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The Energy–Climate Continuum

Lessons from Basic Science and History

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Additional material to this book can be downloaded from http://extras.springer.com/

ISBN 978-3-319-07919-6 ISBN 978-3-319-07920-2 (eBook)
DOI 10.1007/978-3-319-07920-2

Library of Congress Control Number: 2014942706

Springer Cham Heidelberg New York Dordrecht London

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Preface

So I said, let's calculate!

Fred Hoyle, 1987

Climate and energy issues are today almost omnipresent in the media. To no doubt, they are among the most important challenges of this century. The topic is incredibly vast. It involves history, astronomy, physics, chemistry, math… plus a huge amount of facts and data. As a consequence, solutions are often proposed which ignore a number of basics. Before curing people, medical doctors spend years learning about the human body. With respect to the climate/energy continuum, it is extremely tempting to act as a "doctor" who would not have studied medicine. To suggest treatments which disregard facts, or the physics involved, for example.

This is why this book can be viewed as a *conversation starter*. It is not solution-oriented. It is knowledge−oriented instead. It is the fruit of a 4-months course I have been giving in Spain, for the last 10 years. Four months are far too short to review everything one can know on these topics. Yet, it is long enough to understand the basics of the problem, acquire the physical basis of every energy source, and learn how to perform quick estimations and calculations regarding their potential. This book gives an easy access to understand important numbers and orders of magnitudes—for everyone. Based on understandable explanations, an emphasis can be put on fundamental numbers, when relevant. As David McKay puts it in *Sustainable Energy: Without the Hot Air*, "Numbers, not adjectives."

According to a famous saying, "give a man a fish and you feed him for a day; teach a man to fish and you feed him for a lifetime." As we will go through the different topics, we will not simply learn about the results of calculations others did. We will learn instead how to perform the calculations ourselves. The goal is to reach the point where you no longer say "they claim such and such," but "I know such and such, because I understand how it works, and I can do the numbers by myself." As a consequence, many calculations are outlined here. But don't be afraid. Besides Sect. 3.2 and Chap. 8, where the exponential function appears, the text involves simple arithmetic. More technical pieces and further detailed information for the interested reader can additionally be found in the appendices.

It is important to recognize from the beginning that what we have here is more than a mere collection of disconnected chapters. As the title says, the energy/climate problem is a *continuum*, and it is very important to grasp how its components are intertwined. Such a high level of connection echoes in the flow of the book, which goes as follows:

- Chapter 1 explains where we stand energy wise, in broad strokes. Then, even before learning the basics, you need to know who to listen to, how to perform quick calculations for yourself, and a few physics basics. This is Chap. 2. You need to understand what the energy problem is: we rely on fossil fuels, which will run out (not now) and pollute (now). This is Chap. 3. Pollution is spurring climate change. To avoid considerable warming, we need to replace fossil fuels *now*. Climate science is thus treated in Chap. 4.

  That is the first part of the book. Understanding the energy/climate problem.
- The second part then turns to solutions. Which options do we have? Storing energy or carbon could be one. Also engineering the whole planet. This is Chap. 5. Besides these options, some physical principles allow to list exhaustively every kind of alternatives to fossil fuels. We can review them, and assess their global potential. This is Chap. 6. Is there such thing as a perfect, risk free, wastes free, energy source? Probably not. This is Chap. 7. Gathering the numbers and making optimistic assumptions, what do we get for the next 300 years? This is Chap. 8.
- The last part of the book is about history. Why? Because once the magnitude of the challenge set before us is understood, it is natural to wonder if it ever happened in human history. Do we know of past civilizations which faced obstacles of their kind? The answer is yes, and learning about them can be a key part of the conversation starter. Indeed, fragility happens to be a common characteristic of human societies, as explained in Chap. 9. Some civilizations could not overcome their challenge. This is Chap. 10. Some could, may we follow their tracks. This is Chap. 11.

The reader will note a fair amount of references in the body of the text, not unlike scholarly literature. There are two reasons for such a choice. First, very few can be experts in every single topic covered. I thus thought it would be convenient to mention sources as they are evoked. The second reason is quite connected to the first: in order to go over all the necessary material in a reasonable amount of pages, each section must focus on the bare essentials. The desire to read further should then arise naturally and repeatedly. Here again, citing sources in the body of the text allows for an immediate access to more material.

This Book may also be Used as a Textbook…

As previously stated, this book is the fruit of a course. A 4 months, 60 h course. It can therefore be used as a textbook, and I do. A course on these topics is highly rewarding for students who find answers to their many questions, and for the professor as well, who finds motivated students eager to learn.

The course is directed to students in engineering with no advanced training in math or physics, but may also be suitable for early stage students in other science disciplines (such as physics, chemistry, geosciences, biology), or even for physics and science courses for non-scientists. The math involved does not go beyond simple arithmetic. The difficulty of the course is not technical. It rather lies in the large amount of information and notions to digest and put together.

If you choose to use this book as a textbook, you will need problems and solutions, exercises, and so on. Fortunately, the very nature of the topic makes it very easy to make them up “on the fly.” Here is a list of suggestions in this respect:

- The book contains more material than what can be taught in 4 months. It is straightforward to choose any calculation explained, and turn it into a problem.
- Some sections can also be turned into a problem. For example, Sect. 4.2 on the earth energy balance can be started like a quiz: the professor starts noticing the earth has been receiving 1.76×10^{17} J/s (see Eq. 4.1) for more than 4 billion years, and asks “where did all this energy go”? Students will start reviewing the available storage options, evaluate their capacity, and conclude alone that what comes in, must come out.
- Most of the calculations presented can be modified endlessly. For example, the evaluation of the amount of carbon emitted by the Spanish cars in Sect. 2.2 can straightforwardly be adapted to any country.
- Due to the exposure of the topic, media are a constant source of exercises. Take any news related to a brand new green energy project capable of providing current for n households, and have the students check the numbers by computing everything. I have designed many tests this way.
- Along the same line, many newspaper articles can enter an exam under the form of a text to comment.
- The climate science part can be the object of interesting debates between students. For example, Fig. 4.10 shows carbon emissions should start decreasing by now to avoid too strong a warming. Since OECD countries emit much more (per capita) than developing ones, which policies would you implement to cut global emissions in a *fair* way?
- The history part is also a great source of debates between students. For each of the four cases highlighted, we can ask: What can be learned? Which points do we have in common with these past civilizations? Which differences? Regarding Easter Island, for example (Sect. 10.2), this question from Jared Diamond can be asked to the students: “What were Easter Islanders saying as they cut down the last tree on their island?”. An interesting debate always follows.

- The toy model presented in Chap. 8 can easily be computed from an Excel spreadsheet for students to manipulate. Regarding Spain, a similar Excel file[1] has been prepared to let them design energetic scenarios under various constraints (no fossil, no nuclear, no more than x tons of carbon emitted per capita…). This file can quickly be adapted to any country.

May this book allow you to design the most exciting course on the topic.

Completing this manuscript would have been impossible without the help of many friends and colleagues. The remarks from Drs. Isabel de Sivatte, Stéphanie Bellamy, Jean-François Mouhot, Gonzalo González Abad, Ian Hutchinson, Pádraig Mac Cárthaigh, and Laurent Gremillet have been extremely helpful. I also want to thank Drs. Kendal McGuffie, Richard Alley, and Jim Kasting who repeatedly answered my questions on climate science. Finally, I am extremely grateful to all the students who have watched the development of this book over the years. Its current content is definitely the fruit of their curiosity, their remarks, and their questions.

April 2014 Antoine Bret

[1] It can be downloaded from *extras.springer.com*

Contents

Part I
The Problem

1 What Is the Problem? Men and Joules

The time of the finite world begins
Paul Valéry (1945)

Let us start summarizing our current situation. Our civilization relies on fossil fuels. Like Rome's prosperity was fueled by conquests ([1], see Sect. 10.1), ours is fueled by fossil fuels. Because these are *non*-renewable energy sources, sooner or later they will *necessarily* be exhausted. You cannot drink infinitely from a bottle that does not refill. It is sobering to think that on the timescale of humanity, let alone the earth timescale, the fossil fuel era will just have been a few hundred years long parenthesis, like the one pictured on Fig. 1.1. The question, for us in the parenthesis, is to decide what will happen next. It is urgent to start looking for alternative energy sources. How urgent? Regarding oil, we have burnt roughly half of what was easy to extract, and worldwide production should flatten by now before it starts decreasing irrevocably (see Chap. 3).

Yet, there is a lot of gas, coal, and unconventional oil left.[1] Can we thus quietly search energetic alternatives while burning every single gram of fossil resources? No, because of this famous "climate change." Burning fossil fuels since the beginning of the industrial revolution has already significantly heated the planet. And climate scientists are warning: burning all of the available fossil fuels would result in a tremendous global warming (see Sect. 4.5). There is therefore no time to wait, as history seems to teach that leaving behind some habits requires you have something to replace them (see part III).

A little account of the love story between humanity and energy, men and Joules, is indeed useful to realize how staggering our energy dependence is. Suppose you

[1] "Conventional" oil is the oil we have been hearing about from the last 200 years, like crude oil. It is liquid and can be extracted drilling a well. Unconventional oil is a fossil resource demanding much more treatment for its exploitation, like tar sands or shale oil. See Sect. 7.1 or www.iea.org/aboutus/faqs/oil/.

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A. Bret, *The Energy-Climate Continuum*, DOI: 10.1007/978-3-319-07920-2_1

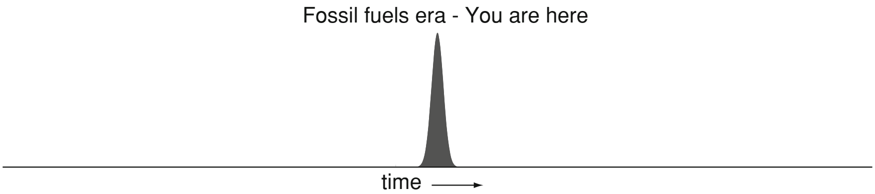

Fig. 1.1 On the timescale of humanity, the fossil fuel era will just have been a few 100 years long parenthesis

are a cave man or woman living way before any energy source was harnessed. You can only rely on your own strength. You need some 2,000 kilocalories per day to survive. Calories are but one more unit of energy, and 1 kilocalories are 4.18×10^3 J (see Appendix A for more on energy units and some explanations on numbers like 10^x). Then, if you ingest an extra 2,000 kilocalories to work, you can give away daily $2{,}000 \times 4.18 \times 10^3 = 8.36 \times 10^6$ J, that is, about 8 mega-joules (MJ). As your muscles are not perfect machines, they require about 4 J of physiological chemical energy to deliver 1 J of mechanical work.[2] You are thus left with 2 MJ a day,[3] which can let you, for example, carry a 2 tons load 100 m up.[4]

What if you want more? You can domesticate animals and have them work for you. For cattle and horse, that was done around 8000 and 3500 BC, respectively [4,5]. Searching for even more, you can use wind to sail. The earliest evidences for such technique date back to 5000 BC [6]. Wind can also power a windmill, evidences of which have been found from the third century BC [7]. Each time you find a new source of energy, you quickly get used to it and look soon for the next one. The next step was to harness people. This is called slavery. Evidences for it has been found in Egypt as soon as the third millennium BC ([8, p. 28]), and the Sumerian Code of Ur-Nammu, dated around 2100 BC, already includes regulations such as "If a slave marries a slave, and that slave is set free, he does not leave the household".[5]

Until the eighteenth century, this is all we had: ourselves, animals, wind, and slaves. We should sum to the list the water wheel, known from the fourth century BC [9], and biomass fuels (wood, crop residues, food wastes…) mainly used as a heat source ([10, p. 26]). Then, came James Watt with his steam engine in 1769. As simple as it sounds, this is truly revolutionary for it allows you to convert heat into *work*. Fire had been known for nearly 800,000 years [11]. But without the steam engine, you

[2] See Wikipedia on "Muscle Efficiency."

[3] This is an average power output of 23 W. The best bikers in the world can deliver some 400 W on average during a few hours [2] Assuming they do so for 5 h, and rest for the rest of the day, these are more than 7 MJ of mechanical work produced daily. But they are top athletes, and they do not sustain such exercise all year long. During the final of the 100 m at the 2009 World Championships in Berlin, Usain Bolt may have delivered more than 2,600 W around the first second of his race. But that lasted only for a flash [3].

[4] Just compute Energy = mass×height×acceleration of gravity, with mass = 2,000 kg, height = 100 m and acceleration of gravity = 9.8 ms^{-2}.

[5] See http://en.wikipedia.org/wiki/Code_of_Ur-Nammu.

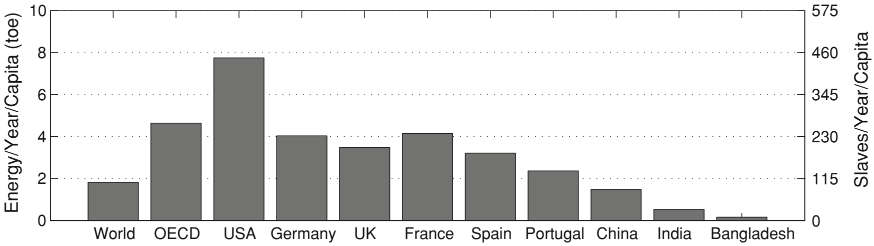

Fig. 1.2 Yearly energy consumption per capita for various countries, or group of countries. *Left scale* In tons oil equivalent (toe). *Right scale* In "energy slaves" equivalent, accounting for 2 MJ/day for a slave. *Source* International Energy Agency, Key World Statistics 2010 [14]

cannot do anything with fire but heating or burning. Without the steam engine, fire is useless to power a plow, a stagecoach, or a boat. The invention of the steam engine eventually amounts to harnessing chemistry. Suddenly, it becomes possible to use any kind of exothermic chemical reactions such as *combustion* reactions, to power whatever you need. As soon as you have heat, whether it be by burning wood, coal, gas, or oil, you can have work.[6] This invention triggered the industrial revolution.

As already stated, once you find a new source of energy, you quickly get used to it and look for more. This is exactly what happened during the last 200 years, as our fossil fuels consumption has been steadily growing. At the beginning of the nineteenth century, fossil fuel consumption, exclusively coal at the time, was 3.5×10^{17} J a year ([10, p. 155]). In 2010, it was 3.6×10^{20} J [14]. A thousandfold increase in 200 years when the world population has only been multiplied by 7 during the same period [15, 16].

Figure 1.2 displays the 2010 energy consumption per capita for various countries, or group of countries. In order to grasp these numbers, we follow Richard Buckminster Fuller who coined the term "energy slaves" in 1940 [17] (see also more recently [18–20]). The left scale shows the numbers in "tons oil equivalent" (toe). The right scale translates the amounts of oil burnt to the number of "energy slaves" required to deliver an equivalent energy. On average, each world citizen consumes a little less than 2 toe of energy per year, this is, 84 giga-joules (GJ).[7] Considering a slave would deliver 2 MJ a day, 84 GJ represent one year of work of 115 slaves! Clearly, numbers vary greatly from nearly 445 in the US to 9 in Bangladesh, but the result is appalling. If each member of an OECD country had to forget about his 4.6 toe of fossil fuel energy, he would require the "service" of 266 energy slaves.[8]

Historians tell us Louis XIV (1638–1715) had about 4,000 servants running the Palace of Versailles [21]. Each one of us in the Western world benefits from a signif-

[6] Oil ([12, p. 23]), coal ([10, p. 28]), and gas ([13, p. 41]) were all exploited way before the industrial revolution. Yet, they needed the steam engine to trigger it.

[7] See the oil/energy equivalence in Appendix A.

[8] The numbers vary according to how you compute the "energy slave" unit. But the result is always surprising.

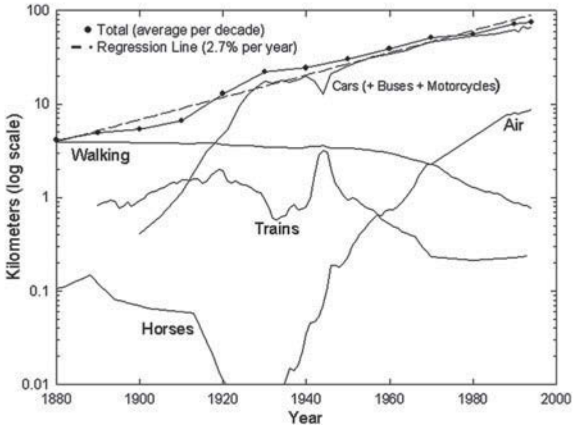

Fig. 1.3 US passenger travel per capita per day by all modes. From [22]

icant fraction of one of the most magnificent king of France privileges. Just imagine Louis XIV home alone in Versailles, without his servants. This gives an idea of how much we now rely on external sources of energy.

Another graph is very interesting in this respect. Figure 1.3 shows the evolution of US passengers daily travel per capita. Back in 1880, a US citizen would on average walk 4 km a day and ride 100 m. By the beginning of the twentieth century, Henry Ford introduced his Model T claiming "I will build a motor car for the great multitude" ([23, p. 73]) and since 1920, more distance is covered daily by car than by walking. Although train experienced a boost during the Second World War, it never surpassed walking. Finally, flying has been preceding walking since 1970. All in all, it has been nearly 100 years since the number one conveyance requires a lot of extra energy. It means the US, with at least the rest of the OECD countries (even if the numbers would change), are no longer adapted to the sole human scale. Whether we commute, shop, visit family and friends, go to the doctor or on vacations, we no longer rely on our own legs. Even the dishes on our table traveled thousands of kilometers to get there.[9]

The historian Ian Morris chooses "energy capture" as the first trait to measure social development throughout history[10] ([26, p. 147]), and Kenneth Pomerantz, another prominent historian, definitely agrees [27]. It is therefore no surprise that among the top ten worldwide companies by revenue in 2012, 8 belonged to the energy industry.[11] Our present world is fundamentally designed to function with an army of slaves serving each one of us. So, if you free them too quickly, you cannot expect anything but chaos.

[9] The term "food-miles" was coined to measure this. See [24,25].

[10] Morris defines social development as "a group's ability to master its physical and intellectual environment to get things done" ([26, p. 144]).

[11] *CNN Money* 2012 ranking.

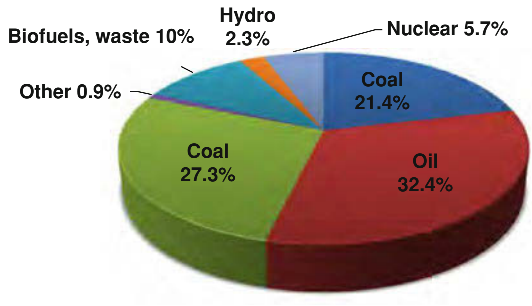

Fig. 1.4 Global primary energy supply by kind of fuel in 2010. "Other" includes geothermal, solar, wind, heat, etc. The total amounts to 12,717 Mtoe. From [14]

Who are these slaves, for now? Figure 1.4 shows a snapshot of the global primary energy supply by kind of fuel, in 2010. A total of 12,717 million toe were produced. Nothing else than 7 billion people burning 1.8 toe each. Fossil fuels that should be left behind, delivered 81.1 % of the total.

Noteworthily, this book deals exclusively with fossil fuels as energy sources. Yet, our addiction also relates to a host of *non*-energetic uses of these substances. Plastic, for example, is made from them. In 2012, 288 megatons of it were produced worldwide.[12] Considering crudely that only oil was used and that it takes 1 kg of oil to generate 1 kg of plastic, we find about 1.5 billion barrels were dedicated to plastic production alone in 2012. This is about 5 % of the overall oil production for the same year.[13] Leaving fossil fuels behind is not just an energy challenge.

The big problem is that there is so far no easy solution. This is, as easy as fossil fuels. Later on in the book, we shall look at the ways you can store energy (Chap. 5) and find out oil is incredibly efficient at it. The reason why it is difficult to phase out is precisely because it is the most efficient form of encapsulating energy. Just dig at the right place, and you collect an incredibly energetic substance nature has done for you. And on the top of it, it is almost free. At \$120 per barrel (160 L), the 42 MJ of 1 L are yours for less than \$1. Cheaper than most mineral waters. So even if there were no climate issues shortening the delay, finding alternative energy sources to replace fossil fuels would be a tremendous task.

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[12] See http://plasticseurope.org.

[13] See Fig. 3.1. This order of magnitude fits the real numbers ([28, p. 60]).