



**HAL**  
open science

## Powering the world: how much energy will humanity need?

Gregory de Temmerman, Léa Trin, Dimitri Chuard, Jean-Baptiste Rudelle

► **To cite this version:**

Gregory de Temmerman, Léa Trin, Dimitri Chuard, Jean-Baptiste Rudelle. Powering the world: how much energy will humanity need?. [Technical Report] Mines ParisTech - Ecole des mines de Paris. 2021. hal-03524462

**HAL Id: hal-03524462**

**<https://hal.science/hal-03524462>**

Submitted on 15 Mar 2022

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

RESEARCH NOTE  
SEPTEMBER 2021

# POWERING THE WORLD

How much energy will  
humanity need?



# HOW MUCH ENERGY WILL HUMANITY NEED?

## The role of energy in our societies

---

Energy is an interesting concept in that it is a widely used term that very few people can define properly. The standard definition of 'the capacity for doing work'<sup>1</sup> is indeed relatively vague for a non-physicist. This is paradoxical given that the ability to mobilize ever-increasing quantities of energy has been a key factor for the development of society as we know it<sup>2</sup>.

For a very long time, the energy use per capita has remained stable. Estimates for the Roman empire give 10-20 GJ/cap/yr<sup>3,4</sup>, with about half of it for wood, while Morris<sup>5</sup> estimates are up to 42 GJ/cap/yr, which is most likely an overestimate. Right before the Industrial Revolution, in 1800, the world average was still around 20 GJ/cap/yr<sup>6</sup>, while the most developed parts (e.g. the UK) were already at 60<sup>7</sup>. This took off quite rapidly with the use of coal and the deployment of the steam engine. In 2020, the global average is 71 GJ/cap/yr<sup>8</sup> but there are large

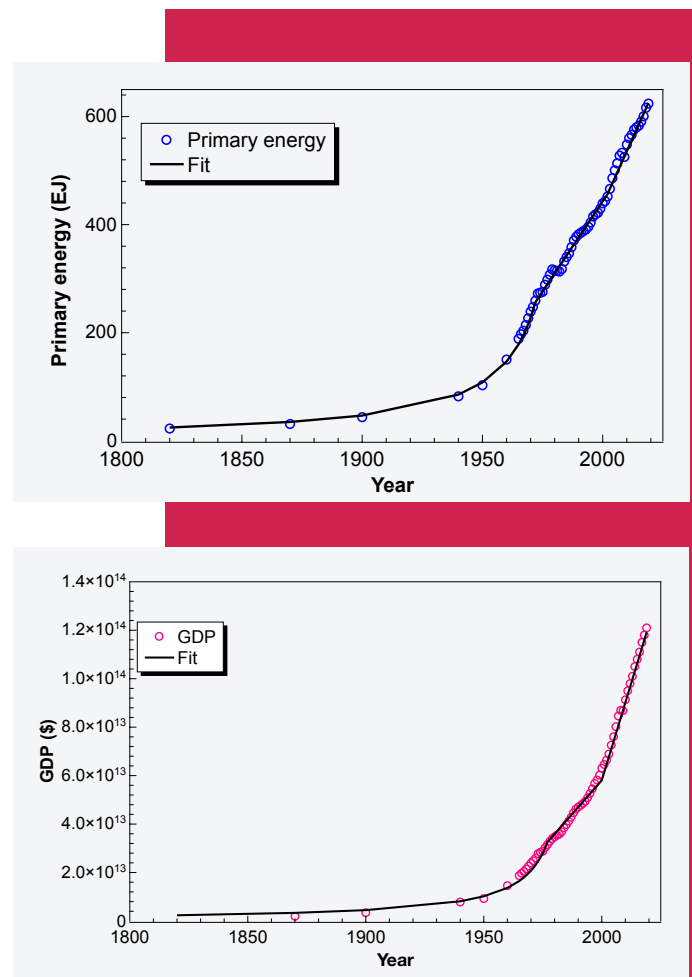
disparities. Qatar is at 590 GJ/cap/yr, the US at 260, while France and China are at 130 and 100, respectively. The average for Africa is about 14 GJ/cap/yr. It is interesting to note that among the countries with the highest energy use per capita, many are oil producing countries<sup>9</sup>.

Since the Industrial Revolution, the world energy demand, the gross domestic product (GDP\*; see fig. 1), but also the world population have known a strong increase which accelerated after 1950 - a period that is sometimes referred to as 'the Great Acceleration'<sup>10,11</sup>. This has led to strong improvements in the quality of life within industrialized countries. Indeed, the Human Development Index (HDI), which accounts for life expectancy, gross national income per capita and education level<sup>12</sup>, increases strongly with the primary energy use per capita<sup>13-15</sup> (up to about 100-150 GJ/cap/yr, after which it saturates) and the GDP per capita<sup>16</sup>.

The post-1950 period has seen a strong increase in many indicators in addition to those already mentioned, such as fertilizer and water use, number of motorized vehicles, number of international tourists, etc., which characterize the human footprint on nature. To define this footprint, a group of scientists led by Johan Rockström has proposed in 2009 a framework based on the concept of 'planetary boundaries'<sup>17</sup>. These nine boundaries characterize the planet's biophysical systems and if crossed could threaten the planet's habitability. They pinpoint a 'safe operating space for humanity' within the biosphere. It has now been established that humanity has exceeded several of those planetary boundaries: species extinction rate,

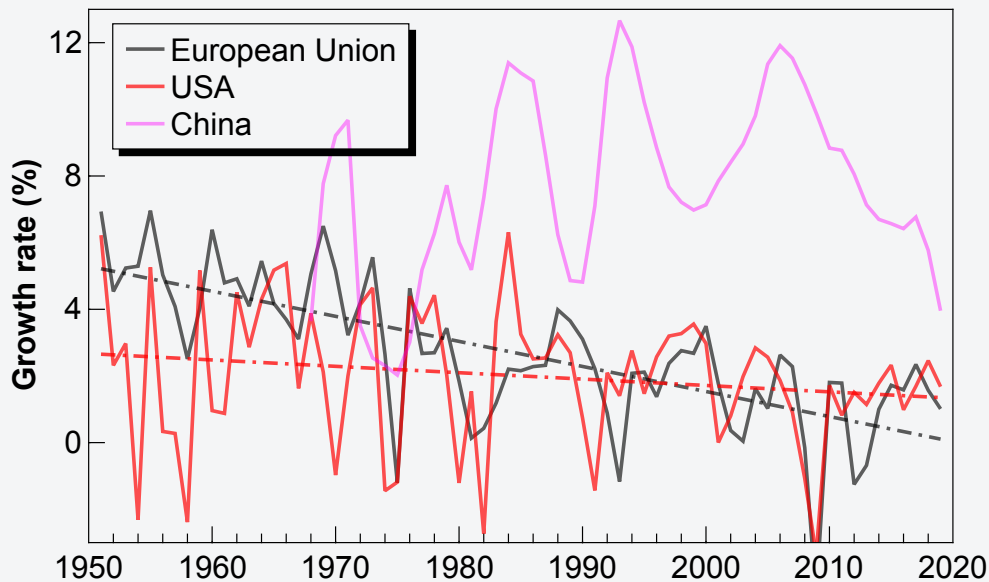
deforestation, atmospheric carbon dioxide levels (causing climate change) and the flows of nitrogen and phosphorus<sup>18</sup>.

Currently, most advanced economies continue to experience annual economic growth, i.e. an annual increase in their GDP, typically at a rate of a few percent per year. The growth rate for OECD countries has steadily decreased from an average of 5 percent per year in 1967 to 1-2 percent per year in 2013<sup>19</sup>. Fig. 2 shows the data for the EU, the US, and China for comparison.



**Figure 1:** Evolution of the World Primary Energy use (top) and GDP (in 2011 \$, bottom) for the period 1820-2020. The solid lines are fit to the data by time periods: a hyperbolic fit (growth rate increasing with time) until around 1970 and two linear fits from 1970-2000 and 2000 to 2019. Data from BP Statistical Review of World Energy<sup>9</sup>.

\*One could use the Gross World Product but following common practice we will make use of the GDP in this report. They are strictly equivalent.



**Figure 2:** Evolution of the GDP annual growth rate for China, the US, and the EU over the period 1950-2019. The dash-dotted lines show the best linear fits for the US and the EU time series. Data from World Bank.

During the period 1990-2010, the Chinese GDP has grown at an average rate of about 10 percent. Other emerging countries are also experiencing an acceleration of their economies. The relative slowdown in developed countries is more than compensated by the strong growth in emerging countries, which explains the continuous and strong growth of the world GDP (fig. 1).

Economic output is strongly linked with the availability of capital, labour and useful energy<sup>20</sup>. The remarkable economic growth

**Many scenarios see an ever-growing energy demand with no sign of stabilization by the end of the considered timeline, which raises the question of how long such a growth can be continued.**

experienced during the last 70 years has been made possible by the abundance of cheap fossil fuels. Globally, there is a very strong correlation between primary energy (PE) consumption and GDP as showed in fig. 3, although the correlation is evolving over time as the energy intensity of the GDP is decreasing. The primary energy demand is increasing at a slower pace than the economy, with a long-lasting trend where less energy is required to generate one dollar of GDP. There is a strong debate in the literature about the direction of the causality between PE and GDP. At the global level, some studies report the causality in the direction from PE to GDP<sup>21,22</sup>, while others point out to inconclusive results<sup>23</sup>. At the national level it appears to be very dependent on the type of economy and the level of development<sup>24-26</sup>. The production of material goods is energy-intensive, although with productivity gains and increased energy efficiency, the amount of energy required tends to decrease over time, up to a certain limit<sup>27</sup>. Services, on the other hand, are usually less energy-intensive, but the tremendous growth of digital services in the last thirty years has been associated with a bump in electricity consumption.

Economic projections from OECD scenario<sup>28</sup>

foresee a strong economic growth for developing countries and a more modest growth for developed countries, with a tendency towards convergence in the future. The Shared Socio-economic Pathways<sup>29</sup> foresee economic growth in most cases albeit at different rates. Given the correlation between primary energy use and GDP, those projections imply a rising global energy demand. In the SSP framework, global PE demand is expected to increase by 40-210 percent depending on the scenario<sup>30</sup>. The large spread is based on assumptions about evolution of technology improvements (energy efficiency), population behaviour, resource availability and implemented policies. Many of those scenarios see an ever-growing energy demand with no sign of stabilization by the end of the considered timeline, which raises the question of how long such a growth can be continued. Here we will assess the question of how global energy demand might evolve in the future based on an analysis of demand patterns from countries at various stages of development.

## Evolution of the energy-economy correlation

### Global evolution

A closer analysis of the evolution of the world GDP (fig. 1) shows that at the beginning of the 19th century, the world experienced a hyperbolic economic growth, i.e. that the growth rate was increasing every year, which lasted until the first oil crisis. A reacceleration of the growth rate has been observed after 2000, most likely linked with the strong growth of the Chinese GDP. Indeed, the share of China to the world GDP has risen from 3.6 percent in 2000 to 17.8 percent in 2019. The world primary energy consumption experienced a similar hyperbolic growth at the beginning of the 19th century. This period was characterized by a rapid industrialization of western countries whereby the share of agriculture in the economy decreased strongly<sup>32</sup>.

**Figure 3:** Evolution of the relationship between primary energy demand and GDP for the period 1850-2019. The black line shows our fitting model based on three phases: a linear model until the 1970s, then a power law, and finally a linear model again but with a smaller slope. Data from the Maddison project<sup>31</sup> and BP Statistical Review<sup>8</sup>.



Looking at the energy-GDP correlation (fig. 3), the data is best described by three phases. First a linear relationship until the 1970s which means that the economic output was proportional to the primary energy use and that both the energy demand and the GDP were increasing at a similar rate. The creation of one unit of GDP required one unit of energy. After that and until around 2000, the data is best fitted with a power law of the type  $PE \sim GDP^{0.6}$ , a model already proposed in the

literature<sup>33</sup>. During that phase, the economy was growing faster than the energy demand. Since around 2000, the PE-GDP relationship has been linear again but with a smaller slope.

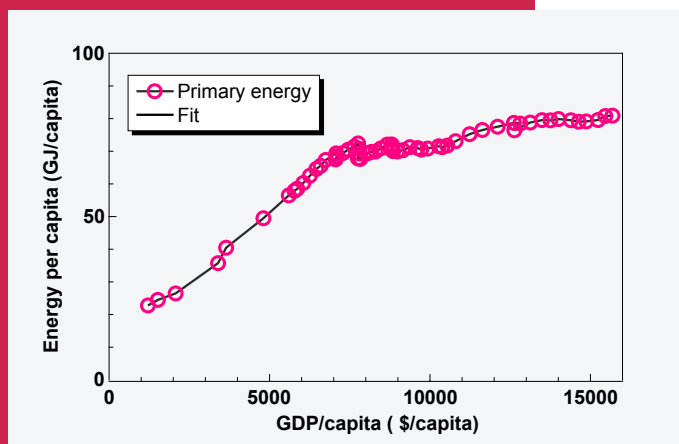
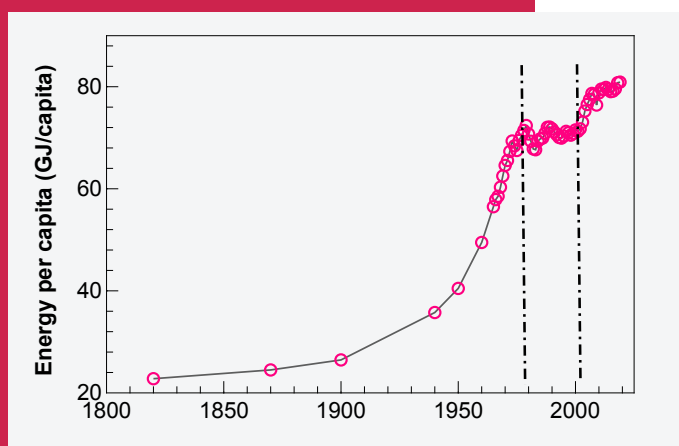
A closer look at the evolution per capita shows interesting trends. After a phase of exponential growth, the energy per capita (fig. 4) entered a period of very low growth until around 2000 when it picked up again. Comparing the evolution of the energy demand per capita with that of the GDP per person (fig. 4) shows that after a phase where both quantities evolved at the same rate, the GDP per capita now increases much faster than the energy use per capita which is rather stable.

Decomposing the GDP evolution using an identity, one can write:

$$\frac{GDP}{POP} = \frac{GDP}{NRJ} \times \frac{NRJ}{POP}$$

with POP the population and NRJ the primary energy demand.

Since the energy use per capita is evolving quite slowly, the increase in the GDP per capita is mainly driven by a strong increase in the energy efficiency of the economy (the inverse of the energy intensity). To put some numbers on this, in the period 2010-2019 (2020 is not representative because of the crisis caused by the Covid pandemic), the term  $NRJ/POP$  has increased by hardly 3 percent,  $GDP/NRJ$  by 20 percent giving an increase of the GDP/capita of about 25 percent. In addition, the global population has increased by 10 percent, and the total GDP by close to 35 percent during that 10-year period (which followed the 2008 financial crisis).



**Figure 4:** Evolution of the global primary energy demand per capita in the period 1825-2019 (top). World average energy demand per capita versus GDP per capita for the same period (bottom). Data from BP Statistical Review<sup>8</sup>.

## A detailed look at the national level

In terms of economy and energy transition, two types of countries can be defined, depending on when their industrialization started. Vaclav Smil<sup>34</sup> classifies them as:

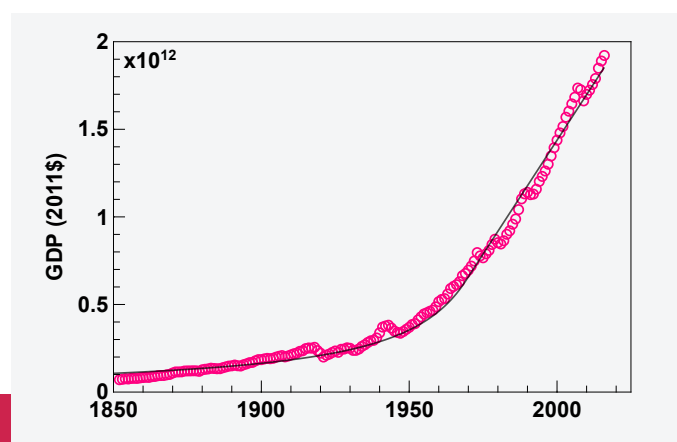
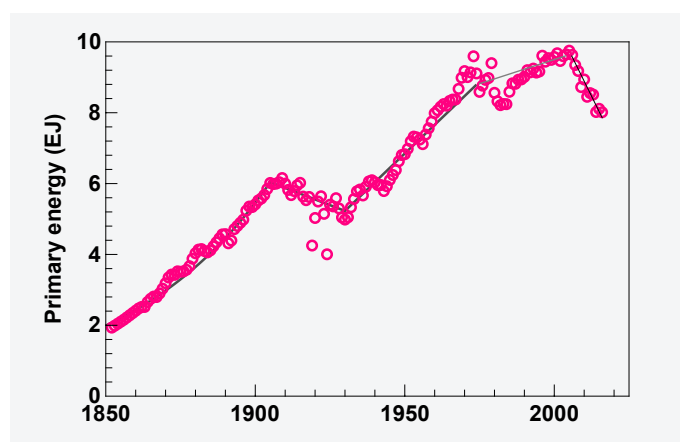
- The 'early innovators', Western Europe and North America, which completed their path towards a high average per capita energy use during the nineteenth century. The UK primary energy use per capita was only 8 percent higher in 2000 than in 1900.
- The 'late innovators' whose dependence on non-fossil (traditional biomass) energies lasted until the end of the 20th century.

In the following, the trends for the evolution of the primary energy demand and GDP growth for different countries will be analysed.

## United Kingdom

Britain was the first country to achieve the energy transition from biomass to coal, and a forerunner in the adoption of oil. It is therefore an interesting historical case offering long-term data series. Figure 5 shows the evolution of both the primary energy demand and the GDP (2011 \$ value) in the period 1850-2019. The evolution of the PE demand exhibits a complex pattern. During the 19th century, primary energy consumption has experienced an exponential growth. The coal production increased from 10 million tons in 1800 to 250 million in 1900, reaching almost 290 million tons at its peak just before World War I<sup>36</sup>. Coal supplied about 98 percent of all thermal energy in Britain in 1900, a share which was still about 76 percent in 1960<sup>34</sup>.

The peak of British coal production in 1913 can be clearly seen on fig. 5, as well as the two massive strikes of 1921 and 1926 in coal mines. During the period 1913-1926, despite the decrease in PE consumption, the country did not experience a recession of equivalent duration. When looking at the energy intensity of the UK economy (fig. 6), the limit in coal supply coincided with a turning point. Until 1913 the energy intensity was increasing,



**Figure 5:** Evolution of the primary energy demand (left) and GDP (right) for the United Kingdom. Data from Center for Energy and Economics, Harvard University<sup>35</sup>.



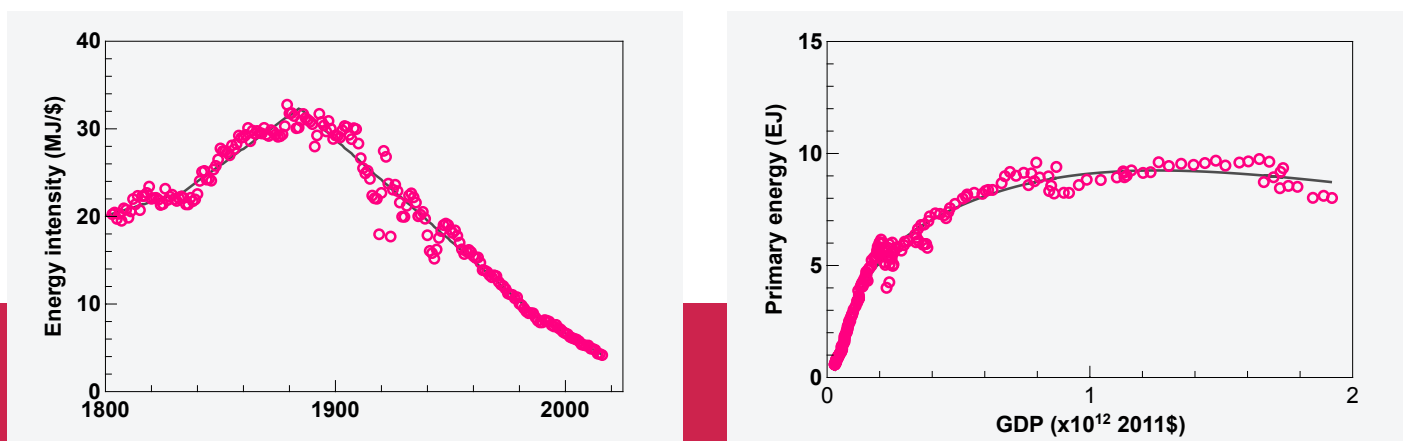
**A detailed decomposition of the energy footprint of the UK shows that most, but not all, of the decrease in energy consumption was due to offshoring. An indirect confirmation can be found in the carbon footprint analysis which accounts for territorial and imported greenhouse gases emissions.**

with more energy needed to generate one unit of GDP. This effect has been observed in most countries and is attributed to the strong increase in energy consumption associated with the industrialization and large-scale deployment of energy-intensive activities<sup>37</sup>. Once the sector service develops, the energy intensity goes down.

The primary energy demand has decreased since 2000 by about 16 percent (as of 2019),

while the GDP has increased by 12 percent. During that period the share of manufacturing in the UK GDP has declined from 15 to 12 percent. At first sight one might wonder if this drop in energy demand is linked with de-industrialisation, which implies an increase in the quantity of goods manufactured abroad and imported. Answering this question requires to account for the energy embodied in traded goods between countries. Several studies have attempted this. They are based on some simplifying assumptions as it is not possible to describe the content of all traded goods. In the case of the UK, in 2010, the net energy embodied in importations was estimated about 10 percent of the total primary energy use<sup>38</sup>. But even when accounting for this, the total energy demand was found to decrease by 3-5 percent over the period 2000-2010. This is in accordance with the Total Energy Footprint Analysis by Lan et al.<sup>39</sup>.

Finally, Hardt et al. performed a detailed decomposition of the energy footprint of the UK and found that most, but not all, of the decrease in energy consumption was due to offshoring<sup>40</sup> - confirming a slight reduction in the period 1997-2013. An indirect confirmation can be found in the carbon footprint analysis which accounts for territorial and imported greenhouse gases emissions.



**Fig. 6:** Left: Evolution of the energy intensity of the UK economy. Right: Evolution of the energy demand versus the UK GDP. Data from Center for Energy and Economics, Harvard University<sup>35</sup>.

Given that importations usually come from countries with a much higher carbon intensity of the energy, the observed decrease in the UK carbon footprint tends to correlate with the observed decreased total energy use.

Looking at the correlation between primary energy use and GDP (fig. 6), one can see that the GDP increases while the energy demand slightly decreases or at least remains flat. While this is different from what is referred to as energy-GDP absolute decoupling, whereby the GDP increases at the same rate as the energy demand decreases<sup>41</sup>, it indicates that in the UK the energy demand per capita is hardly changing while the GDP continues to grow.

In this report we do not discuss in detail why energy or material resource use have reached a maximum and are decreasing. In 2011, Chris Goodall, from a detailed analysis of the consumption of material goods in the UK, introduced the notion that the UK might have passed its 'peak stuff'<sup>42</sup>.

We will now look at different advanced economies to see whether this trend is specific to the UK or not.

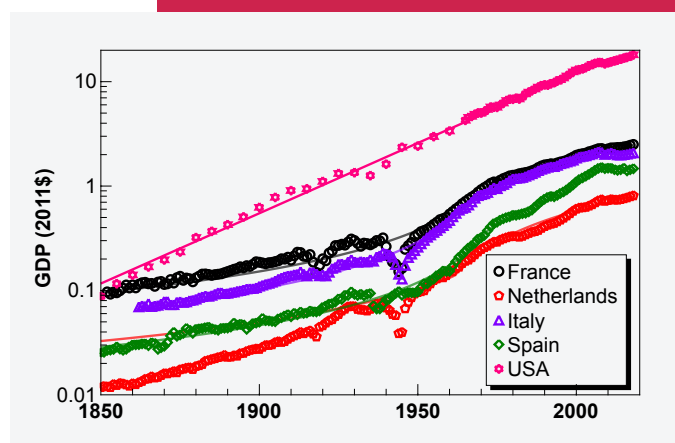
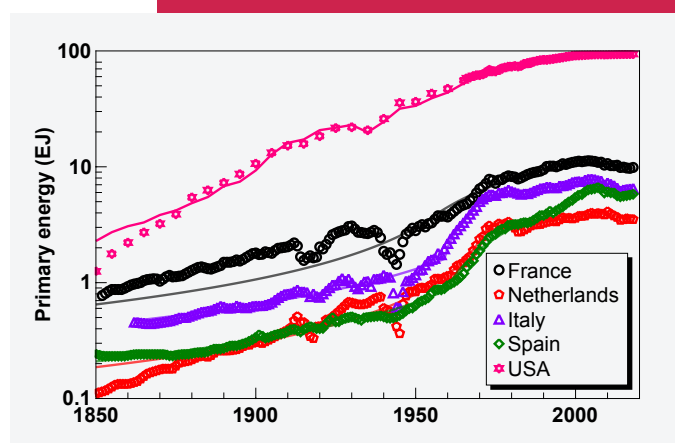
## Other developed countries

Figure 7 shows the evolution of the GDP and PE demand for five western countries: the US, France, Italy, Spain and the Netherlands. Those countries are selected because they show representative features regarding their evolution.

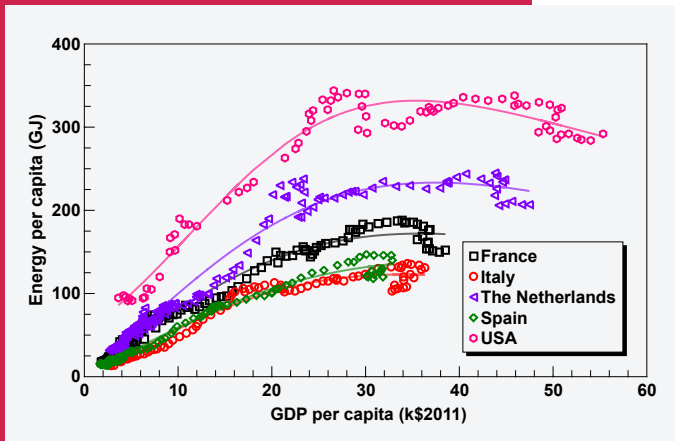
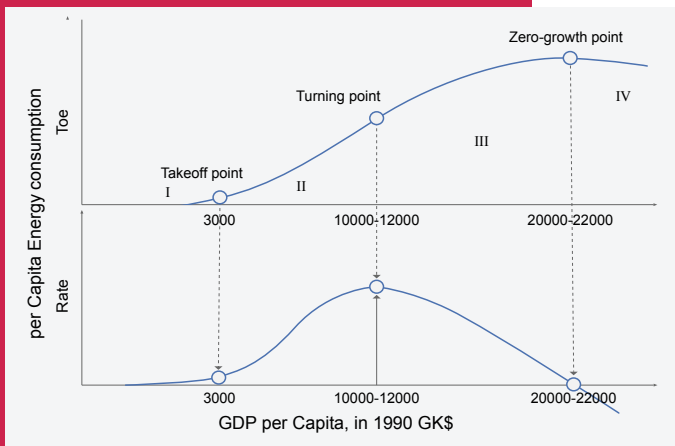
The effects of the two world wars, the Great Depression in the 1930s, and the oil shocks (1973 and 1979) on the evolution of energy demand are visible. Their impact on GDP is less clear: while in most cases the effects

of the oil shocks are hard to distinguish, the effect of the 2008 financial crisis is however very apparent for countries like Spain and Italy where a strong departure from the overall trend is observed. For both countries, the 2019 GDP had hardly recovered its pre-shock level.

If one looks at the energy demand, the variations caused by those different events are much higher in relative value than the effects on GDP. If we look at the case of France, the GDP fell by about 3 percent due to the subprime crisis but recovered to its pre-crisis level within three years. In parallel the primary energy demand fell by about 6 percent and never recovered. Interestingly,



**Figure 7:** Evolution of the primary energy demand (top) and of the GDP (bottom) for a range of advanced economies.



**Figure 8:** Top: S-curve model proposed by Wang et al.<sup>43</sup> to describe the relationship between energy demand and economic development. Bottom: Evolution of the energy demand per capita as a function of the GDP per capita for a range of advanced economies. The fits are made according to the model by Wang et al.<sup>44</sup>. Data from Center for Energy and Economics, Harvard University<sup>35</sup> and BP Statistical Review<sup>8</sup>.

transition around the two oil shocks from an exponential increase of their energy demand to a linear increase – each with a different slope. Looking at the evolution of the energy per capita as a function of the GDP per capita (fig. 8, bottom), the obtained curves (as was the case for the UK) have the appearance of S-curves, which are used to describe a wide range of phenomena in nature<sup>43</sup>.

Wang et al.<sup>44</sup> have proposed a 4-phase description of the S-shaped GDP-PE curves (fig. 8, top). The first phase (I), before the take-off point, corresponds to economies with low energy intensities usually dominated by agriculture. It is then followed by a phase (II) of rapid growth in both energy consumption and GDP, corresponding to the transition from an agriculture-based to an industrial economy. It is usually accompanied with strong increases in the per capita consumption of steel and cement<sup>45</sup> which are fundamental materials for the development of large scale infrastructures<sup>46</sup>. This continues until the turning point when the energy consumption rate per capita for a given GDP per capita starts to decrease. This transition happens at a different level of energy consumption depending on the country, although Wang’s study shows that it typically happens for a GDP of \$10-20,000 per capita.

all countries saw decreasing trends in their primary energy demands. While some countries recovered economic growth, Italy and Spain still have not fully recovered their economic output. This illustrates that at national levels, the GDP-energy relationship can be quite different.

It is striking that the evolution of the energy demand curves for those countries are quite similar, oscillations due to shocks aside, with a decrease of the energy demand since 2007-2008. All five countries also show a

**Most developed countries reach a point where their energy demand either plateaus or even decreases, having the appearance of an S-curve – a curve used to describe a wide range of phenomena in nature.**

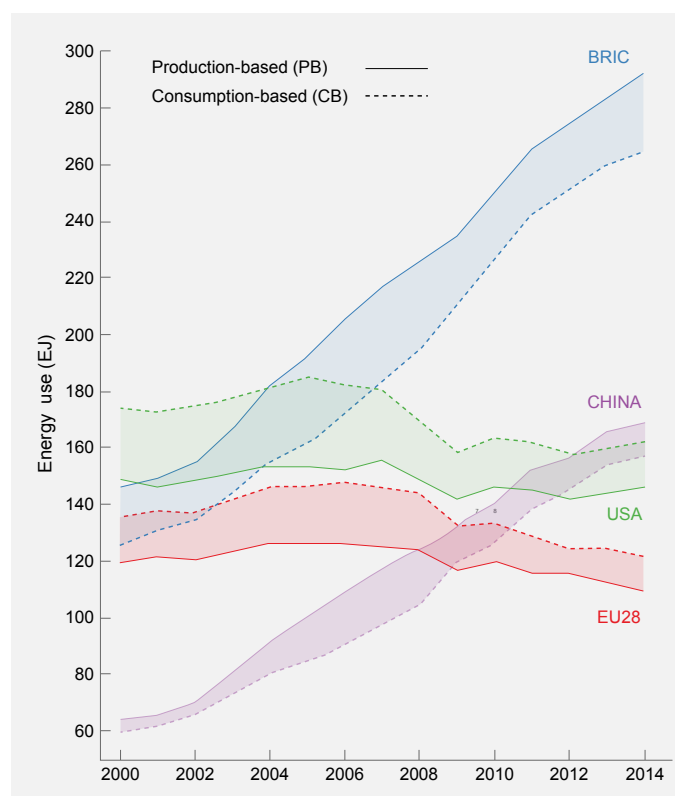
This third phase marks an improvement in the energy efficiency and energy intensity of the economies. The zero-point marks the transition to phase (IV) after which the energy consumption starts to decrease as economies move to a post-industrial phase.

As shown in fig. 8 bottom, many developed countries have entered the phase IV in the 2000s, and so far their energy demand has not picked up again. A more recent analysis<sup>47</sup> for the period 1971-2014 finds similar conclusions as Wang et al. As for the case of the UK, one could wonder whether this is due to the offshoring of manufacturing and if the effect of the embodied energy in imported goods is properly accounted for.

Detailed studies of the energy embodied in trade exist in the literature although there is no agreed single method on how to estimate it. Regrettably, those data are also often neither standardized, nor published on an annual basis. For France, a detailed study for the year 2004<sup>48</sup> shows that the energy embodied in imports is about 40 percent of the national energy demand, while exports count for about 24 percent, so that the energy footprint is about 18 percent higher than the energy demand - quite similar to the case of the UK. Kulionis has developed an analysis of energy embodied in trade with a description similar to that used for carbon footprint analysis, distinguishing production and consumption-based energy demand<sup>49</sup>. For the period 1995-2011, he finds that most developed countries have seen an energy demand (both for production and consumption) increase at a much slower rate than GDP. Four countries (France, US, UK, Denmark) had a decreasing energy demand while their GDP increased - a case of relative decoupling, also both for production and consumption. Interestingly, for most countries, the share of imported goods in the energy demand has increased since 2000. For the countries exhibiting a decrease of their energy demand, it can be

explained by efficiency improvements both in the domestic manufacturing and service industries, but also by rapid improvements in the energy intensity in exporting countries<sup>49</sup>.

Fig. 9 shows the evolution of the energy use (consumption and production) for a group of countries/regions. One can see that the energy use is stable in the US and even declining in the EU over the period 2000-2014<sup>50</sup>. Developed countries have production-based uses lower than their consumption-based use. The contrary applies to emerging countries such as the BRICs. Looking in more details at individual countries<sup>50</sup>, the stabilisation or decrease of the total energy demand is a common pattern across developed countries - although as mentioned above,



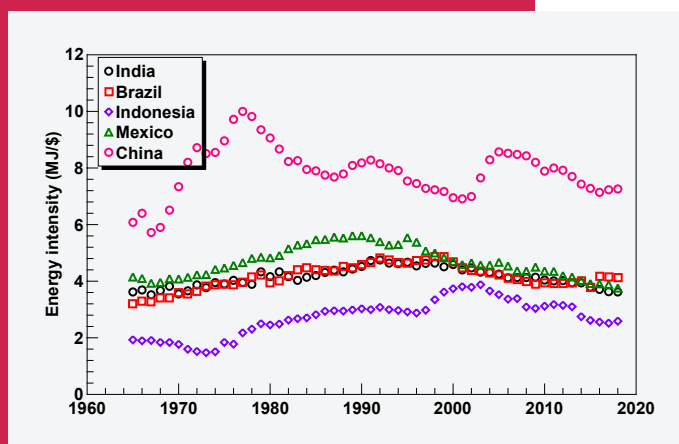
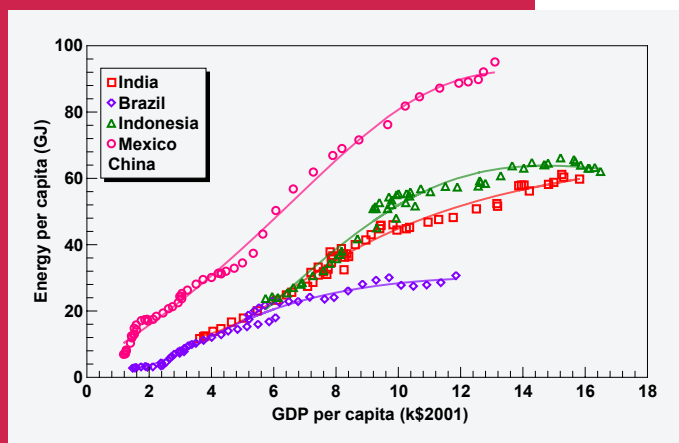
**Figure 9:** Production-based and consumption-based energy use for selected countries/regions for the 2000-2014 period. Dotted lines show the consumption-based while the full lines show the production-based values. Reprinted from Kulionis<sup>50</sup>.

they experienced various levels of economic output.

An independent evaluation of the hidden energy flows embedded in trade based on 44 countries found that the ten most developed countries used in average 18.5 percent more energy than measured through the domestic primary energy demand<sup>51</sup>. As observed by Lan et al.<sup>39</sup>, the relative importance of imports

in the energy demand increases with the level of GDP per capita. A detailed analysis of the energy embodied in the trade of China has been conducted by Zhang et al.<sup>52</sup>. The analysis was made both by industry and by trade partner. While the monetary value of Chinese exports was multiplied by more than two between 2006 and 2014, the embodied energy remained almost constant. This translates into a significant improvement of the energy intensity of goods imported from China, by about 2.3 over fourteen years. Similarly, looking at the US, Japan, and the EU, the embodied traded energy also remained constant for these countries. Since China is a major trade partner for most developed economies, this is an indirect confirmation of the results from Kulionis<sup>50</sup>. It is interesting to note that the traded embodied energy rose strongly over the period 1991-2006 and stabilized afterwards, in line with the energy demand of developed countries<sup>52,53</sup>.

As for the case of the UK, the plateauing energy demand for developed economies is confirmed when looking at the energy footprint and traded goods. While the 2006-2008 crisis has accelerated the trend, most countries were already on a stabilizing path before it. In addition, it is a clear confirmation that the GDP-energy relationship breaks down for developed economies. Such trends can be studied only if the energy embodied in trade is considered, as this represents a significant channel for energy use, especially in developed countries. As a result, the interesting feature is that most countries follow a S-curve for the GDP per capita versus energy per capita relationship. The ultimate energy per capita level depends on the country: the US and Canada have much higher demand levels than European countries of Japan. This can probably be explained by the geography of the countries (more widespread for North America with relatively low population density), the level of infrastructure, standards of living, cultural



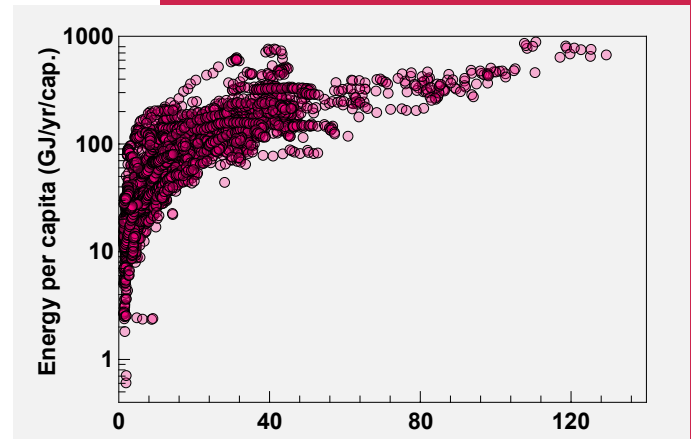
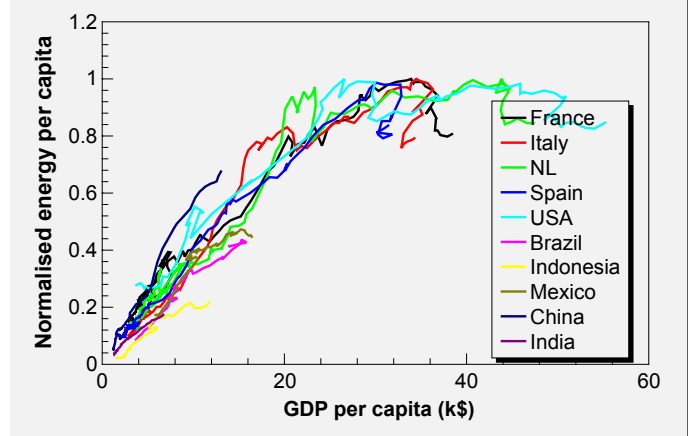
**Figure 10:** Top: Evolution of the energy-GDP relationship for a range of emerging countries. Bottom: Evolution of the energy intensity of their economies.

aspects, and the fact that both the US and Canada are oil producers. However, for the current analysis, the important point is the S-shape evolution and the fact that developed economies seem to reach an asymptote in terms of energy demand.

## The case of emerging countries

Fig. 10 shows the per capita GDP-energy curves for China, India, Brazil, Indonesia, and Mexico. Those countries too show an evolution which resembles the S-curve described above. Their GDP per capita is still much lower than that of advanced economies and since economic development does not proceed through a smooth and continuous evolution, one cannot conclude about the stage those economies are in and whether they have already passed the turning point between stage II and III. In addition, as is evident from fig. 8 (bottom), the actual path through the S-curve is not smooth and their economies could go through a succession of individual S-curves which overall give that

**The energy use in developing countries will strongly increase with the building up of infrastructure since there is a strong relationship between the material footprint (and hence energy) and economic development.**



**Figure 11:** Top: Evolution of the energy demand per capita normalized by its historical maximum for the developed economies, and by the average energy per capita of the EU (140GJ/yr/cap.) for emerging economies, as a function of the GDP per capita. Bottom: Energy per capita as a function of GDP per capita for all countries in the world during the period 1990-2015. Each dot represents the data for one country and for one given year. Source: OurWorldinData<sup>54</sup>.

observed pattern. Looking at the energy intensity of their economy, one sees that most countries have only recently (between 1990 and 2000) transitioned to a phase of continued decrease and much more progress is still possible. The evolution of the energy intensity in China is somehow more difficult to interpret as it seems to go through phases of improvement and decrease.

To further study the possible similarities in the energy-economy development paths of different countries, one can look at relative



## Key Highlights

Most developed countries reach a point where their energy demand either plateaus or even decreases.

As the energy demand of most countries seems to follow a S-curve with an asymptote, applying a logistic function to the historical global energy data allows us to estimate what the energy demand might be if all countries were proceeding along the same path.

Our analysis indicates a possible asymptote for the world energy demand, which implies that the energy demand of humanity might not grow indefinitely.

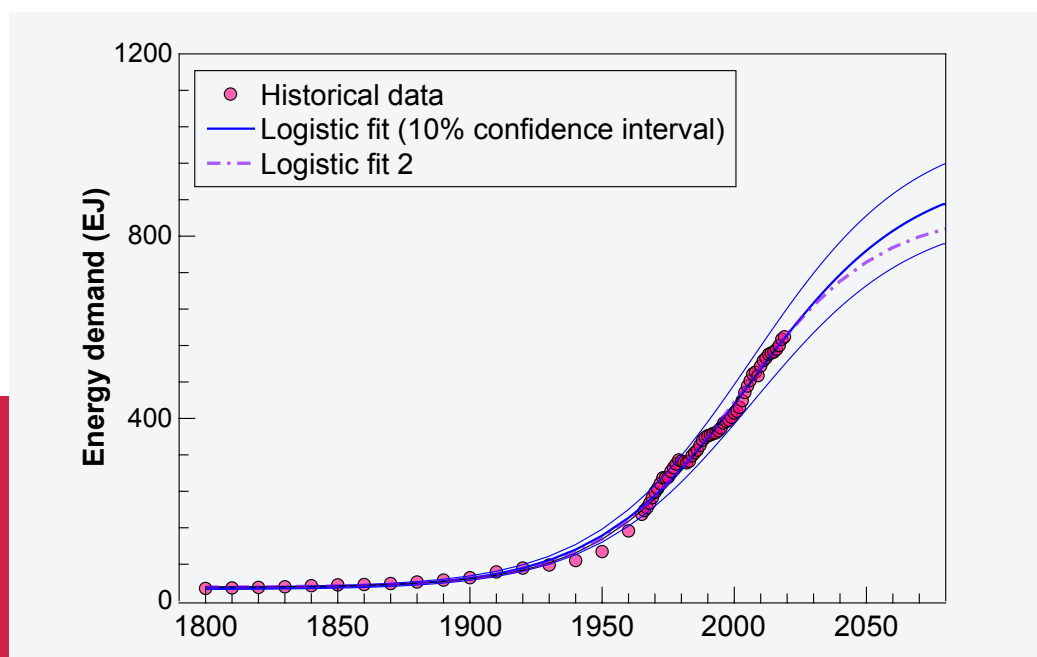
This provides a much more realistic framework than the assumption of a continuous exponential increase, and gives a good scheme to size the energy system that would ensure a good development for humanity. If correct, it also implies that energy might not be a limit for economic growth in the near future.



variations of the energy per capita. For the advanced economies, since their energy per capita has either plateaued or entered a degrowth phase, one can normalize the data shown in fig. 8 (bottom) by their historical maximum. Plotting this normalized energy per capita as a function of GDP per capita gives the curves shown in fig. 11. Since these emerging countries have not yet reached their peak energy demand, the same normalization cannot be applied directly. Extrapolating from fig. 10 would not give a clear picture since development does not proceed through a smooth curve as illustrated by fig. 8 (bottom). Instead, one can assume a target energy consumption, such as the EU average of 140 GJ/cap/yr, which is similar to that of Japan but below the high values in North America. When normalizing by this value, one obtains the curves shown in fig. 12.

The five emerging countries considered here, which are at quite different levels of GDP per capita, show trends which fit well with that of advanced economy. This is consistent with the observations made when looking at the annual statistics of energy and GDP per capita for all countries in the world, during the period 1990-2015 (fig. 11, bottom). One can see that there is a strong increase of the energy demand for GDP up to \$30,000/capita and a tendency for saturation above that value<sup>54</sup>. One unresolved question is whether this turning point will be lower in the future (i.e. for emerging and developing countries), thanks to spreading of cheaper, more efficient technologies for energy intensive activities such as transportation, housing and manufacturing.

The important point is to observe that most countries appear to follow a relatively similar pattern in terms of their energy-economy evolution, which appears to be well-described by a classical S-curve. Developing countries, many of which are in Africa, are further behind in terms of energy and GDP per capita.



**Figure 12:** Logistic fit of the global energy demand over the period 1800-2019 and extrapolation up to 2080, with a 10 percent confidence interval.

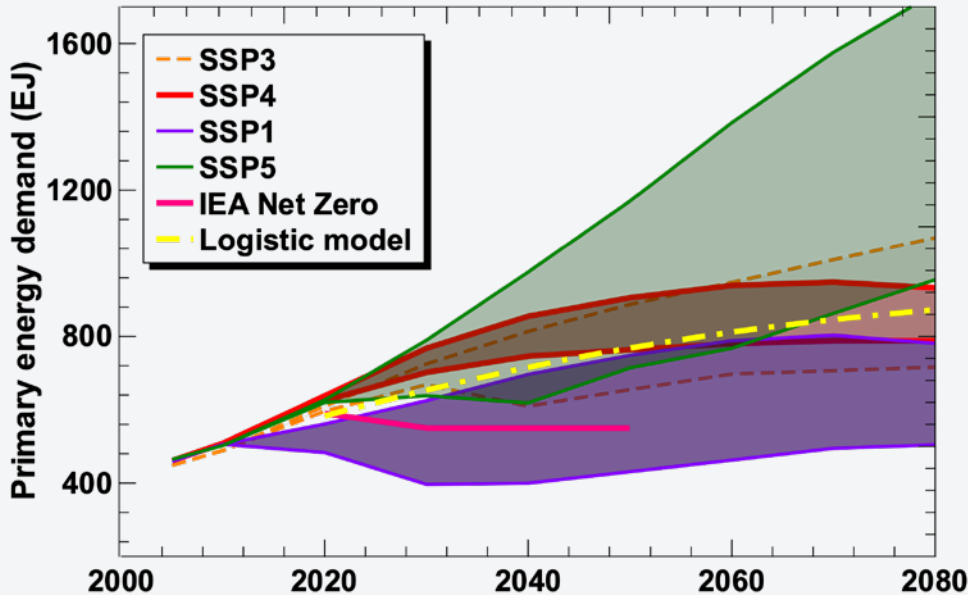
As mentioned above, the average energy use in Africa is 14 GJ/cap/yr, while the average GDP for sub-Saharan Africa is hardly \$1,500 per person. It is therefore difficult to make any projection regarding the much-needed evolution these economies will follow. The concept of leapfrogging is often referred as a way for developing countries to develop without having to go through the same stages discussed above. This is made possible by the availability of technologies (in the area of energy for example) that were not available to advanced economies at a similar stage<sup>55</sup>. A typical example is the phone network which can now be directly mobile and does not require the development of the landline infrastructure<sup>56</sup>.

It is clear, however, that the energy use in developing countries will strongly increase with the building up of infrastructure. There is a strong relationship between the material footprint (and hence energy) and economic development<sup>57,58</sup>. The increasing population

also implies an increasing energy use, although the fertility rate usually decreases strongly with the level of development<sup>59</sup>.

**As the energy demand of most countries seems to follow a S-curve with an asymptote, applying a logistic function to the historical global energy data allows us to estimate what the energy demand might be if all countries were proceeding along the same path.**





**Figure 13:** Evolution of the primary energy demand (in EJ) foreseen by a range of published energy scenarios, namely the SSP scenarios used by IPCC and the IEA Net-Zero by 2050 scenario.

## A possible scenario for the evolution of the world energy demand

How would the world energy demand look like if it was to follow a S-curve? Fig. 13 shows a logistic fit of the total primary energy demand up to 2080. The fit is performed through the period 1850-2019, the trend is then continued. Two different functions are used to illustrate the sensitivity to the assumed function\*. It is interesting to note that the fit finds 2007 as the middle point of the S-curve. With a 10 percent confidence interval, the fit gives an energy demand converging towards 780-950 EJ in 2080. This is 35-65 percent higher than the 2019 energy demand and corresponds to 78-95 GJ/cap/yr for a world population of 10 billion people and 97-120 GJ/cap/yr for a population of 8 billion people. With a global average of 71GJ/cap/yr for 2020 this is in every case a significant increase of the average energy consumption.

This is obviously not a prediction and different models could be used to fit the data. As Smil

extensively discusses in his book *Growth*, while many growth phenomena are described by logistic functions, projections are very difficult unless the inflexion point has been well passed. This only gives an illustration of a possible trend. If one assumes a world average of 140 GJ/cap/yr and a population of 8-10 billion people, the total energy demand would be 1120-1400 EJ.

Fig. 13 shows an overview of different energy scenarios found in the literature, with the median values determined here. Most scenarios foresee a moderate increase in the energy demand with most values for 2050 falling in the range 600-800 EJ. The logistic extrapolation gives 770 EJ for 2050, falling in the same ballpark. In most scenarios the increase in the energy demand is mainly borne out by emerging and developing countries. The SSP scenarios used by the IPCC give a range between 500 and 1600 EJ for 2100<sup>29,30</sup>. They are based on very different assumptions regarding economic growth since the 2100 GDP varies by a factor three between the most conservative and the most optimistic

\* Function 1 has the form:  $A_2 = \frac{A_1 - A_2}{1 + (\frac{t-t_0}{\tau})^p}$  and function 2 has the form:  $A_2 = \frac{A_1 - A_2}{1 + e^{-\frac{t-t_0}{\tau}}}$

## Applying a S-curve to the historical global energy data allows us to extrapolate that the energy demand might be around 780-950 EJ in 2080, consistently with most existing scenarios.

scenario. Recently, the International Energy Agency published its 'Net Zero by 2050' scenario<sup>60</sup>.

It foresees that the total energy supply in 2050 (550 EJ) will be 7 percent lower than in 2020 despite significant increase in the global population and economic growth. This assumes strong improvements in the energy intensity of the GDP (twice higher than during the 2010-2020 period), gains in efficiency and behavioral changes. Since developing countries will see a strong increase in their energy demand, this implies a significant decrease in the energy demand in developed countries.

And indeed, a recent report from the JRC reviewing a range of scenarios compatible with the EU ambitions to reach carbon neutrality by 2050 found that the energy demand has to decrease in all scenarios by 20-45 percent. Note that since it is associated with continuous economic growth, it implies a much stronger decoupling than what has been historically observed. As pointed out by a recent study<sup>61</sup>, most decarbonization scenarios do not specify clearly how they intend to reach absolute decoupling and/or how they will strongly accelerate historical trends. One powerful lever is the increase

of the primary to final energy conversion, through electrification of transportation and heating for example<sup>62,63</sup>. While there is significant room for improvement there are also practical limits on what is possible<sup>27</sup>.

In addition, rebound effects tend to limit the gains expected from energy efficiency improvements. The term 'rebound effect' refers to a variety of behavioral and economic responses to improved energy efficiency, whose net result is to reduce energy savings relative to a counterfactual scenario in which those responses do not occur<sup>64</sup>. A recent literature review<sup>64</sup> noted that this effect decreased the expected gains by 71 percent in average. While the precise rebound effect estimated varies with the method and the context, the evidence suggests that economy-wide rebound effects could erode more than half of the expected energy gains.

As mentioned above, primary energy demand is strongly linked with the HDI. An HDI above 0.8 is defined by the United Nations Development Programme's as a high human development<sup>65</sup>. A statistical analysis of 40 countries indicates that this threshold is reached for a primary energy demand of 124 GJ/cap/yr and for a primary energy footprint of 140 GJ/cap/yr<sup>66</sup>, slightly above the values derived above. Those thresholds bear large uncertainties since there is large scatter in the data, with some countries having an HDI higher than 0.8 for an energy demand of 80 GJ/capita/year, the lowest value derived from the logistic fit. Also, many countries see a relative (in some cases even absolute) decoupling between HDI and energy footprint<sup>67</sup>. This is the case for countries such as France, Hungary, Japan, the UK, Italy and Spain, and that decoupling started between 2003 and 2006, hence before the financial crisis.



# DISCUSSION & CONCLUSION

The correlation between energy demand and economic output is driving many discussions about future energy demand and the possibility for continuous economic growth. As such, a continuous economic growth would imply an ever-increasing energy demand, demand which would eventually be constrained by our ability to tap into energy sources available on Earth - with the incoming solar energy as the ultimate limit.

In this study, we have shown that most developed countries do not actually follow an ever-increasing energy demand; along the path they reach a point where the energy demand either plateaus or even decreases. This analysis considers the energy embodied in international trade, which is a significant part of the energy footprint of developed countries - only with such an indicator can policymakers really judge the relevance of their energy policy. The decrease in the national energy footprint in most developed countries is caused by a variety of factors including improvements in energy efficiency both domestically but also in the countries from which imports come.

At the same time, many developed countries have experienced economic growth while their energy demand was constant or decreasing.



Since the energy demand of most countries seems to follow a S-curve which tends to an asymptote, it seems reasonable to assume that the global energy demand might follow a similar pattern. This indicates a possible asymptote, which implies that it will not grow indefinitely. This provides a much more realistic framework than the assumption of a

continuous exponential increase and gives a good framework to size the energy system that would ensure a good development for humanity. If correct, it also implies that energy might not be a limit for economic growth in the near future.

## References

1. Smil, V. *Energies: An Illustrated Guide to the Biosphere and Civilization*. (2000).
2. Rhodes, R. *Energy: a human history*. in (ed. Schuster, S. and) (2018).
3. Malanima, P. *Energy Consumption in the Roman World*. in *The Ancient Mediterranean Environment between Science and History* 13–36 (BRILL, 2013). doi:10.1163/9789004254053\_003
4. Smil, V. *Why America Is Not a New Rome*. (2010).
5. Morris, I. *The measure of civilization [electronic resource] : how social development decides the fate of nations / Ian Morris*. (Princeton University Press, 2013).
6. Syvitski, J. et al. *Extraordinary human energy consumption and resultant geological impacts beginning around 1950 CE initiated the proposed Anthropocene Epoch*. *Commun. Earth Environ.* 1, 1–13 (2020).
7. Smil, V. *A new world of energy*. in *The Cambridge World History: Volume 7: Production, Destruction and Connection, 1750–Present* (eds. McNeill, J. R. & Pomeranz, K.) 7, 164–184 (Cambridge University Press, 2015).
8. BP. *Statistical Review of World Energy*. (2020).
9. BP. *Statistical review of world energy*. (2021).
10. Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O. & Ludwig, C. *The trajectory of the Anthropocene: The Great Acceleration*. *Anthr. Rev.* 2, 81–98 (2015).
11. Steffen, W. et al. *The anthropocene: from global change to planetary stewardship*. *Ambio* 40, 739–761 (2011).
12. UN Development Programme. *Human Development Reports. IFPRI Discussion Paper 1554* Available at: <http://hdr.undp.org/en/content/human-development-index-hdi>.
13. Steinberger, J. K. & Roberts, J. T. *From constraint to sufficiency: The decoupling of energy and carbon from human needs, 1975-2005*. *Ecol. Econ.* 70, 425–433 (2010).
14. Ouedraogo, N. S. *Energy consumption and human development: Evidence from a panel cointegration and error correction model*. *Energy* 63, 28–41 (2013).
15. Akizu-Gardoki, O. et al. *Discovery of a possible Well-being Turning Point within energy footprint accounts which may support the degrowth theory*. *Energy Sustain. Dev.* 59, 22–32 (2020).
16. Cumming, G. S. & von Cramon-Taubadel, S. *Linking economic growth pathways and environmental sustainability by understanding development as alternate social–ecological regimes*. *Proc. Natl. Acad. Sci.* 115, 9533 LP – 9538 (2018).
17. Rockström, J. et al. *A safe operating space for humanity*. *Nature* 461, 472–475 (2009).
18. Steffen, W. et al. *Planetary boundaries: Guiding human development on a changing planet*. *Science* (80-. ). 347, 1259855 (2015).
19. Laborde Debutquet and David; Martin, W. *Implications of slowing growth in emerging market economies for hunger and poverty in rural areas of developing countries*. (2016).
20. Ayres, R. & Voudouris, V. *The economic growth enigma: Capital, labour and useful energy?* *Energy Policy* 64, 16–28 (2014).
21. Giraud, G. & Kahraman, Z. *How Dependent is Growth from Primary Energy? The Dependency ratio of Energy in 33 Countries (1970-2011)*. (2014).
22. Stern, D. I. *The Role of Energy in Economic Growth*. *SSRN Electron. J.* (2010). doi:10.2139/ssrn.1715855
23. Kalimeris, P., Richardson, C. & Bithas, K. *A meta-analysis investigation of the direction of the energy-GDP causal relationship: implications for the growth-degrowth dialogue*. *J. Clean. Prod.* 67, 1–13 (2014).



24. Soytas, U. & Sari, R. Energy consumption and GDP: causality relationship in G-7 countries and emerging markets. *Energy Econ.* 25, 33–37 (2003).
25. Chontanawat, J., Hunt, L. C. & Pierse, R. Does energy consumption cause economic growth?: Evidence from a systematic study of over 100 countries. *J. Policy Model.* 30, 209–220 (2008).
26. Narayan, P. K. & Popp, S. The energy consumption-real GDP nexus revisited: Empirical evidence from 93 countries. *Econ. Model.* 29, 303–308 (2012).
27. Grubler, A. et al. Chapter 1 - Energy Primer. in *Global Energy Assessment - Toward a Sustainable Future* 99–150 (2012).
28. Guillemette, Y. & Turner, D. *The Long View: Scenarios for the World Economy to 2060.* (2018). doi:<https://doi.org/10.1787/b4f4e03e-en>
29. Riahi, K. et al. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Glob. Environ. Chang.* 42, 153–168 (2017).
30. Bauer, N. et al. Shared Socio-Economic Pathways of the Energy Sector – Quantifying the Narratives. *Glob. Environ. Chang.* 42, 316–330 (2017).
31. Bolt, J., Inklaar, R., de Jong, H. & van Zanden, J. L. Maddison Project Database. (2018).
32. Herrendorf, B., Rogerson, R. & Valentinyi, Á. Chapter 6 - Growth and Structural Transformation. in *Handbook of Economic Growth* (eds. Aghion, P. & Durlauf, S. N. B. T.-H. of E. G.) 2, 855–941 (Elsevier, 2014).
33. King, C. W. Systems Thinking for Energy and the Economy: Size and Structure BT - The Economic Superorganism: Beyond the Competing Narratives on Energy, Growth, and Policy. in (ed. King, C. W.) 197–247 (Springer International Publishing, 2021). doi:10.1007/978-3-030-50295-9\_5
34. Smil, V. *Energy Transitions: Global and National Perspectives* (Second expanded and updated edition). (Praeger, 2016).
35. Center for History and Economics. *Energy history.* (2021).
36. Ritchie, H. The death of UK coal in five charts. (2019).
37. *Global Energy Assessment: towards a sustainable future.* (2012).
38. Tang, X., Snowden, S. & Höök, M. Analysis of energy embodied in the international trade of UK. *Energy Policy* 57, 418–428 (2013).
39. Lan, J., Malik, A., Lenzen, M., McBain, D. & Kanemoto, K. A structural decomposition analysis of global energy footprints. *Appl. Energy* 163, 436–451 (2016).
40. Hardt, L. et al. Untangling the drivers of energy reduction in the UK productive sectors: Efficiency or offshoring? *Appl. Energy* 223, 124–133 (2018).
41. Haberl, H. et al. A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part II: synthesizing the insights. *Environ. Res. Lett.* 15, 065003 (2020).
42. Goodall, C. Peak stuff: Did the UK reach a maximum use of material resources in the early part of the last decade? (2011).
43. Bejan, A. & Lorente, S. The constructal law origin of the logistics S curve. *J. Appl. Phys.* 110, 024901 (2011).
44. Wang, A. et al. S-curve Model of Relationship Between Energy Consumption and Economic Development. *Nat. Resour. Res.* 24, 53–64 (2015).
45. Bleischwitz, R., Nechifor, V., Winning, M., Huang, B. & Geng, Y. Extrapolation or saturation – Revisiting growth patterns, development stages and decoupling. *Glob. Environ. Chang.* 48, 86–96 (2018).
46. Elhacham, E., Ben-Uri, L., Grozovski, J., Bar-On, Y. M. & Milo, R. Global human-made mass exceeds all living biomass. *Nature* 588, 442–444 (2020).
47. Guo, J., Li, C.-Z. & Wei, C. Decoupling economic and energy growth: aspiration or reality? *Environ. Res. Lett.* 16, 044017 (2021).
48. Pourouchottamin, P. L'emprise énergétique, une façon nouvelle de regarder la consommation d'énergie. (2012).
49. Kulionis, V. & Wood, R. Explaining decoupling in high income countries: A structural decomposition analysis of the change in energy footprint from 1970 to 2009. *Energy* 194, 116909 (2020).
50. Kulionis, V. *Energy Embodied in Trade, 1970–2014.* (Lund University, 2019).
51. Akizu-Gardoki, O. et al. Hidden Energy Flow indicator to reflect the outsourced energy requirements of countries. *J. Clean. Prod.* 278, (2021).
52. Zhang, B., Bai, S. & Ning, Y. Embodied Energy in Export Flows Along Global Value Chain: A Case Study of China's Export Trade . *Frontiers in Energy Research* 9, 157 (2021).
53. Liu, H., Xi, Y., Guo, J. & Li, X. Energy embodied in the international trade of China: An energy input-output analysis. *Energy Policy* 38, 3957–3964 (2010).
54. Roser, M. & Ritchie, H. GDP per capita vs. Energy use, 2015. 2020 Available at: <https://ourworldindata.org/grapher/energy-use-per-capita-vs-gdp-per-capita>.
55. Goldemberg, J. Technological Leapfrogging in the Developing World. *Georg. J. Int. Aff.* 12, 135–141 (2011).
56. Cilliers, J. Technological Innovation and the Power of Leapfrogging BT - The Future of Africa : Challenges and Opportunities. in (ed. Cilliers, J.) 221–247 (Springer International Publishing, 2021). doi:10.1007/978-3-030-46590-2\_10
57. Cibulka, S. & Giljum, S. Towards a Comprehensive Framework of the Relationships

between Resource Footprints, Quality of Life, and Economic Development. *Sustainability* 12, 4734 (2020).

58. Gutowski, T., Cooper, D. & Sahni, S. Why we use more materials. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* 375, 20160368 (2017).

59. Vollset, S. E. et al. Fertility, mortality, migration, and population scenarios for 195 countries and territories from 2017 to 2100: a forecasting analysis for the Global Burden of Disease Study. *Lancet* 396, 1285–1306 (2020).

60. IEA. Net Zero by 2050. (2021).

61. Foley, D., Semieniuk, G., Taylor, L., Rezai, A. & Foley, D. Gregor Semieniuk Plausible energy demand patterns in a growing global economy with climate policy Working Paper Series.

62. Reyna, J. L. & Chester, M. V. Energy efficiency to reduce residential electricity and natural gas use under climate change. *Nat. Commun.* 8, 14916 (2017).

63. Cullen, J. M., Allwood, J. M. & Borgstein, E. H. Reducing Energy Demand: What Are the Practical Limits? *Environ. Sci. Technol.* 45, 1711–1718 (2011).

64. Brockway, P. E., Sorrell, S., Semieniuk, G., Heun, M. K. & Court, V. Energy efficiency and economy-wide rebound effects: A review of the evidence and its implications. *Renew. Sustain. Energy Rev.* 141, 110781 (2021).

65. Jonker, G. & Harmsen, J. Chapter 3 - Structuring the Sustainability Context. in (eds. Jonker, G. & Harmsen, J. B. T.-E. for S.) 35–60 (Elsevier, 2012). doi:<https://doi.org/10.1016/B978-0-444-53846-8.00003-2>

66. Arto, I., Capellán-Pérez, I., Lago, R., Bueno, G. & Bermejo, R. The energy requirements of a developed world. *Energy Sustain. Dev.* 33, 1–13 (2016).

67. Akizu-Gardoki, O. et al. Decoupling between human development and energy consumption within footprint accounts. *J. Clean. Prod.* 202, 1145–1157 (2018).

## Acknowledgments

The authors are thankful to Louis Fréget and Richard Robert for the discussions and help during the preparation of this report.

This study was funded by Zenon Research and supported by PSL University and Mines ParisTech PSL.

## Authors and contributors

### Greg De Temmerman

Zenon Research  
Mines ParisTech PSL, IHEIE  
[greg@zenonresearch.org](mailto:greg@zenonresearch.org)

### Léa Trin

Mines ParisTech PSL  
[lea.trin@mines-paristech.fr](mailto:lea.trin@mines-paristech.fr)

### Dimitri Chuard

Mines ParisTech PSL, IHEIE  
[dimitri.chuard@mines-paristech.fr](mailto:dimitri.chuard@mines-paristech.fr)

### Jean-Baptiste Rudelle

Zenon Research  
[jb@zenonresearch.org](mailto:jb@zenonresearch.org)





## About Zenon Research

**Zenon Research is a think tank whose mission is to highlight the key factors leading to changes in the long-term future.**

---

When it comes to the future, the best we can do is to define scenarios and study their respective likelihood. In a constrained world, it is essential to separate plausible scenarios from what will remain in the realm of science-fiction.

Our aim is to estimate hard limits and boundaries within which possible futures can happen. With this approach, we help decision-makers on vision and planning.

Zenon Research produces original works with a cross-disciplinary approach in the form of white papers, reports, and videos for the general public.

Our approach is pragmatic and combines science and economics, as we believe that both economic and technical aspects are key driving forces shaping the future.

**This note should be cited as:**

G. De Temmerman, L. Trin, D. Chuard and J.-B. Rudelle, 2021: Powering the world: how much energy will humanity need? Zenon Research, Paris, France.

