IN A RESOURCE-CONSTRAINED WORLD:

THINK EXERGY, NOT ENERGY

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EXECUTIVE SUMMARY

When we think about energy, we consider it in terms of quantity. However, in a resource-constrained world, energy must also be appreciated from the point of view of quality, which is essentially a measure of its usefulness, or its ability to do work. In order to account for the quality and not just the quantity of energy, we need to measure exergy.

Exergy analysis can be applied not only to individual processes, but also to industries, and even to whole national economies. It provides a firm basis from which to judge the effect of policy measures taken towards energy, resource and climate efficiency. In the future, consumers could be informed about products and services in terms of their exergy-destruction footprint in much the same way as they are about their carbon emissions.

In its recent Opinion Paper 'A Common Scale for Our Common Future: Exergy, a Thermodynamic Metric for Energy', the former Science Europe Scientific Committee for the Physical, Chemical and Mathematical Sciences explained the concept of exergy and its application to energy efficiency.[1] In doing so, the Committee reached out to policy makers to call for the formation of an International Exergy Panel to:

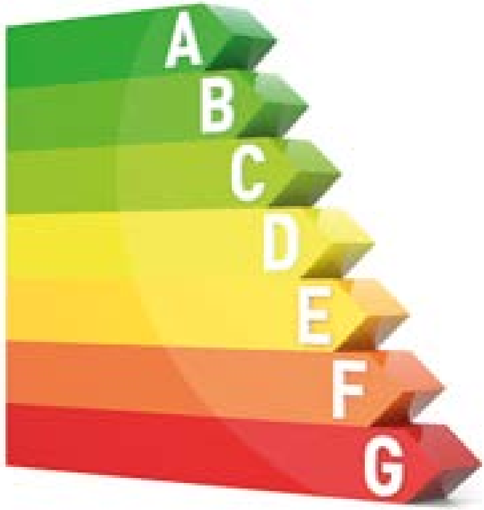
- bridge the gap between the science of energy and energy policy, leading to the systematic use of the concept of exergy where appropriate;
- provide an evidence-base for interrelated energy-, climate change- and economic policies;
- drive interdisciplinary research and development on the causes of exergy 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 (IPCC).

Energy awareness is increasing within Europe through various initiatives, including the European Commission's adoption of 'A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy', a decade of EU Sustainable Energy Week (EUSEW) programmes addressing the EU's sustainable energy agenda with stakeholders and the general public, and the historic 2015 Paris climate conference (COP21).

In this context, the authors would like to take this opportunity to expand on the previous publication, and set out the benefits of applying exergy in a finite world in this brochure.

Educators, researchers, policy makers, stakeholders and citizens are urged to consider energy and natural resources on the basis of exergy, and in doing so understand that:

- exergy measures energy and resource quality;
- exergy-destruction footprinting promotes improvements in industrial efficiency;
- exergy offers a common international energy-efficiency metric;
- optimal use of our limited mineral resources can be achieved by the application of exergy rarity; and
- exergy should be integrated into policy, law and everyday practice.



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EXERGY-BASED ENERGY AND RESOURCE EFFICIENCY: THE BASICS

The Need to Measure Energy and Resource Efficiency

The European Commission highlighted seven societal challenges to reflect the policy priorities of its 'Europe 2020' strategy. Out of these seven challenges, at least four are directly related to the availability of energy and resources:

- Food security, sustainable agriculture and forestry, marine and maritime and inland water research, and the Bioeconomy
- Secure, clean and efficient energy
- Smart, green and integrated transport
- Climate action, environment, resource efficiency and raw materials

If the aim is to improve energy and resource efficiency, the question arises of how to measure this. Of course, the amount of energy and raw materials that go into making something, or that go into services such as heating, communication, or transport, can be easily measured. However, that does not consider the quality of the energy nor the rarity of the materials used. In order to account for the quality and not just the quantity of energy, as well as factoring in the raw materials used, we need to measure exergy.

Exergy can be considered to be useful energy, or the ability of energy to do work. Exergy can be measured not only for individual processes, but also for entire industries, and even for whole national economies. It provides a firm basis from which to judge the effect of policy measures taken to improve energy and resource efficiency, and to mitigate the effects of climate change.

Exergy as a Measure of Energy Quality

The need to take the quality of energy into account can be shown with a simple everyday example (see Figure 1).

The energy contained in the movement of air molecules in a 20m^3 office at 20°C is more than the energy stored in three standard 12V car batteries. While you can only use the energy in the air to keep yourself warm, you could use the energy in the batteries to start your car, cook your lunch, and run your computer. The reason is that even if their quantities were the same, the quality – or usefulness – of the energy in the air and in the battery is different. In the air, the energy is randomly distributed, not readily accessible, and not easily used for anything other than keeping you warm. In contrast, the electric energy in the battery is concentrated, controllable, and available for all sorts of uses. This difference is taken into account by exergy.

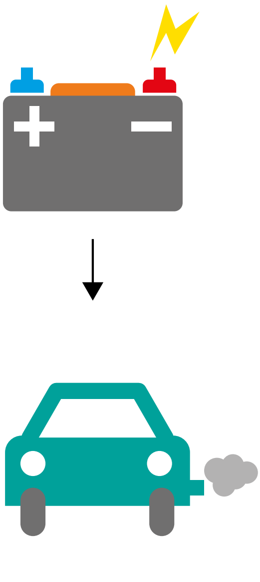

Figure 1 Everyday example of exergy showing (A) battery used to start a car versus (B) air molecules in an office used to heat the occupant.

Thermodynamics is the Science of Energy

The concept of exergy is inextricably contained within the basic physical laws governing energy and resources, called thermodynamics. These laws cannot be ignored: they are fundamental. Two of the basic laws in thermodynamics need to be considered:

First – Energy is conserved.

Second – Heat cannot be fully converted into useful energy.

The second law concerns the concept of exergy. Every energy-conversion process destroys exergy.

Take for example a conventional fossil-fuel power station, shown schematically in Figure 2. Such a station transforms the chemical energy stored in coal to produce steam in a boiler, which is then converted by a turbine into mechanical energy and finally by a generator into electricity. In this process, only 30–35% of the chemical energy contained in the coal is converted into electrical energy; the remaining 65–70% is lost in the form of heat.

Exergy analysis of this power generation plant identifies the boiler and turbine as the major sources of exergy loss. In order to improve the exergy efficiency, the boiler and turbine systems need to be altered through technical design and operational changes.

It is of utmost importance to look at the exergy balance of processes. In fact, we need to go much further: the exergy balance of whole economies can and should be routinely considered, as will be shown later.

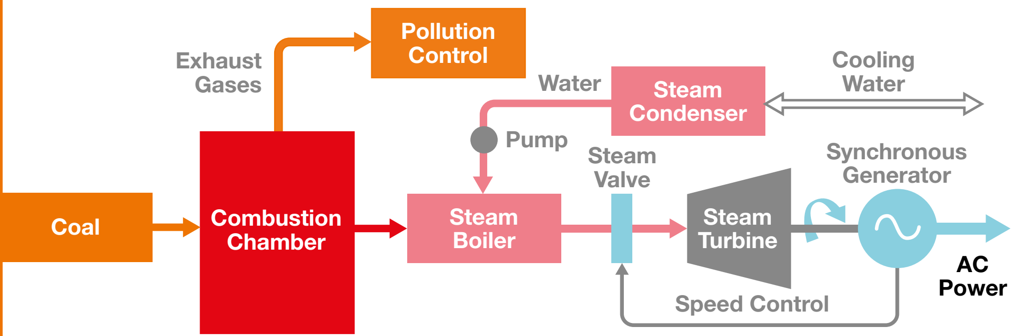

Figure 2 Fossil-fuel powered steam turbine electricity generation.

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Exergy as a Measure of Resource Quality

Exergy can also be applied in order to take the quality of resources into account. A diluted resource is much more difficult to use than a concentrated one, as it first has to be collected or refined. The measure to take the concentration of a resource into account is its chemical potential (or chemical exergy). The chemical potential of pure iron is much higher than the chemical potential of an iron ore diluted by other rocks.

An exergy consideration of any process takes into account the chemical potential of the resources used in the process. The problem with chemical potentials, however, is that it is only possible to measure their difference. In order to study the chemical potential of a specific resource, a reference point is needed. An interesting proposal as a reference point for natural minerals is the concept of 'Thanatia', a hypothetical version of our planet where all mineral deposits have been exploited and their materials have been dispersed throughout the crust.[2] Using Thanatia as a model, it is possible to determine the exergy content of the Earth's resources. By adding up all exergy expenditures, the rarity of resources and their products can be assessed.

Exergy Destruction in the Process Industry

Industry is a large user of both material and energy resources. Typically, an industrial production process needs the input of materials and of energy to transform those materials into products. Much of these inputs end up being discarded: in the case of materials as waste, and in the case of energy as heat. This is exergy destruction, since – recalling the Second Law of Thermodynamics – not all inputs can be fully recovered as useful energy.

Methanol, for example, is a primary liquid petrochemical manufactured from natural gas. It is a key component of hundreds of chemicals that are integral parts of our daily lives such as plastics, synthetic fibres, adhesives, insulation, paints, pigments, and dyes. Before methanol production even begins, 10% of the natural gas is used to warm the chemical reactor. Subsequently, during production further reactor losses amount to 50%. This contributes to the exergy-destruction footprint of methanol production and of all its products.

How can we Increase the Energy Efficiency of Production?

While exergy destruction for any process is never zero, it can be minimised. Every process has a characteristic exergy-destruction footprint. Knowledge of this footprint can be used to rationalise resource choices before production begins and to monitor the use of energy and resources during production. In a full life-cycle approach, it can be used to consider the total energy and resource 'cost' of a product: essentially its exergy-destruction footprint.

An example of a process where reducing exergy destruction can increase energy efficiency is distillation. Distillation is the most commonly applied separation technology in the world, responsible for up to 50% of both capital and operating costs in industrial processes. It is a process used to separate the different substances from a liquid mixture by selective evaporation and condensation. Commercially, distillation has many applications; in the previous example of methanol production, it is used to purify the methanol by removing reaction by-products from it, such as water.

The conventional separation of chemicals by distillation occurs in a column that is heated from below by a boiler, with the desired product (referred to as the condensate) produced from a condenser at the top, as illustrated in the left-hand side of Figure 3. The exergy efficiency of this distillation setup is about 30%.

The obvious question is whether the same distillation results can be achieved with a higher exergy efficiency by operating the column differently. The answer to that question is yes, as there are better ways to add heat to the column than by a boiler. The boiler and condenser can be replaced by a series of heat exchangers along the column, such as on the right-hand side of Figure 3, producing a more exergy-efficient heating pattern. This arrangement minimises the exergy destruction in the system, reducing the exergy footprint of the process. In this way, the same product can be obtained with only 60% of the original exergy loss. This of course requires investment in replacing or retrofitting the technology, but in the long run such costs are compensated by lower operating costs. Financial benefits aside, the potential impact of technological development driven by exergy analysis on the energy and material efficiency of industry, is enormous.

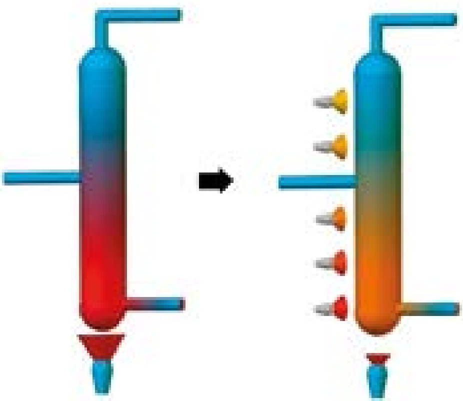

Figure 3 Exergy destruction of 1025 kWh for the left hand side distillation column compared with 673 kWh for the right hand side [adapted from reference 3].

It is important to keep in mind that there is no production without an exergy destruction footprint.

The Exergy Destruction Footprint – Developing More Environmental-friendly Technologies

When exergy analysis is performed on a process, the exergy losses can be identified and the exergy-destruction footprint can be minimised. In the fossil-fuel industry, for example, single- and two-stage crude oil distillation are used to obtain materials from crude oil for fuels and for chemical feedstocks.

A single-stage system consists of a single heating furnace and a distillation column; a two-stage system adds another furnace (to heat the product of the first unit) and a second column.

Table 1 shows the comparison of the exergy streams of these systems and reveals a considerable reduction in exergy losses and hence a higher efficiency of the two-stage system.[4] The two-stage system can be better controlled than the one-stage system, and comes closer to the minimal required exergy in the best-case scenario. Adding more stages gives even better control.

It is important to keep in mind that there is no production without an exergy-destruction footprint. A systematic effort to reduce exergy destruction to a minimum is an ideal to strive for when developing more environmental-friendly technologies.

SYSTEM	EXERGY STREAM IN (MW)	EXERGY STREAM OUT (MW)	EXERGY DESTRUCTED (MW)	EXERGY EFFICIENCY (%)
Single stage	498.8	69.8	429.0	**14.0**
Two stage	352.0	110.9	241.1	**31.5**

Tabel 1 Exergy streams in single- or two-stage crude oil distillation systems.[4] The feed and product streams are the same.

A Large-scale Problem Needs a Common-scale Solution

In 2013, industry accounted for 25% of the EU's total final energy consumption,[5] making it the third-largest end-user after buildings and transport. Over 50% of industry's total final energy consumption is attributed to just three sectors: iron and steel, chemical and pharmaceutical, and petroleum and refineries.

Between 2001 and 2011, EU industry reduced its energy intensity by 19%.[5] However, significant efficiency potential remains. As previous examples of several industrial processes have shown, exergy analysis offers a guide to the development of more energy-efficient technologies and provides an objective basis for the comparison of sustainable alternatives.

Energy analysis explains that electric and thermal energy are equivalent according to the First Law of Thermodynamics, and that heating by an electric resistance heater can be 100% efficient. Exergy analysis, however, explains that heating by an electric heater wastes useful energy. When we know about this kind of waste, we can start to reduce it by minimising exergy destruction.

While the given examples have focused on industrial processes, exergy analysis can also tackle the energy and resource efficiency of larger consumers of energy, such as the buildings and transport sectors. It is important to highlight that exergy analysis can be used not only to quantify the historical resource use, efficiency and environmental performance, but also to explore future transport pathways, building structures and industrial processes.

As explained in the Opinion Paper 'A Common Scale for Our Common Future: Exergy, a Thermodynamic Metric for Energy',[1] a major roadblock for implementing – or even finding – solutions to our societal challenges is the fact that energy and resource efficiency are commonly defined in economic, environmental, physical, and even political terms. Exergy is the resource of value, and considering it as such requires a cultural shift to the thermodynamic-metric approach of energy analysis. Exergy provides an apolitical scale to guide our judgement on the road to sustainability. Exergy is first step to a common-scale solution to our large-scale problems.

ADOPTING EXERGY EFFICIENCY AS THE COMMON NATIONAL ENERGY-EFFICIENCY METRIC

Energy Efficiency as a Key Climate Policy: the Need to Measure Progress with Exergy

Improving the efficiency of energy use and transitioning to renewable energy are the two main climate policies aimed at meeting global carbon-reduction targets. The 2009 Renewable Energy Directive[6] mandates that 20% of energy consumed in the EU should be renewable by 2020. At the same time, the EU's 2012 Energy Efficiency Directive[7] sets a 20% reduction target for energy use.

Progress towards the renewable-energy target is straightforward to measure, since national energy use by renewable sources is collected and readily available. Indeed, for many citizens, the proportion of domestic electrical energy generated from renewable sources appears clearly defined on their electricity bills.
In contrast, national-scale energy efficiency remains unclear and a qualitative comparison of renewable sources is lacking. A central problem is that there is no single, universal definition of national energy efficiency. In this void, a wide range of metrics is inconsistently adopted, based on economic activity, physical intensity or hybrid economic–physical indicators.

None of these methods are based on thermodynamics, however, making them inherently incapable of measuring energy efficiency in a meaningful way. As such, they are unable to contribute to evidence-based policy making or to measure progress towards energy-efficiency targets. The EU is not alone, there is currently no national-scale thermodynamic based reporting of energy efficiency by any country in the world.

Second-law thermodynamic efficiency – in other words, exergy efficiency – stands alone in offering a common scale for national, economy-wide energy-efficiency measurement, applicable at all scales and across all sectors.

Figure 4 shows a flow diagram from primary exergy to useful work for the United Kingdom for the year 2010.[8] Energy supplied from coal, oil, gas, renewables, and food and feed provides the primary exergy. It is transformed into ready-to-use energy, such as diesel or electricity, which then provides 'useful energy' through high-temperature heat, mechanical drive, or electrical devices.

The useful energy is the last point of common thermodynamic measurement before it is exchanged for energy services, such as thermal comfort, motion, or light.

The national exergy efficiency $\varepsilon_{National}$ therefore represents the second-law thermodynamic efficiency of the energy conversion, defined in exergy terms as:

$$\varepsilon_{National} = \text{(Sum of Useful Work) / (Sum of Primary Exergy)}$$

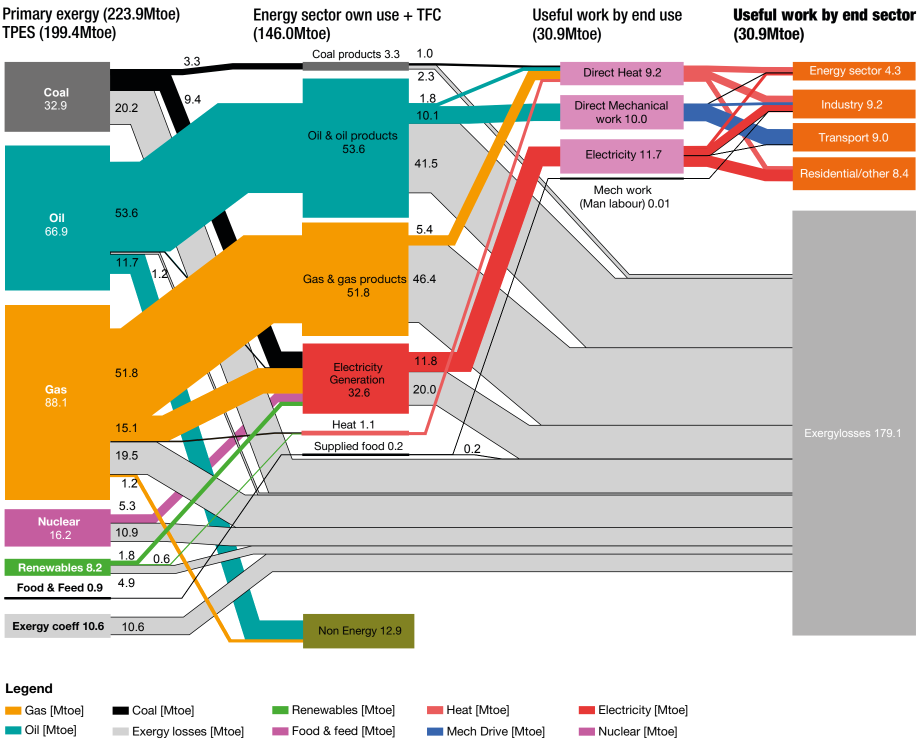

Figure 4 2010 United Kingdom Exergy flow chart: primary to final energy.[8]

The Benefits of Exergy-efficiency Reporting

Once this formal definition is in place, reporting exergy-efficiency at a national scale is not only desirable, but also possible. Widespread use would enable comparison between technologies, sectors, and countries, enabling best practice and energy-efficiency opportunities to be identified. Figure 5 shows the aggregate exergy-efficiency percentage of China, the United States and the United Kingdom for the period 1971 to 2010.[9] The figure shows an increase in exergy efficiency in the United Kingdom and China, while it remains stagnant in the United States. Such comparisons provide detailed insight into the reality of current energy-efficiency policies and their implementation in everyday life.

In the 1970s and 1980s, Eurostat collected national accounts of useful energy. This accounting practice needs to be reinstated. One of the downstream benefits of formalising the national-scale exergy-efficiency definition and development of a consistent reporting framework, is that it enables exergy -efficiency to be included as part of the overall policy-design process. Energy use and efficiency can then be tracked to view progress towards targets and policies can be amended if the desired energy reduction is not occurring.

It should not be misunderstood, however, that the benefits of adopting exergy-efficiency as the common national energy-efficiency metric is to merely satisfy a reporting exercise. In the words of Fatih Birol, the International Energy Agency's Executive Director: "any progress with climate change must have the energy sector at its core or risk being judged a failure".[10] The energy sector can only be understood by applying second-law thermodynamics, or exergy.

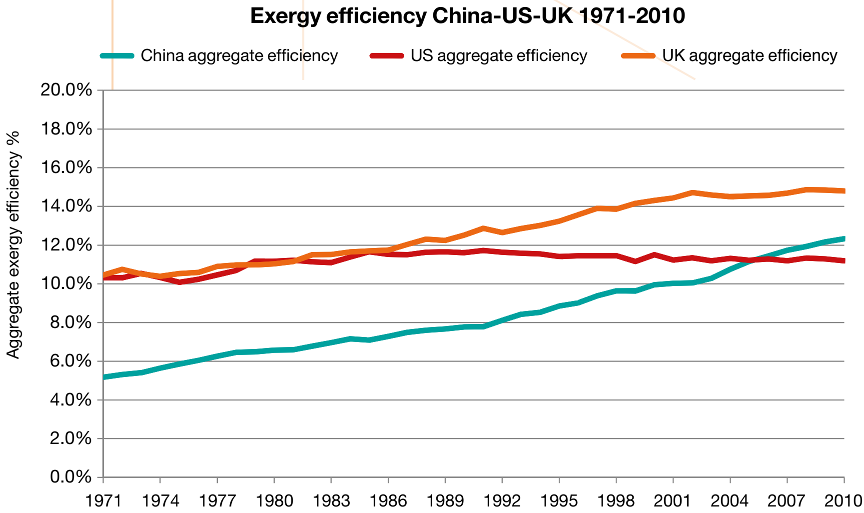

Figure 5 Comparison of the exergy efficiency % of China, US and UK over time.[9]

NATURAL RESOURCE CONSUMPTION

From Gaia to Thanatia: How to Assess the Loss of Natural Resources

As technology today uses an increasing number of elements from the periodic table, the demand for raw materials profoundly impacts on the mining sector. As ever lower grades of ore are being extracted from the earth, the use of energy, water and waste rock per unit of extracted material increases, resulting in greater environmental and social impact. Globally, the metal sector requires about 10% of the total primary energy consumption, mostly provided by fossil fuels. By 2050, the demand for many minerals, including gold, silver, indium, nickel, tin, copper, zinc, lead, and antimony, is predicted to be greater than their current reserves. Regrettably, many rare elements are profusely used, with limited recycling.

The loss of natural resources cannot be expressed in money, which is a volatile unit of measurement that is too far removed from the objective reality of physical loss. Neither can it be expressed in tonnage or energy alone, as these do not capture quality and value. Exergy can solve such shortcomings and be applied to resource consumption through the idea of 'exergy cost': the embodied exergy of any material, which takes the concentration of resources into account measured with reference to the 'dead state' of Thanatia (see Figure 8).

Figure 8 Evolution of Planet Earth to complete exhaustion.[2]

Thanatia – from the Greek "Θανατος", the personification of Death – is a hypothetical dead state of the anthroposphere, conceiving an ultimate landfill where all mineral resources are irreversibly lost and dispersed, or in other words, at an evenly distributed crustal composition. If our society is squandering the natural resources that the Sun and geological evolution of the Earth have stored, we are converting their chemical exergy into a degraded environment that progressively becomes less able to support usual economic activities and eventually will fail to sustain life itself. The end state would be Thanatia, a possible end to the 'Anthropocene' period. It does not represent the end of life on our planet, but it does imply that mineral resources are no longer available in a concentrated form.

The Price the Planet Pays

To put the situation in context, consider the example of a hotel building in Greece, with an exergetic lifecycle of construction, use and withdrawal phases. Table 2 compares the exergy, embodied exergy and composition of the total building for selected materials.

The comparison of the embodied exergy reveals that the main material used in large quantities is concrete, which has the lowest embodied exergy of the listed materials (1.7 MJ/Kg), while aluminium is the least used material but has the highest embodied exergy (249 MJ/Kg), due to the very high energy demand during its production. In general, exergy analysis finds that three quarters of the building's exergy consumption over an 80-year life cycle, stems from the period it is in use (heating, cooling, lighting), while the remaining relates to its construction period (material extraction, process, transport).

The exergy concept can be applied to the whole process involving a building, not just the use of materials in its construction, but also the energy use, eventual demolition, and recycling.

While this example gives invaluable insight into the environmental impact of materials that we typically consume, it is important to go further in appreciating the cost of our living to our planet.

An Essential Approach to Making Better Use of our Mineral Resources: the Application of Mineral Exergy Rarity

The exergy of a mineral resource as calculated with Thanatia as a reference can be measured as the minimum energy that could be used to extract that resource from bare rocks, instead of from its current mineral deposit. This is an essential approach, since the European Commission's Communication 'Towards a Circular Economy: A Zero Waste Programme for Europe',[12] states that "valuable materials are leaking from our economies" and that "pressure on resources is causing greater environmental degradation and fragility, Europe can benefit economically and environmentally from making better use of those resources."
Applied to minerals we can define a 'Mineral Exergy Rarity' (in kWh) as "the amount of exergy resources needed to obtain a mineral commodity from bare

MATERIAL	COMPOSITION (%)	EXERGY (GJ)	EMBODIED EXERGY (MJ/KG)
CONCRETE	83.2	8,640	1.7
BRICKS	3.8	620	2.7
MARBLE	2.8	2,080	12
STEEL	4.1	11,800	47
ALUMINIUM	0.1	1,360	249

Table 2 Exergy (GJ), embodied exergy (MJ/kg) and composition of the total building material (%) for selected materials used in the lifecycle of a hotel [data extracted from reference 11].

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rocks, using prevailing technologies".[2] The 'exergy rarity' concept is thus able to quantify the rate of mineral capital depletion, taking a completely resource-exhausted planet as a reference. This rarity assessment allows for a complete vision of mineral resources via a cradle-to-grave analysis. Exergy rarity is, in fact, a measure of the exergy-destruction footprint of a mineral, taking Thanatia as a reference.

Given a certain state of technology, the exergy rarity is an identifying property of any commodity incorporating metals. Hence, exergy rarity (in kWh/kg) may be assessed for all mineral resources and artefacts thereof, from raw materials and chemical substances to electric and electronic appliances, renewable energies, and new materials. Especially those made with critical raw materials, whose recycling and recovery technologies should further enhance. Such thinking is a step towards "a better preservation of the Earth's resources endowment and the use of the Laws of Thermodynamics for the assessment of energy and material resources as well as the planet's dissipation of useful energy". This message was launched in the Brescia Appeal to the UN and the EU of a group of thirty-one scientists in the field of exergy.[13] More than ever, the issue of dwindling resources needs an integrated global approach. Issues such as assessing exhaustion, dispersal, or scarcity are absent from economic considerations. An annual exergy-content account of not only production, but of the depletion and dispersion of raw materials would enable a sound management of our material resources.

Unfortunately, similar to the problem of inconsistent national energy-efficiency measurement, there is also a lack of consistency in natural-resource assessment, which is necessary for effective policy making.[2] Integration of exergy analysis into our daily lives through laws and even taxes is long overdue, but progress is slow.

INTEGRATING EXERGY ANALYSIS INTO OUR DAILY LIVES

Exergy-based Law-making

As far back as 1974, the Congress of the United States passed Public Law 93.577, the Federal Non-Nuclear Energy Research and Development Act, to establish a national programme for research and development in non-nuclear energy sources, with the governing principle that the potential for production of net energy be analysed and considered in evaluating the potential of any proposed technology.[14] In effect, this legislation states that net energy, rather than conventional economic analysis, should provide the basis for prospective energy technologies.

As a result of this legislation, the net energy yields of renewable and non-renewable energy supply technologies are now publically available.

Unfortunately, despite the fact that exergy analysis has matured in the intervening years, it has remained largely confined to the academic world. An exception is the canton of Geneva, which in 2001 introduced a new article featuring the exergy concept in their energy law.[15] Geneva authorities require city developers to include an exergy approach in their project proposal. The law applies to about 20% of total developments in particular buildings

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or building areas used for apartments, offices, and commercial premises, representing close to 80% of the energy consumption of new building developments. In practice, an internet framework allowing users to calculate their efficiency indicators was set-up. Today, the law seems to be fully implemented with energy efficiency featuring heavily within the building application process.[16]

The Cost of a Recycling Policy – a Cautionary Tale

Recycling contributes significantly to the preservation of natural resources. At least, that is what policy and legislation leads us to believe. However, exergy analysis shows that well-intended legislation may actually not have the desired effects.

Since recycling technology itself requires materials and energy input, both of which contribute to the depletion of natural resources, it is important to evaluate the efficiency of the whole recycling chain to determine its actual benefit. Exergy analysis allows evaluation and optimisation of any recycling system's environmental performance on a fundamental basis, capturing efficiency in the system as a function of physical, metallurgical, and thermal processing, and of the quality of reclaimed materials. Such studies have shown that the high recycling quotas for end-of-life vehicles as required by EU legislation appear to be totally erroneous, since they are based on first-law arguments.[17] The present stringent legislation is violating fundamental thermodynamics and contrary to its intention, is potentially damaging the environment.

Charging Exergy Loss, not Energy Use – Radical Thinking or Just Common Sense?

One of the leading proponents of the 1974 US Federal Non-Nuclear Energy Research and Development Act, Senator Mark Hatfield, interpreted the Act as a step towards replacing money with energy as the standard of value. While still some way off from an 'energy currency', there have been repeated calls for an energy-based tax as an incentive for exergy and resource conservation. Current EU rules for taxing energy products and electricity are laid down in the Energy Tax Directive 2003/96/EC,[18] which entered into force in 2004 with the aim of reducing distortions caused by divergent national tax rates, removing competitive distortions between mineral oils and other energy products, and creating incentives for energy efficiency and emission reductions. However, as the taxation rates are based on volume, rather than energy content, products with lower energy content, such as renewables, carry a heavier tax burden than the fuels they are competing with.

Encouragingly, in 2011, the European Commission presented a proposal to revise the rules on taxation of energy products in the EU, in order to reflect CO_2 emissions and energy content (€/GJ), rather than on volume. The following year, however, the European Parliament voted against

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the draft Energy Taxation Directive, stating that it was not a good moment to increase energy taxes in a time of economic austerity and high fuel costs. The European Council has had several debates on the topic since 2012, but has not yet released an official position on the matter.

In the beginning of 2015, the Commission withdrew the proposal, because, in the words of First Vice-President Frans Timmermans at the Presentation of the 2015 Commission Work Programme to the European Parliament, "the Council has watered it down so it no longer meets our environmental objectives of taxing fuel in a way that reflects real energy content and CO_2 emissions".[19]

As previously demonstrated, the second-law thermodynamics consideration of energy has the advantage that it can be applied with a common measurement scale to natural resources, fuels and products. It can be applied to individual processes, to industries, and to whole national economies. It provides a firm basis from which to judge the effect of policy measures taken towards energy, and resource and climate efficiency.
There is little doubt that the Energy Tax Directive 2003/96/EC inadequately supports the EU's current energy and climate change policies. However, is the economic crisis and national-interests-driven rejection of its proposed revision a missed opportunity, or rather a timely opening for a radical common-sense thermodynamics approach to taxation on energy?

It is time to charge for exergy use rather than for energy use. In the future, consumers should be informed about products and services in terms of their exergy content and destruction footprints in much the same way as they are about carbon emissions, and pay the price accordingly. That gives a scientific basis for charging for loss of valuable resources.

CONCLUDING REMARKS AND RECOMMENDATIONS

Thermodynamics is the science of energy. Exergy measures useful energy. Exergy efficiency is the real efficiency of an energy system or process. To this end, and compared with conventional first-law thermodynamics energy approaches, the second-law exergy approach can identify and quantify the causes of inefficiencies. Exergy is therefore the right metric to value energy use and resource scarcity.

In December 2015, world leaders signed a historic climate agreement in Paris. For the first time, all countries agreed to play their part in keeping the global temperature increase below 1.5°C. But the Paris negotiations may turn out to have been the easy part. Any progress with climate change must tackle energy use. Decision-makers must see beyond economic and national interests to chart a new course of radical climate policies based on the science of energy.

With this in mind, the authors make the following recommendations:

- The teaching of concepts related to exergy in schools and universities
- The promotion of the exergy concept, with policy makers and energy stakeholders taking a lead in informing the public
- The introduction of exergy destruction footprints to give a useful basis for work on energy efficiency improvements
- The reintroduction of national useful energy accounting
- Taxation of excess exergy destruction footprints to drive the development of more energy efficient technology
- Use of exergy rarity to monitor the earth's mineral resources
- The creation of accounts of exergy destruction footprints and exergy rarity to support the IPCC in finding measures to mitigate climate changes

The EU has a moral responsibility to show the same leadership in implementing the Paris agreement as it did in making the agreement possible. The climate crisis was not solved in Paris: the COP21 was just one step in the right direction. The second step requires the common sense and courage to implement exergy as the rightful metric for energy and natural resource use.

As wisely said by Howard Scott in 1933:

"It is the fact that all forms of energy, of whatever sort, may be measured in units of ergs, joules or calories that is of the utmost importance. The solution of the social problems of our time depends upon the recognition of this fact. A dollar may be worth - in buying power - so much today and more or less tomorrow, but a unit of work or heat is the same in 1900, 1929, 1933 or the year 2000."[20]

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