The impact of energy on the development of human societies and the global economy

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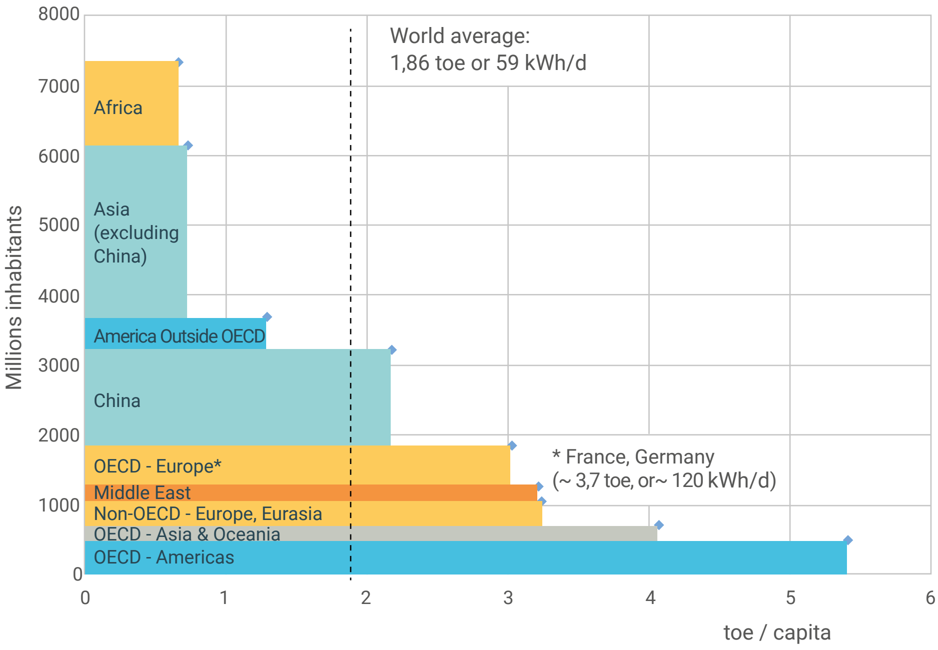
While the real weight of energy in the economy is still largely under-estimated in many macro-economic models, this article explains the strong interrelationship between energy, human development and the economy. Against a backdrop of growing global demand and the urgent need to decarbonise energy use, the article discusses a number of ways of reducing greenhouse gas emissions, based on technical innovations.

Access to energy is a prerequisite for the development of human societies. The same applies to human societies as to the living beings that make them up: they are, from a thermodynamic point of view, open systems, which cannot maintain themselves and grow in complexity and organisation without sufficient supplies of energy and resources. The dynamics of evolutionary processes and self-organisation in nature are governed by the laws of thermodynamics, from which human societies cannot escape either.

The regional distributions of primary consumption and GDP per capita around the world, shown in Figures 1 and 2, are strikingly similar. This is a simple manifestation, albeit in broad strokes, of the correlation between energy consumption and GDP, which we will analyse in more detail below. The geographical distribution of primary energy consumption (fig. 1) also shows that a good half of the world's population currently has to make



1. Regional breakdown of annual primary energy consumption per capita expressed in toe per capita (1 toe = 11.63 MWh). based on data from the International Energy Agency (IEA, www.iea.org/).

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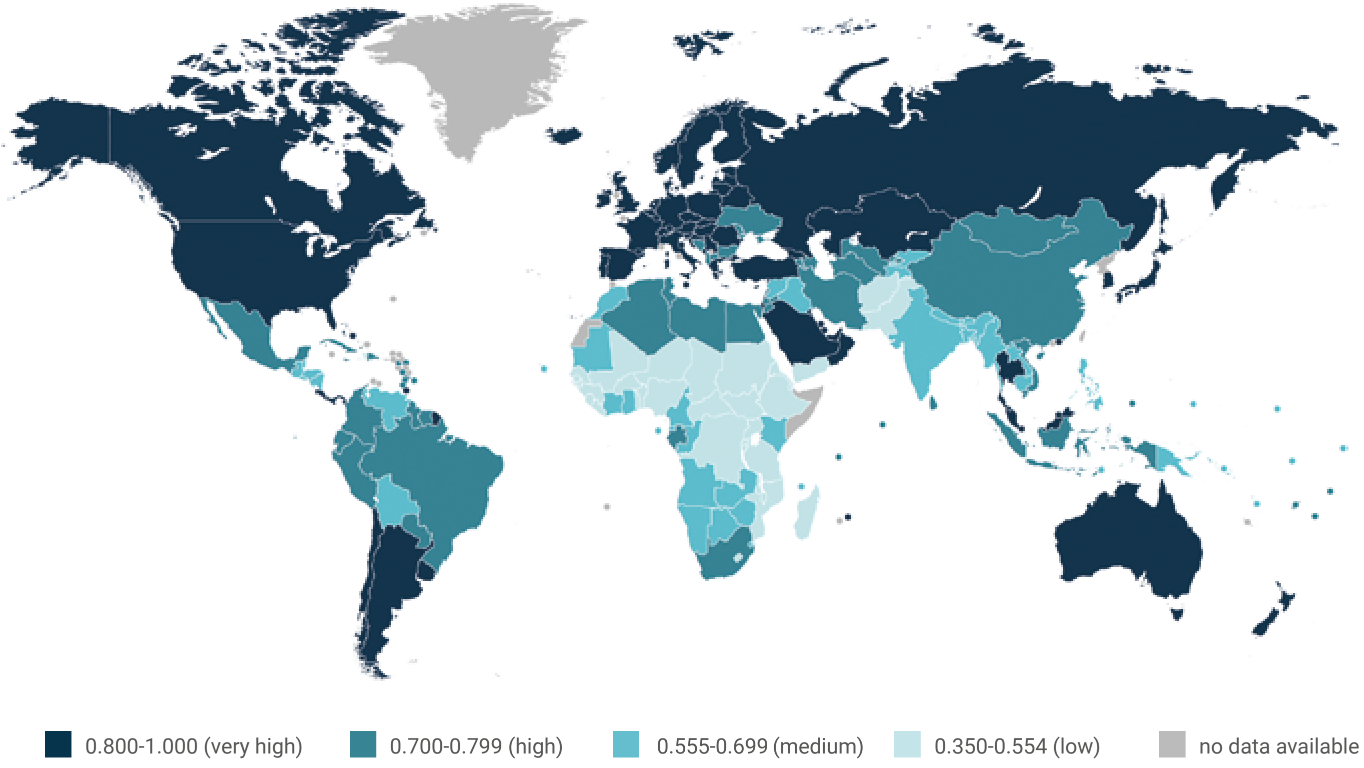

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Map of the world's countries by Human Development Index (HDI) category, according to the UN in 2021.

do with around a third of the world average per capita, whereas we consume twice as much in France. There can be no access to development and more services for all of humanity without growth in energy consumption. Demographic change and development mean that the world's energy needs are growing.

We begin by discussing the role of energy in the evolution of human societies, based on principles familiar to physicists, and then by observing the relationship between the Human Development Index (HDI) and per capita energy consumption. We then report on the totally consistent results of two different approaches, which prove the crucial role of energy in the formation of GDP. This role is still largely underestimated by many economists, despite the fact that energy is the universal measure of the transformations of matter associated with the creation of goods and services. In the final section, we show that certain technological innovations can open up avenues for reducing greenhouse gas emissions.

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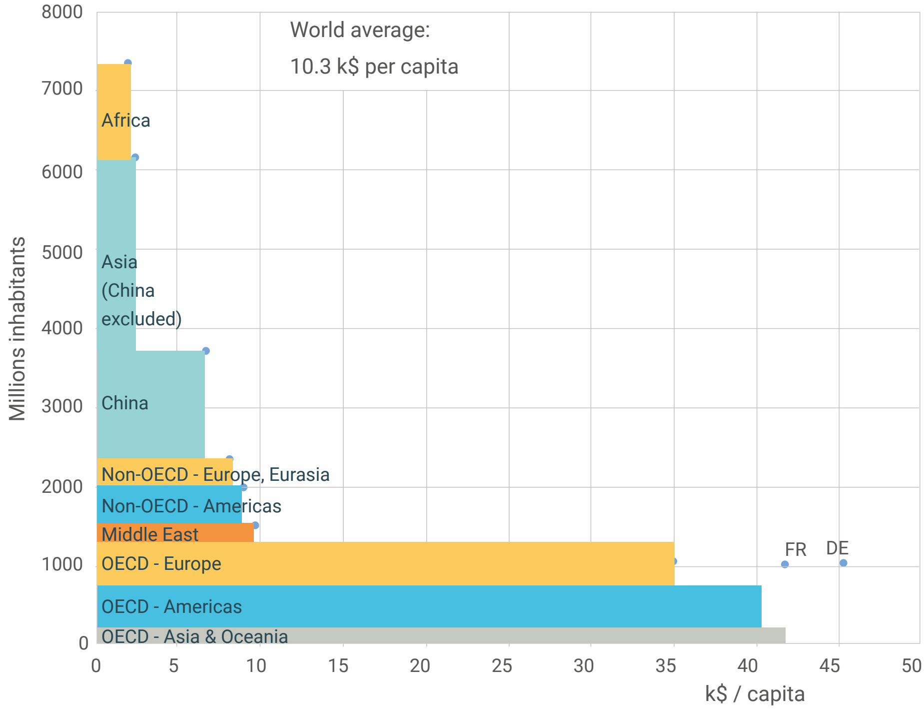

2. Global breakdown of gross domestic product (GDP) per capita (based on IEA data) **.**

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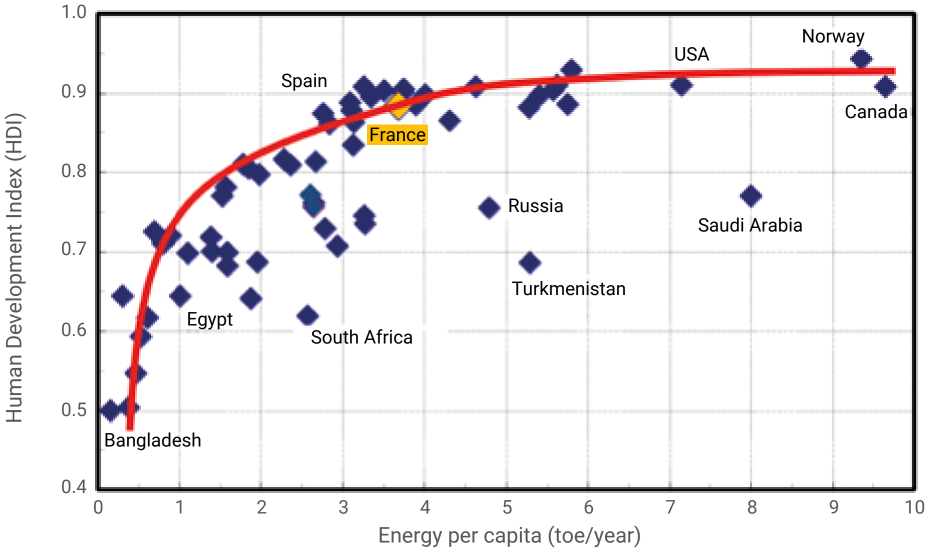
Energy and macroeconomics



3. Human development index as a function of energy consumption, expressed in toe/year (1 toe = 11.63 MWh). Source: H. Safa [10]

Energy and evolutionary dynamics

Throughout their life cycles, the exchanges between living organisms and their environment are governed by the laws of thermodynamics. They are open systems that can only develop and maintain their organised state if they receive sufficient food. For the sake of clarity, it should be remembered that the energy consumed by our metabolism is 3 kWh/day, which corresponds to an average power of 130 W, of which only 30 to 40 W is converted into muscular work. The majority is consumed in chemical processes and in maintaining our body temperature. It is ultimately dissipated in the form of heat into the environment, leading to the production of entropy, in accordance with the first and second principles of thermodynamics. Human societies, seen from the angle of their exchanges of energy and resources with their environment, cannot escape these two fundamental principles.

It is thanks to the driving role of energy, which enables stable structures to be formed and maintained, that living organisms and societies can develop and survive. The processes of extinction, development and the emergence of new structures are always linked to variations in accessible energy. This was the case for human societies, whose evolution corresponded to leaps in the ability to transform matter, thanks first to the mastery of fire, then agriculture, and finally the use of fossil resources. For example, while for hunter-gatherer groups the average energy consumption per individual, including food, after the domestication of fire, is estimated at 6 kWh/d (roughly 2 kWh of food and 1 kg of wood), in the first agrarian societies this consumption jumped to 14 kWh/d, then to 30 kWh/d during the European Middle Ages, and finally, after the industrial revolution, it rose to over 100 kWh/d in our developed societies(a). At the same time, access to new energy resources has led to the creation of new, more complex social structures, organised on a larger scale and requiring an ever greater share of the energy available to maintain their consumption. Intuitively, we can see that this growing weight in the energy consumption of infrastructures and superstructures shared by individuals in a developed society could be measured by comparing total consumption and direct household consumption. At present, the latter accounts for only 35% to 40% of total consumption (36% for electricity in France in 2019), whereas among hunter-gatherers it accounts for almost all.

The dynamics of cosmic evolution (cf. for example E. Chaisson [1]) and of natural selection within living organisms have prompted certain researchers, following Lotka's intuitions (1922) [2], to look for an additional principle to provide a physical basis for their observations. (See, for example, the work of Martyushev [3], who proposed a principle of maximum entropy production, and the discussion by Herrmann-Pillath [4] for more on this area of research). But even without having to rely on such a principle, observations clearly show that a plant, an animal or a human society cannot maintain itself if it receives too little (water, food, energy) from its environment, or too much!

By transposing the constraints imposed by thermodynamics to a human society, we can understand that in order to maintain and develop, this society must only devote a fraction of its energy resources to obtaining these same resources. For example, there may have been hunter-gatherer societies that enjoyed relative "abundance" [5] when this fraction was low. But it is above all for this reason that coal, and later oil and gas, have enabled our industrial societies to flourish. These energy sources have gradually been used in preference to biomass, because they contain two to three times more energy per unit mass(b). Energy density is crucial, particularly for mobile use. The concept of energy return, measured by EROI (Energy Return On Investment), is one of the main physical criteria to be used for evaluating energy sources or complete energy systems. It will be discussed in the following article by G. Bonhomme and J. Treiner (p. 24). The application of this concept to a society was studied by Lambert and Hall [6], who defined a societal EROI.

It would be a dangerous illusion to believe that we could maintain a prosperous society without consuming energy or resources. This is totally incompatible with what thermodynamics teaches us about the world.

Energy and the Human Development Index (HDI[c])

It is very difficult to quantify exactly the level of human development in a given country by going beyond a simple measure of economic wealth. Nevertheless, following the work of the United Nations Development Programme (UNDP), a composite statistical index was introduced to assess the rate of human development of the world' s countries. The HDI, which has been improved since 2010, was based on three criteria: GDP per capita, life expectancy at birth and the level of education of children aged 17 and over. Figure 3, which plots this index against per capita primary energy consumption for different countries, clearly shows that :

(i) all countries with low energy consumption (< 2 toe/year/head) also have a low HDI;

(ii) above 4 toe/year/head, there is no longer a clear correlation between HDI and consumption levels, indicating that excess consumption could be considered as waste.

We can therefore assume that there is a threshold of around 1.5 toe/year (i.e. 50 kWh/day), a value that corresponds roughly to the world average of 59 kWh/day (see Figure 1) and a saturation effect above 4 toe/year (or 130 kWh/day), which corresponds to European consumption.

Even if this inescapable fact is still far from being recognised by mainstream economics, prosperity and economic development are inextricably linked to energy. No substitute exists.

Energy and gross domestic product (GDP)

GDP is a standard measure of a country's global economy, quite similar to the economic part of the HDI. As it is obtained by counting all the production of goods and services involving the transformation of matter and therefore the consumption of energy, the similarity between Figures 1 and 2 is not surprising. A more direct observation of the relationship between GDP and primary energy consumption is provided by Figure 4, which plots this relationship at global level from 1965 to 2019. It shows a close dependence between the two quantities, with a slight upward trend in energy efficiency indicating that GDP can still maintain its upward trend with a relative decrease in energy consumption. Only this aggregation of data at global level can mask the sudden variations resulting from the globalisation of trade and relocations, which would be observed on representations by regional blocks. It is important to be cautious when interpreting curves representing regional trends, and not to forget to take account of the consequences for GDP evolution in a given country of other factors linked in particular to globalisation.

Although the strong link between GDP and energy is fairly clear, no direct theory has provided a quantified assessment of the impact of energy on GDP. Instead, a large number of economists use so-called neoclassical macroeconomic equilibrium models (for more details, cf. Kümmel [7]), based on methods of fitting empirical data to power laws of the Cobb-Douglas type. These models provide, in the vicinity of an assumed equilibrium, variations in GDP expressed using a production function[d] dependent on the variables capital, materials, labour and energy, known as the "factors of production". A production function, of the Cobb-Douglas type for example, is comparable to a thermodynamic potential and the exponents, called elasticities, measure how the relative variation in one of these factors affects the relative variation in GDP. Assuming that the factors of production are perfectly substitutable, linearisation in the vicinity of equilibrium leads to these elasticities being given directly by the weight of the cost of each factor in GDP ("cost share theorem"). Typical values for industrialised countries are, as for France, of the order of 5% for energy, 15% for materials, 35% for capital and 45% for labour, which only reflects the respective costs, but contradicts the observations.

The reason is, of course, that the factors are not totally substitutable, and that energy in particular cannot be replaced without limitation by human labour! Approaches based on similar models, but maximising under constraints (i.e. taking into account the physical and technological constraints that restrict the freedom of choice of production

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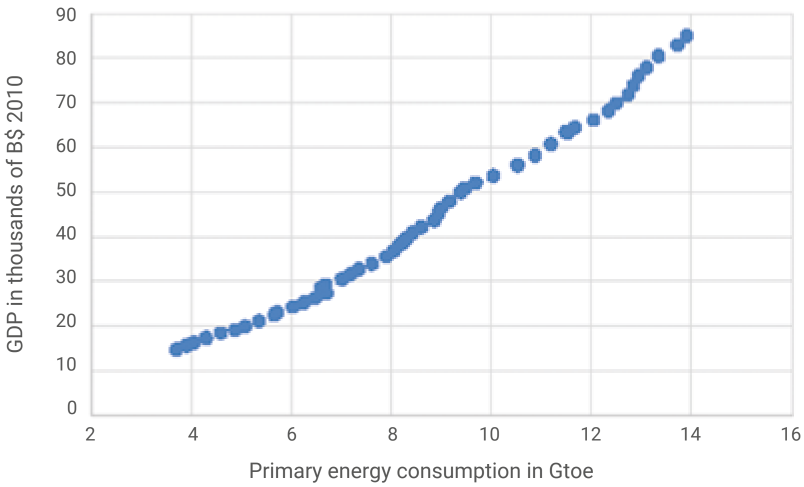

4. Change in world GDP from 1965 to 2019 (expressed in constant dollars) **as a function of primary energy consumption.** (Sources: World Bank, IEA).

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factors), lead to completely different results, showing in particular that the elasticity for the energy factor is of the order of 60% to 70% (cf. Ayres [8], Kümmel and Lindenberger [9]), in full agreement this time with the empirical data.

This result has been confirmed (cf. Safa [10]) by a direct assessment of the influence of energy on the activities included in GDP. This is certainly more tedious and time-consuming than deriving optimal values from a simple linear regression equation. The undeniable advantage is that it also provides additional detailed information on the energy impact of each activity or sector.

These results help us to understand the origin of the illusion that GDP growth could be decoupled from energy consumption. In fact, and rather obviously, the apparent decoupling observed stems from the shift over recent decades of jobs from the industrial production and agricultural sectors to services, while production has been progressively relocated to low labour cost countries. This has reduced the cost of products, as well as their energy cost, so that their contribution to GDP has fallen. As a result, there has been a corresponding sharp increase in GDP per quantity of energy used, and hence in energy efficiency.

Energy and the fight against climate change

Reducing greenhouse gases

The combustion of fossil fuels (coal, oil and natural gas) releases carbon dioxide into the earth's atmosphere. This energy-related pollution is the main contributor to the greenhouse gases (GHGs) that are slowly but surely affecting our climate. The greenhouse effect will cause a warming of the atmosphere that could potentially lead to uncontrollable catastrophic events on our planet later this century. We absolutely must mitigate this threat through a strong and deliberate reduction in our GHG emissions. Given the impact of energy on the economy, as described above, the introduction of a carbon tax, as advocated by some economists to reduce the use of fossil fuels, is a good way of reducing our greenhouse gas emissions may not be either economically viable or compatible with the energy needs of a large proportion of humanity in developing countries.

Based on the projections of the various scenarios produced by government agencies and oil companies, it can be estimated that global primary energy demand in 2040 will be around 18,000 Mtoe, or 200 000 TWh. This figure is the same as the current average per capita consumption of 60 kWh per day for a population of 9 billion.

The enormous challenge we face is therefore to find economically viable technical solutions that will enable us to drastically reduce our reliance on fossil fuels without restricting our ability to meet energy needs. For its part, the European Union plans to comply with the Paris climate agreements by aiming for carbon neutrality by 2050.

Technological innovation as a lever for transition

A significant and decisive reduction in greenhouse gas emissions in just a few decades will only be possible if there is a deliberate shift from the current energy mix, which is mainly based on fossil fuels (oil, coal and gas), to energies that do not emit greenhouse gases, such as hydroelectricity, nuclear power and renewable energies. This will undoubtedly mean greater use of electricity for end uses (electricity currently accounts for only 23% of end uses in Europe). This is of course conditional on the production of electricity itself being decarbonised, which is far from being the case in all European countries. The European Union is forecasting a 53% increase in electricity consumption by 2050. End uses, which are mainly based on fossil fuels, include heating needs in the residential and tertiary sectors and the transport sector.

Two areas of technological innovation could pave the way for a genuine energy transition: the switch to electric vehicles for road transport and the recovery of waste heat from power stations [11] for homes,

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2• A. J. Lotka, ”Contribution to the Energetics of Evolution”, *PNAS*, **8**(6) (1922) 147-151, et “Natural Selection as a Physical Principle”, *PNAS*, **8**(6) (1922) 151-154.

3• L.M. Martyushev et V.D. Seleznev, “Maximum entropy production principle in physics, chemistry and biology", *Physics Reports* **426** (2006) 1-45.

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5• M. Sahlins, *Âge de pierre, âge d'abondance - L'économie des sociétés primitives*, Gallimard, (1976), 420 p. (ISBN 978-2-07-029285-1).

6• J. G. Lambert *et al.*, "Energy, EROI and quality of life", *Energy Policy*, **64** (2014) 153-167.

7• R. Kümmel, *The Second Law of Economics: Energy, Entropy, and the Origins of Wealth*, Springer, Berlin (2011), ISBN 978-1-441-99364-9

8• R.U. Ayres et B. Warr, *The Economic Growth Engine: How Energy and Work Drive Material Prosperity*, Edward Elgar Publishing (2009).

9• R. Kümmel et D. Lindenberger, ”How energy conversion drives economic growth far from the equilibrium of neoclassical economics”, *New Journal of Physics* **16** (2014) 125008.

10• H. Safa, "The Impact of Energy on Global Economy”, *Int. Journal of Energy Economics and Policy*, **7**(2), (2017) 287-295.

11• H. Safa, “Heat recovery from nuclear power plants”, *Electrical Power and Energy Systems*, **42** (2012) 553-559.

business centres and industrial processes. Here we provide an overview of these two major disruptive technologies.

Cogeneration and production of carbon-free heat

A significant proportion of energy needs is heat, and 65% of these needs correspond to low-temperature heat, i.e. below 120°C. However, for reasons linked to the laws of thermodynamics, the process of converting primary energy into electrical energy also generates, in proportions that depend on the temperature of the hot source, enormous quantities of waste heat (in 2018, of the 5.48 Gtoe of input energy supplying all the world's power stations, 2.84 Gtoe was wasted!). We would benefit from recovering this wasted energy to meet some of our heating needs, provided that the temperature at which the energy is recovered can be used to heat our homes. recovery can supply heating networks instead of heating the atmosphere, river water or the sea. This is the principle of cogeneration, to which an article by M. Leurent and H. Safa is devoted in the second part (p. 73).

Electrification of transport

Today, transport is heavily dependent on oil resources, since 92.3% of the world's energy used for transport is made up of petroleum products. The reason for this is the very high energy density of liquid fuels (11 600 Wh/kg). The use of electricity, either directly through the use of electric motors powered either by electrochemical batteries or hydrogen fuel cells, could open up new possibilities. fuel cells, could open up new avenues, despite the specific technological and economic hurdles that will be discussed in the third section.

Let's just note at this stage that the use of hydrogen produced by electrolysis to replace fossil fuels would lead, if it were to have any significant influence, to an enormous increase in electrical energy requirements. In fact, if France were to use hydrogen to replace 20% of its final energy consumption from fossil fuels by 2050, it would need to produce around 10 million tonnes a year. Production by electrolysis would require around 500 TWh of electrical energy, i.e. as much as current annual consumption.

Conclusion

Although energy only accounts for between 2% and 7% of GDP in the developed countries of the West, its importance is crucial to all activities in our modern economies, affecting over 60% of production costs in France. This vital role of energy is, of course, in perfect accord with the laws of nature and thermodynamics, which also apply to living beings and human societies. Evaluating the contribution of energy to GDP growth shows that its real weight in the economy is such that the substitution of energy for other goods and services would be impossible. Economy is such that the substitution of either capital (to increase energy efficiency, for example) or labour cannot suffice. It is therefore a dangerous illusion to believe that we can maintain a society with a high level of services while drastically reducing the consumption of energy and resources. The enormous challenge we face, in the short time available because of the climate emergency, is to implement decarbonised solutions that are economic solutions that limit as far as possible the impact on the environment, i.e. the discharge of polluting waste and the need for mineral resources. Technological breakthroughs are essential to facilitate the energy transition from fossil fuels to carbon-free sources. ▮

(a) The invention of agriculture enabled a leap of about a factor of 1000 in the average quantity of resources (food for humans and farm animals), which thus went from the range of kWh/ha/year to that of MWh/ha/year. Current energy consumption in Europe, with a population density of 1.14 inhabitants/ha, corresponds to 40 MWh/ha/year. (Note: with 10 MW/km^2 of unit installed capacity, annual unit onshore wind power is of the order of 200 MWh/ha, but a realistic maximum surface coverage rate of 2 to 3% leads to around 5 MWh/ha. For example, in Germany in 2019, wind power production was 101 TWh for 53 GW of installed capacity on 0.9% of the country's surface area, which corresponds to around 2.8 MWh/ha for the whole country.)

(b) Oil provides 11600 Wh/kg, compared with 2000 to 4000 Wh/kg for biomass, depending on its moisture content.

(c) The HDI is based on a weighting of GDP, education and health. It was developed in 1990 by the Indian economist Amartya Sen, winner of the Nobel Prize for Economics, and the Pakistani economist Mahbub ul Haq. For details of the composition of the Human Development Index, visit the United Nations website at https://cutt.ly/human-development-index

(d) In economics, a production function expresses in equation form the relationship between the production factors K, L, E (capital, labour, energy) of an organisation and the quantity produced. The so-called Cobb-Douglas form, $Y_{CD} = Y_0 K^{0a} L^{0b} E^{1-a0-b0}$, of the production function is obtained from two assumptions: (i) Y is a doubly differentiable state function, where the elasticities α, β and γ must satisfy Maxwell's relations; (ii) Y is a homogeneous linearthis follows, for example, from the condition that a doubling of the production system, by doubling each of the factors ofproduction, leads to a doubling of output. But this solution assumes complete substitutability of the factors of production, i.e. energycould, for example, be completely replaced by labour (cf. R. Kümmel *et al.*, *New Journal of Physics* **16** (2014) 125008).