this backdrop, the EC adopted a ‘European Energy Security Strategy’. Shortly afterwards, the opening statement in the EP on the political guidelines for the new EC’s mandate included a ‘Resilient Energy Union with a Forward-Looking Climate Change Policy’ as one of ten priority areas.

In support of this new impetus for co-ordination and integration of energy policies, in the newly structured College of the EC, one of five Vice-Presidents was designated with the priority of the Energy Union. Furthermore, the Directorate-General (DG) for Energy, which focuses on developing and implementing a secure, sustainable, and competitive energy policy for Europe, was united under the remit of a single Commissioner with the DG for Climate Action, which leads international negotiations on climate, helps the EU to deal with the consequences of climate change and to meet its targets for 2020, and develops and implements the EU Emissions Trading System (ETS). This is a clear recognition that energy and climate challenges are inextricably linked.

In early 2015, the EC published ‘A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy’ together with communications on electricity network interconnections and on the EU’s contribution to the international climate change negotiations.³ The vision is of an integrated, competitive and borderless energy system: a fifth freedom, complementing the EU’s four fundamental freedoms that underpin its single market – the free movement of people, goods, services and capital. With the headline ‘making energy more secure, affordable and sustainable’, it sets out a holistic approach to transform the energy system, focusing on five dimensions: energy security; completing the internal energy market; energy efficiency; decarbonisation; and research and innovation. These dimensions are addressed in 15 action points including new legislation, implementation and enforcement of existing legislation, development of strategies, support and financing, actions by Member States, and the use of external policy instruments.

Stakeholders have generally welcomed the Energy Union initiative, which is now backed by the EP and European Council, but some fear a conflict between decarbonisation efforts and the construction and upgrading of traditional infrastructures, such as pipelines to diversify the EU’s gas supply. In an attempt to alleviate such fears, in support of the Energy Union strategy, EU leaders agreed to develop innovative strategies for a new generation of renewable energies and increased energy efficiency.

The First Fuel: a Fundamental Rethink on Energy Efficiency

Although energy efficiency has long been a component of the EU's common energy policy, in the past it has often been a mere side effect of efforts to tackle climate change. More recently, at least in policy circles, it is referred to as an energy source in its own right. In addition to overarching action plans, strategies and roadmaps, sector-specific approaches to energy efficiency have also been pursued, such as in eco-design of products, efficiency classes for labelling household appliances and energy performance of buildings.

With the realisation that the EU is not on course to achieve its 2020 energy efficiency target, an Energy Efficiency Plan was published in 2011 and the EED entered into force in 2012 with several concrete deliverables including: building renovation; assessment of cogeneration and district heating and cooling options; mandatory energy audits for large companies; and the introduction of smart grids and meters. The EU Commissioner for Climate Action and Energy has made 'efficiency first' his abiding motto and says that "it is really difficult to find an alternative energy source that is more environmentally friendly, free from geopolitical risks and that pays off more than energy efficiency."⁴ In this sense, the potential to increase efficiency can be regarded as a potential 'fuel' gained. In a report entitled 'Energy Efficiency – The First Fuel for the EU Economy: How to Drive New Finance for Energy Efficiency Investments', The Energy Efficiency Financial Institutions Group (EEFIG), a specialist expert working group of the EC and United Nations Environment Programme Finance Initiative (UNEP FI), identified the strategic importance of energy efficiency investment for the EU.⁵

However, the Physical, Chemical and Mathematical Sciences Committee believes that the fundamental rethink on energy efficiency as an energy source needs to go much further.

The Problem: Comparing Apples and Oranges

The energy conversion chain is made up of a multitude of technologies: from exploration and production of resources, to power generation and transmission, to final use in industry, buildings and transportation. These technologies are more or less efficient. Their selection is not trivial when considering multiple environmental, economic and social concerns, especially as options continue to be discovered, developed, and deployed, supported by public and private, national and international investments.

From joint EU funding alone, almost €6 billion goes towards energy projects in the EU Horizon 2020 Framework Programme for Research and Innovation, covering areas such as energy efficiency, renewables, smart energy networks and energy storage. Although there are also activities within the 'Excellent Science' and 'Industrial Leadership' pillars of Horizon 2020, energy efficiency is specifically addressed under the 'Societal Challenges' pillar, amounting to 7,7% of the total budget for the Programme of almost €80 billion (2014–2020).⁶ As a response to the financial crisis within the EU, 2008 saw the adoption of the European Economic Recovery plan (EERP) 2010–2013. Within its research

and technological development (RTD) measures, one of the three Public–Private Partnerships (PPPs) established in 2009 to develop new technologies and assist the transition to a more sustainable economy, re-launched with an additional five PPPs in 2013, was an ‘Energy Efficient Buildings’ initiative (EeB) for the construction sector. On the deployment side, the ECs European Strategic Energy Technology Plan (SET-Plan), established in 2008, aims to accelerate the market introduction and take-up of low-carbon and energy efficient technologies. In the EC’s Communication on Energy Technologies and Innovation, published in 2013, which sets out the strategy for enabling the EU to have technology and innovation solutions to cope with the challenges of 2020 and beyond, the SET-Plan remains the “core instrument to deliver on the challenges and provides the reference point for EU, national, regional and private investments in energy research and innovation.”⁷

If we understand the considerable aforementioned research and technical development efforts as being a systematic activity combining both basic and applied research, and aimed at discovering solutions to problems or creating new goods and knowledge, then immediately there is an assumption of coherence, scale and metric. Therein lays the major roadblock for implementing, or even finding, energy efficient solutions to our societal challenges. The Physical, Chemical and Mathematical Sciences Committee believes that there is no coherence, no common scale and no agreed metric for energy efficiency. It is often erratically defined in economic, environmental, physical and even political terms. For example, ‘efficiency’ as defined by the EED uses economic terms only, a severely flawed approach in environmental and physical contexts. The problem is worsened by the involvement of a diverse array of stakeholders concerned with energy efficiency. Of some 40 agencies that contribute to EU governance, through various executive or regulatory tasks, no less than 11 are specifically energy-related, and there are countless national and regional agencies and a diffuse network of stakeholders, such as consumers, suppliers, industry associations and environmental non-governmental organisations.

The absence of an apolitical scale for energy efficiency has resulted in a long history of inconsistencies in technical solutions, misleading policy and inept legislation. The harsh reality is that when it comes to energy efficiency, we have been comparing apples and oranges.

The Solution: Forget Energy, Think Exergy

So, how should we define energy and moreover, its efficiency? In their paper ‘Energy, Entropy and Exergy Concepts and their Roles in Thermal Engineering’, Dincer and Cengel say that “the concept of energy is so familiar to us today that it is intuitively obvious, yet we have difficulty in defining it exactly.”⁸

The vast majority of calculations of energy efficiency are based solely on the energy conservation principle, the first law of thermodynamics. According to the first law of thermodynamics, energy is always conserved. During conversion, it can change forms, say from chemical energy to heat. The conservation is expressed as

$$\Delta U = q + w$$

where ΔU is the change in internal energy of a system, q is the heat delivered to the system from its surroundings, and w is the work done on the system. The second law of thermodynamics states that the entropy change of the system and its surroundings, ΔS , which gives the degree of energy dispersion of a system, will always increase:

$$\Delta S \geq 0$$

Exergy is defined as the ideal potential of energy and matter *to do work*. In other words, it is referred to as ‘available’ or ‘useful’ energy. Anergy is the complementary part of the energy that cannot be converted into work. It is directly related to the entropy change. This gives

$$\text{Energy} = \text{Exergy} + \text{Anergy}$$

The second law reflects that there are always frictional losses during energy conversion. Only in the case of a reversible process can ΔS or anergy be equal to zero. In real life, truly reversible processes never happen or take an infinitely long time. In layman’s terms, the second law of thermodynamics asserts the existence of an energy quality and quantity (measured as exergy) and that all processes result in a quantitative loss of quality in terms of anergy (due to generation of disorder or entropy). When this quantity is small, we have an efficient process.

The concepts of energy, exergy, and entropy are simply illustrated in Fig. 1. Fig. 1(a) shows 100 kJ of energy as electricity stored in a battery compared with a kilogram of warm water. One can calculate that these two systems have the same internal energy, but they have vastly different exergy, because they have vastly different ability to do work. Clearly, we should focus, save or spare the type of energy (exergy) represented by the battery.

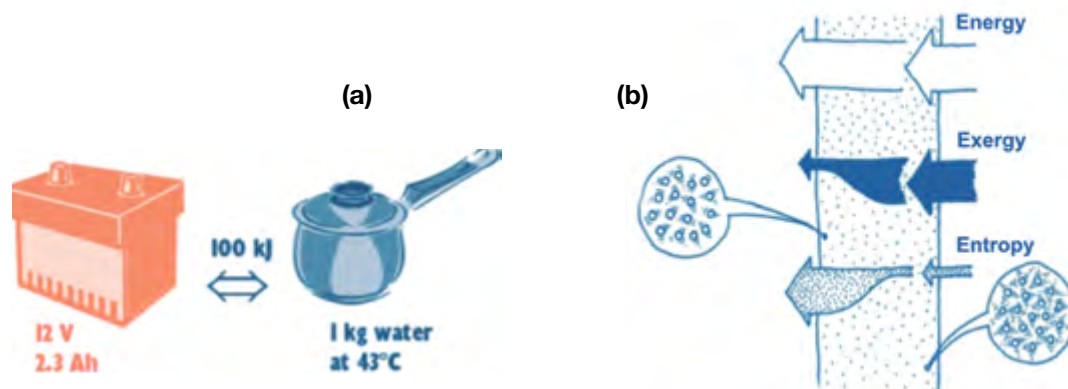


Figure 1 (a) Two systems that contain the same amount of energy but not the same amount of exergy, and (b) energy, exergy and entropy flow in and out of a building envelope system.⁹

The amounts of energy flowing in and out of a building envelope system in Fig. 1(b) are the same under steady-state conditions according to the law of energy conservation, the first law of thermodynamics. On the other hand, the amount of entropy flowing out is larger than flowing in according to the law of entropy increase, the second law of thermodynamics. The amount of exergy flowing out is smaller than flowing in, since exergy is destroyed within the system to produce entropy. Clearly, a combination of the first and second laws of thermodynamics is required to evaluate the rational use of energy.

Thermodynamics-based Efficiency, Put Simply

Now that we have established the difference between energy and exergy, the concept of efficiency and assessment of energy flows can be explored. Again, the basic principles are explained by Dincer and Cengel.⁸

Engineers make frequent use of efficiencies to assess the performance of devices and the effectiveness of processes. A good measure of performance takes into account limitations imposed by the second law of thermodynamics. To illustrate the idea of exergy efficiency and to contrast it with an analogous energy-based efficiency, consider again the energy and exergy equations. Conservation of energy is also expressed as

$$\text{(Energy in)} = \text{(Energy out)} = \text{(Energy out in product)} + \text{(Energy loss)}$$

$$\begin{aligned} \text{(Exergy in)} &= \text{(Exergy out)} + \text{(Exergy destruction)} = \\ &\text{(Exergy out in product + Exergy loss)} + \text{(Exergy destruction)} \end{aligned}$$

The product term in these equations could, for example, refer to electricity generated by a turbine. The 'exergy destruction' term, also called anergy above, refers to internal irreversibilities, like friction or imperfections in the turbine. Energy or exergy losses are the result of waste heat or gases being vented to the surroundings that could have been useful. The precise target for system improvements is therefore specified here, and only here. We can define a measure of how effectively (efficiently) the input is converted to the product by the ratio of product to input. Using the first law and energy as a basis we obtain

$$\eta_{en} = \text{(Energy out in product)} / \text{(Energy in)}$$

By taking the energy produced by the turbine and dividing it by the energy required for its operation, the energy efficiency is calculated without considering whether the energy in or out is useful or not (the total energy in is always the total energy out). The exergy efficiency η_{ex} gives another understanding of the performance of the turbine. Now the energy flows are considered in terms of quality (usefulness) as well as quantity. It recognises that both losses and internal irreversibilities need to be dealt with to improve the performance of the turbine.

$$\eta_{ex} = \text{(Exergy out in product)} / \text{(Exergy in)} = 1 - [(\text{Loss} + \text{Destruction}) / \text{Input}]$$

Fig. 2 illustrates the real-life differences between energy and exergy flows, and thereby the different efficiencies possible, for four conversion systems: an oil furnace, an electric heater, a heat pump and a combined power and heat plant. For the conversion of fuel into heat in an ordinary oil furnace, the energy efficiency is about 85%, principally through stack losses. The significantly lower efficiency according to exergy analysis, about 4%, is due to the fact that the decrease in temperature when a thousand degree flame heats water to 60°C is not utilised. This information is not present in the first calculation. Similarly, we find substantially higher energy – as opposed to exergy – efficiencies for the electric heater, heat pump and cogeneration plant. Physically, this means that when most energy is converted to heat, its 'quality' is badly degraded, an aspect only captured by exergy efficiency. In fact, if the environment is ignored, the conversion of electrical energy or fuels into heat can be well over 100%,

as seen for the heat pump. However, as follows from the second law of thermodynamics, no system can ever be 100% efficient. Furthermore, exergy efficiency identifies and quantifies the types, causes and locations of energy loss as compared to energy efficiency.

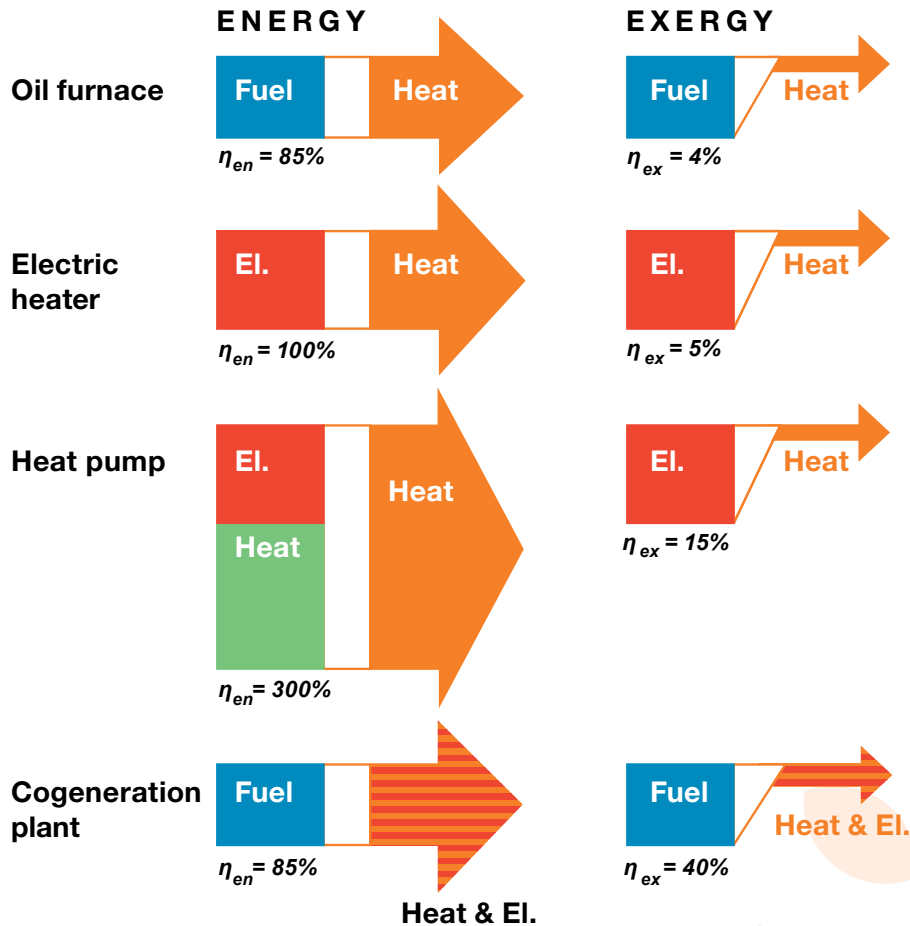


Figure 2 Energy and exergy flows through some typical energy systems where η_{en} is the energy efficiency, η_{ex} is the exergy efficiency and El. is electricity. We see that energy is always conserved (only the first law is considered), while exergy is always degraded (first and second laws are considered). Image adapted with permission.¹⁰

As explained by the American Council for Energy-Efficient Economy (ACEEE), “given these significant distinctions, we begin to see that when we talk about tracking energy instead of the exergy necessary to power the economy, we are already confusing concepts and data in ways that can mislead businesses and policymakers about smart economic development solutions founded on the improved and more productive use of exergy.”¹¹



From Domestic Heating to National Economies; the Interdisciplinary Nature of Exergy

In exploring the fundamental relationship between energy and monetary costs, known as thermoeconomics, Ayres and Warr explained that raw energy input cannot account for economic growth.¹² Inefficient conversion results in the most substantial fraction being wasted, such that it cannot contribute to the economy and, in fact, creates environmental, financial and societal burdens.

In a 2013 report for the ACEEE, entitled ‘Linking Energy Efficiency to Economic Productivity: Recommendations for Improving the Robustness of the US Economy’, J.A. Laitner explored the need for a more critical accounting of exergy efficiency at national economy level.¹¹ With the phrase, “If you can’t measure it, you can’t manage it”, he describes the dynamic link between energy and the economy, such that inefficiency constrains economic growth to the detriment of social prosperity. Considering historical trends from 1950 and future projections up to 2040, he reports decreasing productivity due to decreasing exergy efficiency. Supporting his argument for improved measurement of energy flows and consumption based on exergy efficiency to improve energy policy and investment in the US, he reports that, shockingly, 86% of all energy used in the production of goods and services is currently wasted.

Although the Energy Union targets the EU as a whole, a common driver to any integrated policy are cross-country and even, in the context of global challenges, cross-continent comparisons, which so-called exergy accounting provides on an absolute scale. Brockway et al. related the quality of primary energy input with economic growth to reveal diverging trends in the US and UK efficiencies.¹³ In Fig. 3, their 2010 energy flow, from primary exergy to useful work for the UK, shows that 86% of the input is lost, leaving only 14% – a figure that actually increased from 9% for the period 1960 to 2010. In contrast, the US efficiency remained stable at about 11% due to ‘efficiency dilution’, that is device-level efficiency gains offset by structural shifts to lower efficiency consumption, for example in air-conditioning. Brockway et al. have also examined China’s energy consumption for the period 1971 to 2010 to reveal a ten-fold increase in useful work, fuelled by a four-fold increase in primary energy input coupled with an exergy efficiency growth from 5% to 12%, placing it between the UK and the US.¹⁴ Interestingly, the increase in aggregate exergy conversion efficiency in China is mainly attributed to structural rather than technological drivers. Comparing the fine detail of the energy flows for China and the UK exposes differences in useful work by end use. In the UK, the useful work stage splits fairly evenly between heat, mechanical and electricity end use, while in China it is dominated by heat followed by electricity and then mechanical work. Moreover, the analyses indicate that most useful work growth in the US arises from increasing the exergy input and that China’s future energy demand is significantly above previous projections, in both cases raising the question of future sustainability.

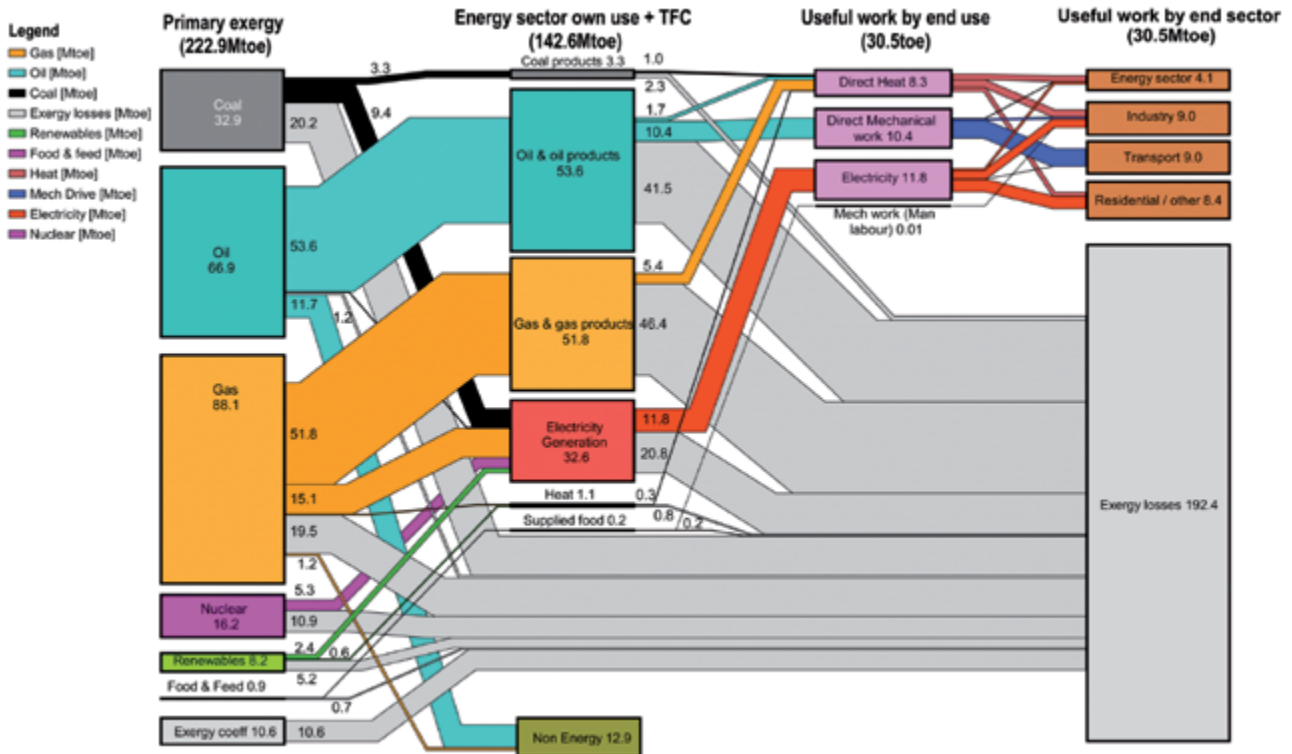


Figure 3 UK exergy to useful work flowchart (2010).¹³

These extreme examples in Fig. 2 and 3 illustrate simply but effectively the relevance of exergy efficiency analysis from the consumer deciding on domestic heating systems through to policy makers designing national energy strategies. It also has the ability to bridge the scale to the molecular level events¹ allowing for a concerted action of chemists, physicists, engineers and policy makers. But this discussion would be found wanting if the interdisciplinary nature of exergy was not also emphasised. During the past decade, exergy analysis has developed far beyond measurement of energy quality, and its efficiency has received considerable attention from various disciplines, fuelling an expansion from its roots in science and engineering to ecology, sustainability, business, social studies, and beyond. Although it is not within the scope of this Opinion Paper to review the field, it is worth highlighting ‘A Brief Commented History of Exergy from the Beginnings to 2004’ by Sciubba and Wall, with references to some 2600 publications relevant to the 200-year long development of the concept and its applications.¹⁵

While the potential and limitations of exergy analysis of natural ecosystems coupled with economic analysis are the subject of ongoing research, its application to technical system analysis and resource and efficiency aspects of sustainable technology development is a well-established field.¹⁶ Hence, a common and pressing theme of current discussion within the exergy community is their appeal to decision-makers to use exergy analysis as a basis for establishing policies for energy use.¹⁷ As a first step towards this, exergy based ‘energy efficiency’ can be implemented immediately and will open the door to a world of possibilities using exergy analysis. This approach can then be developed in the broadest sense to include evaluations of industrial development, natural resource management, environmental impact assessment and sustainability. Current research on resource efficiencies concern exergy destruction measures.¹⁸ There are convincing arguments to use exergy measures in a cradle-to-cradle view of the Earth’s abiotic resources¹⁹ and in process optimisation.²⁰

Public Awareness and Counting the Cost

Assuming that policy makers can be convinced to embrace a thermodynamic metric for energy, what of the general public? For decades, there has been intense debate regarding the so-called 'energy efficiency gap' or 'energy paradox' or rebound effects; the reality that there is an apparent under-investment by consumers in energy-efficient technologies, relative to the predictions of benefits from engineering and economic models, and energy consumption frequently increases following an energy efficiency improvement. Without wishing to enter that specific debate, it is worth speculating that perhaps consumers have not been convinced by the comparison of apples and oranges. The Physical, Chemical and Mathematical Sciences Committee emphasises that, on the contrary, the exergy concept tells the truth about energy.

The energy flow diagram in Fig. 3 captures the pathway from primary exergy consumption to end use in one succinct image. While visually extremely informative, it is perhaps best suited to the professional. For layman's appreciation, the complementary representation of an exergy destruction footprint is likely to be more appealing. Footprint-style indicators have, over the past two decades, been introduced to successfully raise public awareness of the environmental impact of human activity. Modern methods of so-called 'extended exergy accounting' address energy flows in domestic, industrial, environmental and societal systems, including non-material and non-energetic factors such as labour and capital in costing resource depletion in a true life-cycle approach. The resulting 'exergy destruction footprint' would be valuable not only as a stand-alone quantitative performance indicator, but also as a complementary indicator in the family of ecological, carbon and water footprints necessary for environmental impact assessment and sustainability evaluation. It can be used to characterise products and services. One might well foresee a future where industries report their exergy destruction along with their carbon emissions. The exergy destruction footprint could then serve as a technology driver, in much the same way as the carbon emission indicator.

Recommendations

Bridging the Gap between Science and Policy

As the first fuel, efficiency satisfies supply security, economic competitiveness and environmental sustainability and is recognised as such in the context of the EU Energy Union. In a report on 'Energy Efficiency Policies – What Works and What Does Not,' the World Energy Council explain that "although the benefits of energy efficiency are obvious and the potential for its improvement is significant, the progress so far has not matched the expectations. Therefore, it is important to identify the factors that are holding back the progress."²¹

In this Opinion Paper, the Science Europe Physical, Chemical and Mathematical Sciences Committee highlights a key barrier to progress; that is, the misunderstanding of basic thermodynamics that proliferates within the energy debate. We misuse energy conservation when we mean exergy conservation, we misuse energy efficiency when we mean exergy efficiency, we misuse energy crisis when we mean exergy crisis, and so on. Exergy is the resource of value, not energy, and considering it as such requires a cultural shift to the thermodynamic metric approach of exergy analysis.

Exergy analysis not only rationalises efficiency from domestic devices to national economies, but can also be extended to embrace the bigger picture of natural resource management and sustainability, allowing resource accounting on a global scale. In recognition of the maturity of the exergy field, and in support of the steady trend in Europe towards energy integration that can only succeed if energy is measured on a common scale, the Physical, Chemical and Mathematical Sciences Committee joins the call from the exergy community for the establishment of an International Exergy Panel¹⁷ to:

- bridge the gap between the science of energy and energy policy leading to the systematic use of the concept of exergy where appropriate;
- provide an evidence base for interrelated energy, climate change and economic policies;
- drive interdisciplinary research and development on the causes of exergy destruction and how we can minimise this destruction, from the molecular to global scale;
- guide the establishment of exergy destruction footprints for commodities and services; and
- collaborate with the intergovernmental panel on climate change.

Concluding Remarks

It seems only fitting to end this Opinion Paper with a definition of sustainable development from 'Our Common Future', also known as the Brundtland Report:

“ Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains within it two key concepts: the concept of needs, in particular the essential needs of the world's poor, to which overriding priority should be given; and the idea of limitations imposed by the state of technology and social organisation on the environment's ability to meet present and future needs... In essence, sustainable development is a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development; and institutional change are all in harmony and enhance both current and future potential to meet human needs and aspirations.²² ”

From this definition, sustainability requires a delicate balance of the needs and limitations of the world as a system that can only be addressed by intimately understanding the entwined physical, technical, economic, social and environmental implications of our natural resources. Given our current unsustainable path, one way or another, policy and behavior will have to adapt because, as clever as we are, there is no defying the laws of physics. We need an apolitical scale to guide our judgement on the road to sustainability. Exergy provides a common scale for our common future.

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