Energy and Climate: A Global Perspective

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Abstract Global warming and energy transition are two of the most important challenges humanity will ever meet. These are complex issues by themselves and by the interconnection they have with each other. The purpose of this chapter is to present an integrated picture of these problems, of their connections, and of a number of scientific and historical facts that should be known before elaborating scenarios for the future.

Keywords Climate, Collapse, Energy, Global warming, History

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1 Introduction

Climate and energy issues are now routinely making headlines. Expressions like greenhouse gases, peak oil, and global warming, to name a few, have entered our everyday vocabulary. Yet, the abundance of information makes it difficult to get a global picture of the problem. These notions are notoriously interconnected, but it is not always easy to tell how exactly. Like an exhaustive list of the streets of Paris does not easily convey a map of the city, all the climate and energy news in the world do not necessarily show how they fit together.

Instead of a research work, the present chapter is rather a tutorial in which its goal is to supply a global perspective of the climate/energy problem. Section 2 starts emphasizing the world's current energy status. Two observations will be made: First, current energy needs are tremendous, and second, there is no, strictly speaking, short-term fossil fuel shortage. Clearly, these fuels will eventually run out, but the main reason to switch away from them comes from global warming, as will be emphasized in Sect. 3. Section 4 will then review the possible alternatives to oil, coal, and carbon. From a physicist's point of view, it is possible to set up an exhaustive list of energy sources. Some back-of-the-envelope estimates [1] of what it would take them to provide our world the energy it needs will show the magnitude of the challenge that lies ahead of us. This is why the last section will focus on historical examples of past societies who encountered similar challenges.

2 Where Do We Stand?

The historian Ian Morris wrote that greed, fear, and sloth are the motors of history ([2], p. 26). Throughout history, energy is definitely an object of greed. Plant domestication can be viewed as a first attempt to harness solar energy. Mammal domestication, and even slavery, can be considered as the exploitation of extra mechanical energy. Yet, the energy consumption per capita hardly increased before the beginning of the nineteenth century. On average, it was about 15 GJ per capita per year in 1700, versus "at least 10 GJ" per capita at the time of the Roman Empire [3, 4].

How is it then that in spite of being so coveted, energy use did not grow before 1800 or so? The reason is simply that preindustrial energy sources were quite limited in their usage. The main one, biomass burning, was, for example, nearly exclusively restricted to heating. But you cannot plow a field just with heat. Indeed, the key element which triggered the industrial revolution was the steam engine. Suddenly, the steam engine made it possible to use heat for something else than heating. Once it became possible to perform every kind of mechanical work from heat, the thirst for energy grew exponentially.

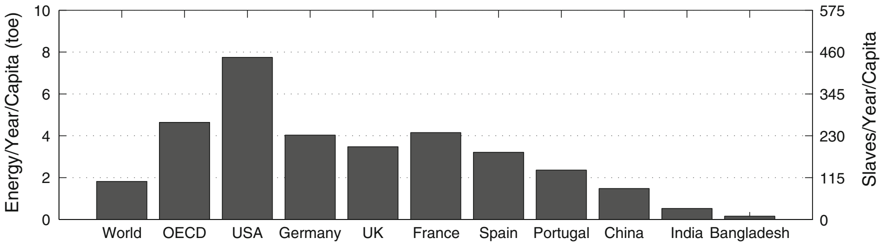

Fig. 1 Yearly energy consumption per capita for various countries or group of countries. *Left scale*: in tons of oil equivalent (toe). *Right scale*: in "energy slaves" equivalent, accounting for 2 MJ/day for a slave ([1], p. 5)

2.1 Energy Slaves

Today, after two centuries of exponential growth, the annual energy consumption per capita in the OECD countries is 4.6 tons of oil equivalent, nearly 200 GJ [5]. The consumption is nearly constant for millennia, before it increases more than tenfold in just two centuries.

An interesting way of grasping how deep our energy dependence has become is to translate joules into "energy slaves." The idea of drawing a parallel between slaves and machines goes back at least to the fourth century BC, where Aristotle noted the latter could replace the former [6]. The term "energy slave" was coined in 1940 by Richard Buckminster Fuller [7] and has been recently picked up by various authors [8–10] to emphasize the depth of our current energy dependence.

Assuming a slave would be given 4,000 calories a day, among which 2,000 should be used for his metabolism, the other 2,000 could be dedicated to mechanical work. Accounting for a muscle efficiency of 25%, he would be left with 500 calories for external work, that is, $500 \times 4.18 \times 10^3 = 2$ MJ/day or 0.7 GJ/year. An OECD citizen, with his 200 GJ/year, uses the work of $200/0.7 = 260$ energy slaves.

Figure 1 features the yearly energy consumption for various countries or group of countries. The left scale gives the consumption in tons of oil equivalent. The right scale translates the result to the equivalent number of "energy slaves."

If, then, a Westerner had to give up every single external energy source, he would need 260 slaves at his service, 24/7. This figure can be compared to the 462 workers registered in the US White House staff.[1] It means that every one of us in the Western world counts on a significant fraction of President Obama's staff. Clearly, we have been living this way for so long that things are irreversible. The world we have built is fundamentally designed to function with far more than our own energy.

[1] See http://www.whitehouse.gov.

2.2 Food Miles

Yet another way of expressing the magnitude of our energy dependence is to look at the amount of transportation implicitly required by our daily life. My laptop was assembled in China, while its hard disk came from Thailand and its memory from Korea. Some of my shirts, pants, and shoes wear a sticker "made in Bangladesh," "made in Vietnam," and "made in the Dominican Republic," respectively. And "made in China" is everywhere. It means that even before I bought these items, they had traveled thousands of kilometers. Their remote manufacturing was made possible by the energy needed to transport them.

Even our food is subsidized by energy. Although conservation techniques are not new [11], people in the past had to eat food that had been produced nearby. Today, the food consumed by a typical household in the USA traveled on average 6,760 km, from the production site to the fridge. This number, accounting for the overall supply chain, varies considerably in terms of the product. Beverages require only 1,200 km, while red meat demands 20,400 km [12].

2.3 Where Is the Problem?

Like the heart pumps blood in our body, energy moves our society. Energy is the heart of our society. Today, about 80% of the world primary energy production comes from fossil fuels [5]. Is that a problem? To start with, there is only a limited amount of these resources on Earth. Therefore, the day will come when the last gram of oil, coal, and gas will have been burnt. This is simply mathematics. But before production drops to zero, it will have to reach a peak. This is also mathematics. The question is not whether fossil fuels will be exhausted or not one day. The question is *when*.

Figure 2 features the forecasted peaks for all three fossil fuels [13]. While the supply of conventional oil is currently peaking, coal and gas peaks are still ahead of us, so that fossil fuels altogether should peak toward 2060. And the figure does not even account for nonconventional oil (tar sands, shale oil, etc.). Therefore, if it were only for the limited amount of fossil fuels, there would be a few decades left to prepare the transition. The reason why the transition should start now is climate change.

3 Climate Science

Fossil fuels are decomposed organic matter. As such, they are overwhelmingly carbon. As a rule of thumb, one can therefore assume that burning 1 ton of those fuels releases 1 ton of carbon in the atmosphere. Indeed, the 2010 world energy

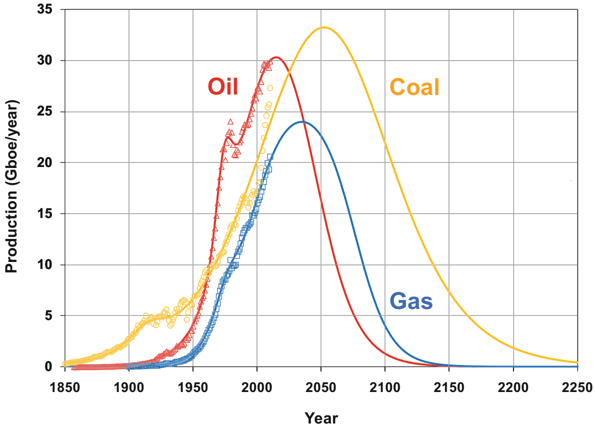

Fig. 2 Forecasted production for oil, coal, and gas [13]. *Plain lines* are the model (Hubbert), and the *symbols* are the historical data

production from fossil fuels was about 10 Gtoe [5], while the measured amount of carbon emitted was 9 Gt.[2]

Carbon is not emitted as such. During combustion, it combines with oxygen to form CO_2. Fossil fuel burning results therefore in carbon dioxide emissions. Are these emissions "important"? In other words, how does the emitted amount relate to the total already in the atmosphere? There are some 720 Gt of carbon in the atmosphere, mostly encapsulated in CO_2 molecules. Releasing 10 Gt more each year is definitely not negligible at all, especially if this is done for more than one century. The total amount of carbon emitted since the beginning of the industrial era is 355 Gt, which is not negligible at all when compared to 720 Gt.

Therefore, if carbon dioxide plays a role in the climate system, then human activity must influence it. And the role it does play is now well recognized: it is a greenhouse gas. The basic rule of climate science is that all the energy the Earth receives from the Sun eventually returns to space [14]. Nothing is stored. The spectrum of the light coming from the Sun is roughly centered on visible light. It is absorbed by the Earth, save a part directly reflected giving rise to the "albedo." Then, the Earth reemits all this energy in the infrared range. Our climate can change either because the incoming amount of energy changes or because the way it is reemitted changes.

The variations of the solar radiation over the last decades are of the order of 0.1%, which is too faint to explain the observed warming. But greenhouse gases tend to block some outgoing wavelengths. More energy must then travel through the non-blocked wavelengths, if the same amount of incoming energy is to be reemitted. The main greenhouse gas is water vapor. But its atmospheric concentration is nearly constant. The next more important greenhouse gases are carbon dioxide and methane (which results from fermentation processes). Carbon dioxide's

[2] See Carbon Dioxide Information Analysis Center, http://cdiac.ornl.gov/.

atmospheric concentration has gone from 280 to 400 ppm since 1800, while methane's concentration has risen from 700 to 1,700 ppb[3] during the same period.

3.1 Mitigating the Warming

The rise of carbon dioxide and methane in the atmosphere perfectly accounts for the current warming. Climate simulations of the last 100 years clearly reproduce the observations if and only if anthropogenic emissions are accounted for ([15], p. 18, 930).

What are then the predictions for the twenty-first century? Since human emissions are difficult to predict, climate scientists resort to various emission scenarios. Figure 3 features two figures of the last report of the International Panel on Climate Change (Workgroup I) [15]. On top, emission scenarios range from the so-called RCP8.5 which peaks toward 2100, to the "RCP2.6" where emissions are cut from 2020. The bottom plot shows the corresponding warming in 2100 with respect to 2000, ranging from +4°C to +1°C.

Since +1°C has already been gained since 1800, burning every single gram of the available fossil fuel is likely to bring an additional +5°C in 2100. Reminding that the global temperature shift between now and the last ice age is about –5°C ([15], p. 400), one can figure out the consequences of a similar warming [16]. Conversely, the RCP2.6 scenario with emissions peaking toward 2020 brings about a more bearable +2°C warming. For us in 2015, 2020 is now. The urgency for alternative energies stems from climate change.

4 Alternative Energies

It is thus clear that avoiding a dramatic warming implies starting to cut fossil fuels now. Which are the alternatives? From the physical point of view, energy can be found in two kinds of vessels: kinetic energy and potential energy. The first one, kinetic energy, is the energy of a moving body. Note that heat is kinetic energy since the heat of an object is nothing but the kinetic energy of its molecules. Potential energy is the energy released when a fundamental force is in action. For example, a falling apple acquires kinetic energy which comes from the gravitational potential energy it had while still hanging on the tree.

Potential energy is therefore always linked to a fundamental force. And there are only four of them: gravity, the electromagnetic force, and the strong and weak nuclear forces. Gravity makes apples fall, electromagnetism makes electrons stick

[3] "ppm" = parts-per-million and "ppb" = parts-per-billion.

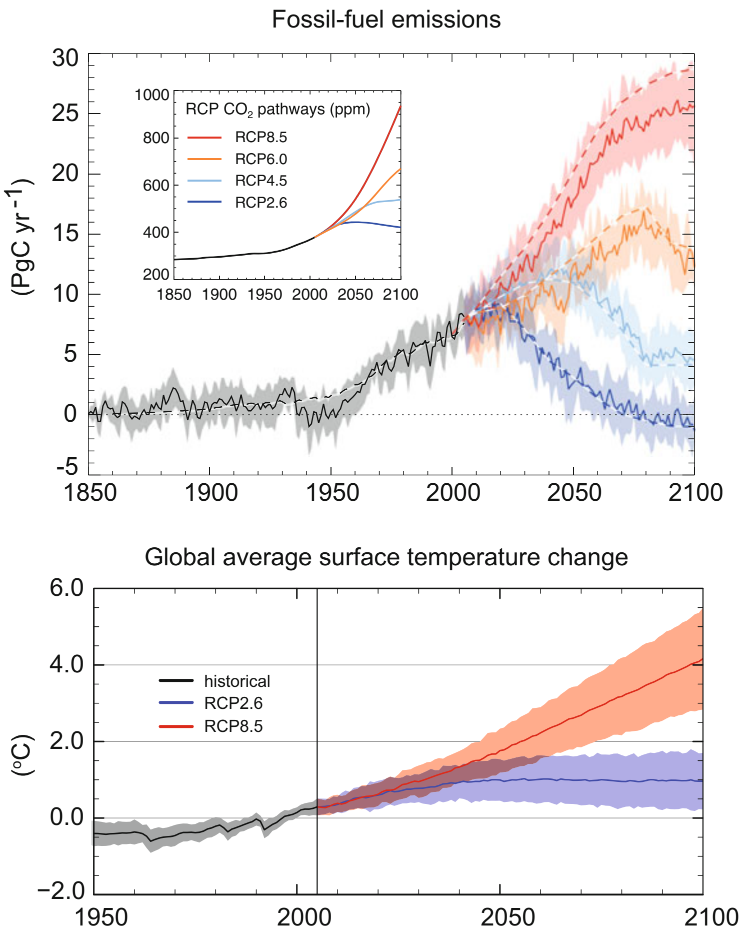

Fig. 3 Emission scenarios considered in the 2013 IPCC report (Workgroup I), together with the corresponding warming. The insert on the top figure shows the projected CO_2 concentration for each scenario. *Source*: Climate Change 2013: The Physical Science Basis. Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Figure SPM.7 (a); Figure TS.19 (top). Cambridge University Press [15]

to their atomic nucleus, and the strong nuclear force makes protons stick together inside the nucleus (we leave the weak nuclear force apart).

Figure 4 features the energetic landscape. Whenever one of these reservoirs is found already filled up, there is an energy source. Otherwise, there can still be a storage option. At any rate, any energy source, renewable or not, must fit in one of these categories. There are no other options in this world. Fossil fuels pertain to the realm of potential electromagnetic energy, as any combustion reaction eventually amounts to a release of such energy.

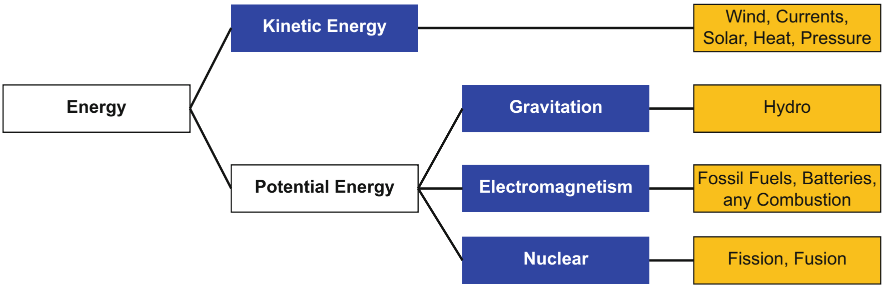

Fig. 4 Energetic bottles where energy can be found. Any energy source, renewable or not, must fit in one of the *blue* categories ([1], p. 21)

As previously said, the 2010 world energy production was 13 Gtoe, that is, 7 billion people burning 1.8 toe each. Let us now review the main renewable energy sources as they appear in Fig. 4 and check what it would take to generate 13 Gtoe. Granted, our energy future is likely to display a mix of solutions, but this exercise will help us figuring things out.

4.1 Kinetic Energy

Starting then with kinetic energy, we need to find something nature is moving for us and extract its kinetic energy. Wind energy comes to mind first. Assuming a windmill can recover some 30% of the kinetic energy of a wind at constant velocity ([17], p. 184), and averaging the result on the typical wind speed distribution (Weibull), a windmill of radius R located in a place where the mean wind speed is V_m can generate in a year

$$E = 22.7 R^2 V_m^2 \ \text{MJ}. \tag{1}$$

When placing the machines in a 2D wind farm, the optimum distance between them in both directions is proportional to their radius. As a consequence, the collected energy density becomes independent of the radius. Considering an optimum spacing of 10 radii,[4] a wind farm of 20 million km^2 is necessary to produce our 13 Gtoe, when setting $V_m = 5$ m/s.

One could think about taking kinetic energy out of ocean currents. The Gulf Stream, for example, is typically 100 km wide, 1 km deep, and flows at 2.5 m/s ([19], p. 249). Yet, the amount of kinetic energy that could be recovered in a year, even assuming a 100% efficiency, is only 4.6% of our 13 Gtoe.

[4] The optimum spacing could be much larger ([18], p. 430).

Geothermal energy also entered the "kinetic energy category." The heat flux from the Earth's interior is 0.087 W/m^2 [20]. Integrating over all the volcanic areas of the globe, namely, ~1% of it [21], yields 0.7% of our target.

Finally, solar energy can be viewed as the capture of the Sun's radiation kinetic energy (it could also fit in the next subsection). Here, the key fact is that each m^2 of the planet receives on average $I = 2.1$ MWh of solar energy per year. Southern Spain has $I = 2$ MWh, while the UK gets only $I = 1$ MWh. Considering the energy can be captured with an efficiency η, the area A needed for the 2010 world energy production is

$$A = \frac{0.14}{\eta I\ [\mathrm{MWh/m^2}]} 10^6\ \mathrm{km}^2. \quad (2)$$

Considering an overall efficiency (captor + portion of the ground covered) of 14% with $I = 2.1$ MWh, gives therefore half a million km^2.

4.2 Potential Energy: Gravity

The next item in Fig. 4 is gravitational potential energy. We thus need to look for substances that nature has put on a height for us and that we could let down. Rain is the obvious choice. If it falls on mountains, dams can be built retaining it. It is thus clear that hydroelectricity needs mountains, plus rain. A direct consequence is that hydro energy production must have a maximum. Once all the dams that could be built have been so, you cannot create more mountains, nor make up more rain. In many European countries like France or Spain, hydroelectricity has nearly reached its full potential. Regarding the whole world, the maximum production could reach 10% of our 13 Gtoe ([22], p. 273).

4.3 Potential Energy: Electromagnetism

All exothermic chemical reactions fall into this category, like fossil fuel burning. Since these fuels are precisely the ones that need to be phased out, they will not be examined any further here.

Solar energy pertains to the present category. Sunlight is composed of electromagnetic radiations, so that solar energy is also electromagnetic energy. Note that a photon of frequency v has the kinetic energy hv, where h is Planck's constant. Therefore, solar energy can equally fit into the "kinetic energy" category.

Biofuels fit here as well. Biofuels are eventually another form of solar energy where the captor is a plant. Which amount of fuel can be generated per year from a 1 hectare field? A good number is 5 tons ([23], p. 34). From this, the area needed for

13 Gtoe is straightforwardly computed with $A = 28 \times 10^6\,\mathrm{km}^2$.

This number is much larger than that obtained for solar energy. It turns out that the mechanism through which plants capture solar energy is photosynthesis. With an efficiency of 5% at best [24], photosynthesis efficiency is the bottleneck.

4.4 Potential Energy: Nuclear

This is the last possible energy reservoir. Because there are only four fundamental forces, there cannot be another reservoir. In order to harness nuclear energy, one has to find exothermic nuclear reactions, in exactly the same way exothermic chemical reactions release energy.

Exothermic chemical reactions release electromagnetic potential energy, and exothermic nuclear reactions release electromagnetic nuclear energy. According to the laws of nuclear physics, there are only two kinds of such nuclear reactions. You can take a big nucleus and split it. This is fission. Or you can take two light nuclei and merge them. This is fusion.

Fission power plants work so far splitting U^{235} nuclei. One single fission event releases 211 MeV so that you need to split 6,310 t of U^{235} to produce 13 Gtoe. Note that U^{235} reserves are running out. But other fission reactions could be used, earning nuclear fission a place among the potential future energies.

Among the existing fusion reactions (some power from the Sun), the one envisioned to produce energy is the fusion of deuterium (^{2}H) and tritium (^{3}H):

$$^2\mathrm{H}+^3\mathrm{H} \rightarrow \mathrm{He} + n + 17.6\ \ \mathrm{MeV}. \tag{3}$$

Merging 630 t of deuterium with 880 t of tritium would produce the needed 13 Gtoe. Although this energy source is very promising, none of the strategies adopted to harness it are likely to be operational before 2050. Fusion is therefore definitely a key player in the long-term energy mix, but it cannot help in the energy transition that has to take place within the next few decades.

Table 1 summarizes the numbers gathered in this section. All estimates are optimistic. The energy needed to grow the biofuel fields is not accounted for with biofuels nor is the energy lost when storing large productions of intermittent sources and so on. These numbers show one thing very clearly: switching away from fossil fuels is not an easy task. Past energy transitions typically took place over 50 years [4]. This is the time scale set before us by climate change. But this time, we need to go from an extremely energetically dense, cheap, and convenient source, fossils fuels, to the items listed in the table.

It is therefore clear that humanity faces a tremendous challenge. Did it happen already? Were there in the past civilizations who ran through similar challenges? Historians say “yes,” definitely. Let us now look at the past and see how some past societies overcame their crisis.

Table 1 Requisites to produce 13 Gtoe from each energy sources or percentage of the same amount that could be attained. See details of the calculations in [1]

Source	
Kinetic energy	
Wind energy	20 million km^2 wind farm
Sea currents	Gulf Stream, 4.6%
Geothermal	All volcanic areas, 0.7%
Solar	Half million km^2 field
Gravity	
Hydro	10%
Electromagnetic	
Biofuels	28 million km^2 field
Nuclear	
Fission	6,310 t of U^{235}
Fusion	630 t of D with 880 t of T

5 Historical Precedents, Vikings and Eskimos in Greenland

To start with, it is important to recognize that collapse is nothing exceptional in history. Indeed, it has rather been the inevitable destiny of every single great civilization. Joseph Tainter reports 18 such cases in *The Collapse of Complex Societies* [25]. Jared Diamond studies six more examples in *Collapse: How Societies Choose to Fail or Succeed* [26]. The Great Pyramids and the Roman Coliseum are vivid proofs that collapse did happen.

Going over each case is clearly impossible within this chapter. Instead, we will focus on two societies which shared the same environment at the same time: the Greenland Norse and the Eskimos. One society, the Norse, eventually collapsed, while the other is still around today [26].

By the beginning of the ninth century, the Vikings started to expand from their homeland, Norway. In 874 AD, they settled in Iceland. In 986 AD, they founded a first colony in the south of Greenland. Soon another colony would follow, to the west. Greenland is not too far from Canada, and indeed, there is evidence of Viking visits at the northern tip of Newfoundland island. Maybe due to the bad relationships with the natives, they could not settle there. But the Greenland colony did flourish. By the middle of the thirteenth century, they counted 5,000 souls. Greenland Norse had a bishop and 22 churches, some of them still standing today. This was the pinnacle of the Viking society in Greenland.

Things then changed quickly, for the worse. In 1406 comes the last report of a trip to Iceland. Then, in 1408 is the last mention of the Greenland colonies in Norwegian chronicles. There are no hints of massive return. The Vikings could not maintain their presence in Greenland beyond the middle of the fourteenth century. And it seems they slowly died out, one after another.

But the Vikings were not the only people living in Greenland. There were Eskimos as well, whose presence dates back at least to 2500 BC [27] and who

Table 2 Vikings vs. Eskimos' way of life

	Eskimos	Vikings
Food	Seal, fish, some caribou	Meat (beef, pork), milk (goat)
Houses	Igloo	Wood
Heating	Seal fat	Firewood
Ships	Kayak (skin + bones)	Wood + metal

have been living there until today. Why then could the Eskimos make it while the Norse could not?

Table 2 compares the Vikings and Eskimos' ways of life. It can help understand the fate of both societies. The Vikings imported their culture to Greenland. They came from a land where forests and pastures abound. Wood, firewood, big mammals, and what is needed to maintain them are abundant in Norway. Yet, living in Greenland means living on a strip of land some 50 km wide, squeezed between the sea and the inland glacier. Seafood and ice are abundant in Greenland, not trees, metal, and pastures.

As a consequence, the Vikings had to rely heavily on trade with Iceland and Norway to maintain their way of life. Like our fuel is fossil fuels, the Vikings' fuel was Norway, from where they imported everything they needed and could not find on-site. Two events then occurred which proved fatal for the Greenland Norse.

On the one hand, the Vikings settled in Greenland during the so-called Medieval Climate Anomaly, characterized by a warm climate over Greenland from 950 to 1250.[5] But starting from the thirteenth century, climate got colder, making life and sailing each time more difficult.

On the other hand, the Black Death hit Europe during the fourteenth century and killed half of Norway in 1350 [28]. Given their reliance on Norway, the Greenland Norse could not stand these two challenges and collapsed.

Meanwhile, Table 2 shows that the Eskimos' way of life was completely adapted to the place. They were relying on locally abundant resources, which explains why they could overcome the end of the Medieval Climate Anomaly and did not care about the Black Death ravaging Europe. Could have the Norse learn from the Eskimos? Maybe, but apparently cultural differences were too large and relationships between the two groups too bad.

[5] The Medieval Climate Anomaly had some regions as warm as in the late twentieth century. But these regional warm periods did not occur as coherently as the warming in the late twentieth century ([15], p. 21).

6 Conclusion

On this first part of the twenty-first century, humanity has reached a crossroad. A global civilization has been built, relying on these nonrenewable fossil fuels. Yet, the need to cut them as soon as possible arises from global warming, not from their limited availability. The business-as-usual scenario, consisting in burning them as long as they are available, would most probably result in a dramatic warming by the end of this century.

From the Roman Empire who was fuelled by conquests and collapsed when they stopped [25] to the Greenland Norse's dependence on Norway, a lesson of history seems to be "do not rely on something that can run out." The uniqueness of our situation may lie in the fact that we need to phase fossil fuels out even before we run out of them.

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