Antoine Bret

The Energy-Climate Continuum

Lessons from Basic Science and History

Springer

The Energy-Climate Continuum

Antoine Bret

The Energy-Climate Continuum

Lessons from Basic Science and History

Springer

Antoine Bret
ETSI Industriales
Universidad Castilla La-Mancha
Ciudad Real
Spain

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

© Springer International Publishing Switzerland 2014
This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Springer. Permissions for use may be obtained through RightsLink at the Copyright Clearance Center. Violations are liable to prosecution under the respective Copyright Law.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Cover image: © Robert Biedermann/Thinkstock

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

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 3
References 7

2 A Few Must-Know 9
2.1 Go to the Experts. The Peer-Reviewed Journals 10
2.2 Do the Numbers 13
2.2.1 Orders of Magnitude 14
2.2.2 Fermi Calculations 15
2.3 Energy Conservation 16
2.4 Some Energy ‘‘Sources’’ are not Sources 18
2.5 Energy Reservoirs and Sources 20
References 22

3 Fossil Fuels 25
3.1 Discoveries and Production 26
3.2 The Hubbert Model 27
3.2.1 The Peak Oil 28
3.3 Pollution 30
References 32

4 ABC of Climate Science 35
4.1 Something’s Happening 36
4.2 Energy Balance 39
4.2.1 Capacity of Forests as a Reservoir 39
4.2.2 Capacity of Oil as a Reservoir 40
4.2.3 Capacity of the Oceans as a Reservoir 40
4.2.4 Conclusion: The Energy Balance 41

4.3 Elements of Climate Modeling 41
  4.3.1 Elementary Model 41
  4.3.2 Beyond the Elementary Model 44
  4.3.3 Testing the Models 46
4.4 So, What's Happening? 46
  4.4.1 It Is Not the Sun 46
  4.4.2 It Is the Atmosphere 48
4.5 Men and Greenhouse 51
  4.5.1 Climate Models and Recent Years 51
  4.5.2 Climate Models and the Future 52
References 53

Part II Elements of Solution

5 Energy Storage, Carbon Sequestration, and Geoengineering 57
5.1 Kinetic Energy Storage 57
5.2 Potential Energy Storage: Gravitation 59
5.3 Potential Energy Storage: Electromagnetic Force 59
  5.3.1 Firewood 60
  5.3.2 Batteries 61
  5.3.3 Hydrogen 61
5.4 Potential Energy: Nuclear Forces 63
5.5 Carbon Sequestration and Absorption 63
  5.5.1 Carbon Sequestration 64
  5.5.2 Planting Trees 65
5.6 Geoengineering 66
References 67

6 Non-fossil Energy Sources 69
6.1 Wind and Water Turbines 69
  6.1.1 Wind Turbines 69
  6.1.2 Water Turbines 73
6.2 Solar Power, Biofuels, and Biomass 74
  6.2.1 Solar Power 74
  6.2.2 Biofuels 76
  6.2.3 Biomass 78
6.3 Geothermal Energy 79
6.4 Hydropower 80
6.5 Nuclear Energy: Fission 82
6.6 Nuclear Energy: Fusion 84
  6.6.1 The Lawson Criterion 86
  6.6.2 Magnetic Confinement 88
  6.6.3 Inertial Confinement 90
References 93

7 Constraints and Hazards 97
7.1 The Energy Return on Investment 97
7.2 Intermittency 99
7.2.1 Storage Assessment 101
7.3 Energy and Hazards 103
7.3.1 Fossil Fuels 104
7.3.2 Hydro Power 106
7.3.3 Nuclear Fission 107
7.3.4 Future Risks 112
References 113

8 A Toy Model 117
References 122

Part III History

9 Why Societies are Fragile 125
9.1 External Versus Structural Factors 126
9.2 Declining Marginal Return 127
9.3 Energy Shortage 129
References 130

10 When Things Went Wrong 131
10.1 Rome: Out of Conquests 131
10.1.1 Connected and Alone 131
10.1.2 The Collapse 132
10.2 Easter Island: Out of Forests 135
10.2.1 Connected and Alone 136
10.2.2 Too Few trees and People 136
10.2.3 About Trees and People 137
10.2.4 The End 138
References 139

11 When Things Went Right 141
11.1 Coal and Slavery 142
11.1.1 Direct Factor 143
11.1.2 Indirect Factors 143
11.1.3 Nineteenth-Century Thoughts 144
11.2 The Ozone Hole 145
References 147

12 Conclusion 149

Notations and Units 153

Wind Power Calculations 157

ABC of Nuclear Physics 163

Index 167

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/.

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

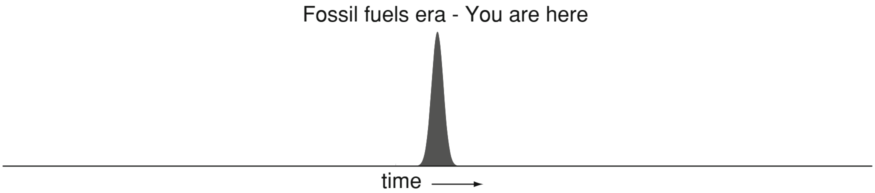

Fig. 1.1 On the timescale of humanity, the fossil fuel era will just have been a few 100 years long parenthesis

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.

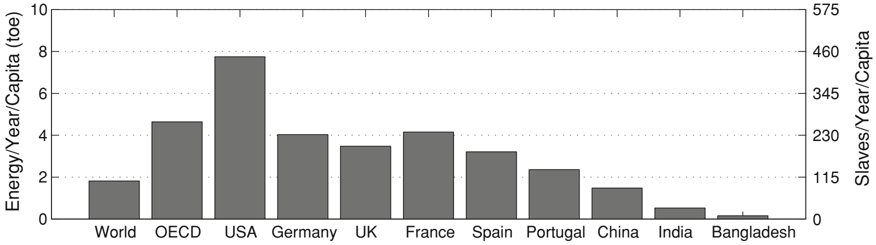

Fig. 1.2 Yearly energy consumption per capita for various countries, or group of countries. *Left scale* In tons oil equivalent (toe). *Right scale* In "energy slaves" equivalent, accounting for 2 MJ/day for a slave. *Source* International Energy Agency, Key World Statistics 2010 [14]

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.

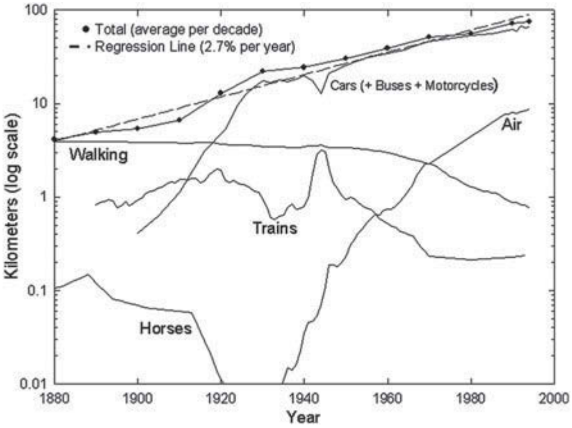

Fig. 1.3 US passenger travel per capita per day by all modes. From [22]

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.

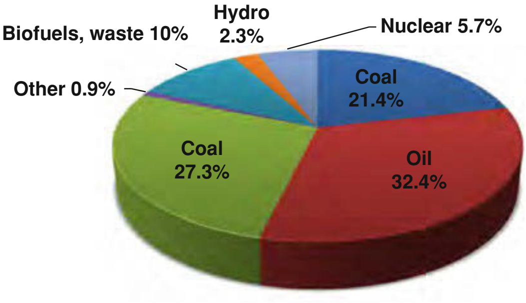

Fig. 1.4 Global primary energy supply by kind of fuel in 2010. "Other" includes geothermal, solar, wind, heat, etc. The total amounts to 12,717 Mtoe. From [14]

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.

References

1. J. Tainter, *The Collapse of Complex Societies. New Studies in Archaeology* (Cambridge University Press, Cambridge, 1990)
2. B.L. Hannas, J.E. Goff, Model of the 2003 Tour de France. American J. Phys. **72**, 575 (2004)
3. J.J. Hernández Gómez, V. Marquina, R.W. Gómez, On the performance of Usain Bolt in the 100m sprint. European J. Phys. **34**(5), 1227 (2013)

---

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

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

4. R.T. Loftus, D.E. MacHugh, D.G. Bradley, P.M. Sharp, P. Cunningham, Evidence for two independent domestications of cattle. Proc. Natl. Acad. Sci. **91**, 2757–2761 (1994)
5. A.K. Outram, N.A. Stear, R. Bendrey, S. Olsen, A. Kasparov, V. Zaibert, N. Thorpe, R.P. Evershed, The earliest horse harnessing and milking. Science **323**, 1332 (2009)
6. R. Carter, Boat remains and maritime trade in the Persian Gulf during the sixth and fifth millennia BC. Antiquity **80**(307), 52–63 (2006)
7. M.J.T. Lewis, The Greeks and the early windmill. Hist. Technol. **15**, 141–189 (1993)
8. O. Pétré-Grenouilleau, *Les traites négrières: Essai d'histoire globale* (Gallimard, Collection Folio. Histoire, 2006)
9. Ö. Wikander, *Handbook of Ancient Water Technology* (Technology and Change in History, Brill, 2000)
10. V. Smil, *Energy Transitions: History, Requirements, Prospects* (Praeger, New York, 2010)
11. N. Goren-Inbar, N. Alperson, M.E. Kislev, O. Simchoni, Y. Mordechai, Y. Melamed, A. Ben-Nun, E. Werker, Evidence of hominin control of fire at gesher benot ya'aqov, Israel. Science **304**(5671), 725–727 (2004)
12. D. Yergin, *The prize: the Epic Quest for Oil, Money, and Power* (Simon & Schuster, New York, 1991)
13. D.C. Wright, *The History of China* (Greenwood Histories of the Modern Nations, Greenwood, 2011)
14. International Energy Agency. Key world energy statistics. International Energy Agency (2012)
15. M. Kremer, Population growth and technological change: one million BC to 1990. Q. J. Econ. **108**(3), 681716 (1993)
16. C. McEvedy, R. Jones, *Atlas of World Population History* (Penguin, Harmondsworth, 1978)
17. R.B. Fuller, The US industrialization. Fortune Mag. **XXI**(2), 57 (1940)
18. J.R. McNeill, *Something New Under the Sun: An Environmental History of the Twentieth-Century World* (The Global Century Series. W. W, Norton, 2001)
19. J.M. Jancovici and A. Grandjean. *Le plein s'il vous plaît !: La solution au problème de l'énergie*. Collection Points. Série Sciences. Éd. du Seuil, (2007)
20. J.-F. Mouhot, Past connections and present similarities in slave ownership and fossil fuel usage. Clim. Change **105**, 329–355 (2011)
21. A. Rambaud. *Petite histoire de la civilisation française depuis les origines jusqu'à nos jours, à l'usage des classes élémentaires: Leçons-résumés-questionnaires-420 gravures*. A. Colin (1896)
22. J.H. Ausubel, C. Marchetti., P. S. Meyer. Toward green mobility: the evolution of transport. European Rev. **6**(2), 137–156 (1998)
23. H. Ford, S. Crowther, *My Life and Work. Library of American Civilization* (Doubleday, Page, New York, 1922)
24. L. Christopher, H. Weber, S. Matthews, Food-miles and the relative climate impacts of food choices in the United States. Environ. Sci. Technol **42**(10), 3508–3513 (2008)
25. G. Lawrence, K. Lyons, T. Wallington, *Food Security* (Nutrition and Sustainability, Taylor & Francis, 2009)
26. I. Morris, *Why the West Rules—for Now: The Patterns of History, and What They Reveal About the Future* (Profile Books, New York, 2010)
27. K. Pomerantz, How big should historians think? A review essay on why the west rules—for now by Ian Morris. Cliodynamics **2**(2), 304 (2011)
28. S. Freinkel, *Plastic: A Toxic Love Story* (Houghton Mifflin Harcourt, Boston, 2011)

A Few Must-Know

2

As noted in the preface, climate and energy issues have become extremely trendy. This is both a blessing and a curse. A blessing, because thanks to this media exposure, everyone knows there is a problem with climate change and energy, or “something like that.” A curse, because you can hear about anyone claiming anything on these issues, so that most people are in fact extremely confused. And as a highly spirited climate scientist rightly claimed, when it comes to climate science issues, it takes ten seconds to proclaim an absurdity, but ten minutes to explain why it is so.

From the TV news to the Internet and the newspapers, the buzz is now permanent, overflowing our poor brains with far more information than they can process. Like a good diet and some physical exercise are good habits to stay healthy, there are good habits to maintain a healthy view of our topic. Because we shall use them throughout the book, we decided to start with them.

In case you are not a climate scientist or an expert in energy issues, how do you make an opinion? You can start listening to the right people. I have never been to Antarctica to extract ice cores and analyze past climate. But I can read the reports written by those who did it. Have you ever hold in your hands a letter sent by Napoleon? Probably not, but you trust historians when they claim he existed and tell his history. Or have you ever seen with your own eyes the DNA in your cells? Again, probably not. But again, you trust biologists when they tell DNA is there. The same is true for every field of knowledge. We can have only a primary, direct knowledge of a very limited portion of what is known. For the rest, we mostly need to trust the experts. What is an “expert”? The section below will answer this question.

Besides listening to the experts, you can of course use your own brain. Once you have understood how a given process goes, you can perfectly work out a few orders of magnitude (we will see what it is) for yourself. Numbers do not lie and you do not need any expert to tell you what is two plus two. So why conjecture when you can calculate?

Finally, this book is all about energy. And physics has a lot to tell about it. Energy is conserved, which will let us perform many back of the envelope calculations independent of technological progresses. As a conserved quantify, it cannot be created, which is why some energy “sources” are not real sources. Also, energy is a quantity

A. Bret, *The Energy-Climate Continuum*, DOI: 10.1007/978-3-319-07920-2_2

that can be found in a finite number of reservoirs, and listing them allows to understand why the number of energy sources is limited.

2.1 Go to the Experts. The Peer-Reviewed Journals

We frequently hear about recent scientific advances. In March 2014, for example, the news spread around the world that the first direct evidence of the so-called cosmic inflation might have been discovered (see [1] for more explanations). The observations have been performed from the South Pole. How do we know we can trust the information? How do we know the telescopes have not been affected by the extreme South Pole cold? How do we know the people who operated them did it well? The journalists who broadcasted the news cannot possibly know enough to check the hundreds of essential technical points involved in the process. Since most of us cannot do it either, how can we trust?

It turns out that every single step involved in the discovery has been closely monitored by the scientific community since the beginning. Indeed, the story did not start in 2014. The scientists who did the discovery were already at work more than 10 years before. Already in 2002, they published a report on preliminary observations which would eventually pave the way to the 2014 announcement [2]. Since then, and as of March 2014, at least 24 scientific trustworthy (we will soon see why) articles had been published.

Now, where were these articles published? Not in mainstream newspapers or magazines, but in these so-called peer-reviewed journals. While TV news or newspapers articles are not systematically checked by experts, what comes out in peer-reviewed journals is. Let us check how it works with our example.

When, in 2002, interesting measurements were performed from the South Pole, the scientists who did them wanted the scientific community to know about it. They wrote an article and sent it to the peer-review journal *Nature*. Upon receiving the article, the *Nature* Editor did not decide by himself whether he would publish the paper or not. Instead, he sent it to at least two experts in the same field of knowledge and ask them a few questions like,[1]

- Are the results announced valid? Are they free of mistakes? A special kind of telescope was brought to the South Pole. How do we know it worked well? The data gathered were then submitted to extensive analysis. How do we know they were correctly conducted? So many questions only experts from the same field can answer.
- Are these new results? Research journals want to publish research results. And a result which has been known for 10 years is not research. Here again, it takes an expert to know where are the limits of knowledge in one field.

---

[1] See *Nature* peer-review policies at www.nature.com/authors/policies/peer_review.html.

- Is the article appropriate for publication in *Nature*? While every peer-review journal will ask the same questions above, this last one depends more on the journal. *Nature*, for example, publishes only articles that are of broad interest. They publish physics and biology papers, and they want physicists to be potentially interested in their biology articles and vice versa. But *The Astrophysical Journal* publishes nothing about history, and *The Historical Journal* publishes nothing about astrophysics.

The experts, or "referees", contacted by *Nature* wrote a report answering these questions and sent it back to the Editor. Since the paper was eventually published [2], the reports must have been positive. "Positive" reports may conclude the paper is fantastic and can be published as it is, or request a few changes before publication. In this latter case, the paper will go back to the Author and then may come back for the referee who requested the changes. But the reports could have been negative. One referee could have concluded the answer to one of the three questions above is "no." In that case, the Editor would have probably decided to reject the article and notify the author of his decision.

An important point of the process is that the author does not know who his referees are. This is important because the numbers of experts knowing about the kind of telescope involved, the measurements made, or the analysis performed is eventually quite small. At this level of specialization, a scientific community is a small village where people know each other's. Anonymity allows the referee to freely report negatively on an article, without having to fear the consequences on his relationship with the author.

Nature is only one among many peer-review journals. *Science* is another one. So are the aforementioned *The Astrophysical Journal* and *The Historical Journal*. Each field of knowledge has its proper peer-review journals, where the most recent advances are published after having been checked by experts of the very same field. And yes, as every scientist will confirm, having a paper rejected by an Editor is nothing exceptional.

In spite of this quite robust screening, some articles that still contain mistakes will make it to the publication stage. Flaws have inevitably been found among the 17,766,400 peer-reviewed articles[2] published from 2000 to 2010. Sometimes, the mistake was only minor. For example, the bulk of the article was sound, but the authors forgot a number in a formula or mislabeled some curve in a plot, without the referees noticing it. In such cases, every journal allows for the publication of an "erratum" where authors can clarify this kind of issues.

More severe are cases where articles should not have been published in the first place. The method used and the conclusion were wrong, but the referees were not knowledgeable enough to notice. Or the authors commented on apparently interesting experiments, but it later came out that the measurements were erroneous. Finally, plain fraud also occurs [3]. In these two latter cases, error and fraud, the journal

---

[2] Number returned by the *ISI Web of Knowledge* database on May 16, 2013, running the query "Year = 2000–2010" and "Documents Types = ARTICLE or LETTER".

issues a “retraction,” stating such and such paper is retracted, and why. Still from 2000 to 2010, 3,166 retractions and 103,109 errata were issued.[3] Although they do not necessarily pertain to the very papers published during the same period, these allow to evaluate that about 0.02 and 0.5 % of the published peer-reviewed articles are retracted and corrected, respectively.

In summary, at least one article out of 5,611 should not have been published.

This is one article of too many, and the scientific community is working to make it better [4]. But the number shows the system is already an excellent filter.

As a consequence, the most trustworthy news about what is going on in science are there to be found. If you are a member of a scientific institution, you can probably access these journals. On the contrary, you can still check the credentials and/or the sources of the author you are reading. Is he personally qualified to write on the topic he is writing on? If not (or even if he is), is he throwing numbers and graphs out of the blue, or is he telling where they came from? Too many times have I checked strange numbers or plots to find out they were just wrong. As former US president Ronald Reagan liked to say, “Trust, but verify.”

Articles in peer-reviewed journals are indexed in databases allowing to search them by authors, topic, year published, and so on (see below). Popular science journals such as *Scientific American* are extremely interesting because articles there are redacted by scientists specialized in the field involved. While they are not peer-reviewed, the author’s knowledgeability is guaranteed.

For all issues related to climate change, the “Intergovernmental Panel on Climate Change” (IPCC) is a great source of information. It is a United Nations endorsed organization whose task is to performed on a regular basis a synthesis of our knowledge on climate science and related issues. Reports are written by the very scientific community who has been conducting the research. The last ones were published in 2013/2014. So the IPCC members are not United Nations employees. They are scientists spending most of their time teaching or conducting research in their respective host institution around the world. The material produced is often translated in many languages and freely available on the IPCC Web site www.ipcc.ch.

What about Wikipedia? Regarding the topics I am reasonably knowledgeable about, I always found Wikipedia articles quite trustworthy. In 2005, *Nature* surveyed Wikipedia’ reliability in science and found it definitely satisfactory [5]. Besides, Wikipedia articles always cite their sources, most of them in peer-reviewed journals. As a consequence, Wikipedia can be considered a very good starting point, which is why this book frequently refers to it.

Besides the aforementioned resources, here is a non-exhaustive list of valuable Web sites connected to our problem:

- Energy statistics
  - International Energy Agency, www.iea.org
  - Energy Information Administration (US), www.eia.gov
  - United Nations databases, www.data.un.org

---

[3] *ISI Web of Knowledge*, consulted May 16, 2013.

  - Eurostat (Europe), www.ec.europa.eu/eurostat
  - British Petroleum Statistical Review, www.bp.com/statisticalreview
  - Great animated stats on tons of topics, www.gapminder.org
  - Google data platform, www.google.com/publicdata

- Greenhouse gases emissions, climate science
  - Intergovernmental Panel on Climate Change, www.ipcc.ch
  - Bulletin of the American Meteorological Society, State of the Climate, www.ncdc.noaa.gov/bams-state-of-the-climate/
  - United Nations Framework Convention on Climate Change, www.unfccc.int
  - Carbon Dioxide Information Analysis Center, www.cdiac.ornl.gov
  - NASA Goddard Institute for Space Studies, www.giss.nasa.gov
  - National Oceanic and Atmospheric Administration, www.noaa.gov
  - Explore and visualize carbon fluxes, www.globalcarbonatlas.org

- Peer-reviewed journals databases
  - Smithsonian Astrophysical Observatory/NASA Astrophysics Data System (free), www.adsabs.harvard.edu
  - ISI Web of Knowledge (requires subscription), www.webofknowledge.com
  - Scopus (requires subscription), www.scopus.com

- Some peer-reviewed journals
  - Science, www.sciencemag.org
  - Nature, www.nature.com
  - Proceedings of the National Academy of Sciences, www.pnas.org
  - Geophysical Research Letters, www.onlinelibrary.wiley.com/journal/10.1002/(ISSN)1944-8007

- Popular science journals
  - Scientific American,[4] www.scientificamerican.com
  - American Scientist, www.americanscientist.org
  - New Scientist, www.newscientist.com

2.2 Do the Numbers

As previously noted, you do not need any expert to tell you two plus two is four. So why not doing the numbers for yourself? In general, an accurate evaluation of, say, the hydroelectrical potential of a country requires detailed calculations. But a quick estimate of an *order of magnitude* like the ones performed in Chap. 6, for instance, is quite easy. For this, the prerequisite is simply an understanding of the mechanisms at

---

[4] "Investigación y Ciencia," "Pour la Science," and "Spektrum der Wissenschaft" are the Spanish, French, and German versions, respectively, of "Scientific American."

work and a pocket calculator. This method will be used repeatedly in this book, and we now explain how it goes. Let us start explaining the notion of order of magnitude.

2.2.1 Orders of Magnitude

An "order of magnitude" is something everybody understands intuitively, without necessarily being aware of it. To illustrate this point, here are a few questions with a satisfactory answer:

- What is the earth radius? 6,400 km.
- What is the Rome–Milan distance? 600 km.
- What is the size of a car? A few meters.
- What is the size of an ant? A few millimeters.

It turns out that we spontaneously tune the unit and the precision of the answer in terms of the magnitude involved. For example, it seems natural to express the earth radius in kilometers. And it seems equally natural in this case to forget about the tens and the units. We take "6,400 km" for an answer, without wondering whether it is 6,380 or 6,410. Indeed, the earth is not exactly spherical and according to the NASA Earth Fact Sheet,[5] its equatorial radius is 6,378 km, while its polar radius is 6,356 km. But we are happy with 6,400 km. Likewise, we forget about the meters when referring to the Rome–Milan distance and turn to millimeters when measuring an ant. Simply put, we adapt the yardstick to the problem.

We do not think this way for lengths only, but also for time, weights, and anything you can think about. When setting an appointment, you never say "see you at 09:02 a.m. and 5 s." But when asked how fast Usain Bolt ran the 100 m final during the 2012 Olympic games, you automatically switch to the hundredth of a second precision. Like Monsieur Jourdain in Molière's play *The Middle-Class Gentleman*, who had been speaking prose for forty years without knowing it,[6] we constantly deal with "orders of magnitude", even if we do not even know the word.

The numbers we are about to deal with are so disparate, and sometimes unexpected, that guessing their order of magnitude is already satisfactory. What is the word energy production? What is the world electricity production? Which amount of energy can be stored in 1 L of hydrogen? Finding the exact answers requires accurate calculations, or consulting databases. But finding the order of magnitude of the answers is simple once the underlying mechanism is understood. We will check repeatedly how this strategy proves right with almost every issue dealt with in this book. We will first highlight the mechanisms at work in a given process and then proceed to some quick calculations in order to get an idea of the answer. Let us now talk about why conducting this kind of calculation and how.

---

[5] See www.nssdc.gsfc.nasa.gov/planetary/factsheet/earthfact.html.

[6] Molière, *Le Bourgeois Gentilhomme*, Act II, Scene IV.

2.2.2 Fermi Calculations

No one would claim “I *think* one plus one is two.” This is not an opinion. In the same way, countless useless discussions could be saved just using a pocket calculator. Here again, a few examples will be helpful,

- Before deciding whether or not wind power could generate the electricity we need, it is extremely interesting to know how many wind turbines you need to replace a single coal fire power plant. Would you need a 10 km, a 100 km, or a 1,000 km long row? We could argue, but why arguing when we can calculate? We can go through the calculations reported in Sect. 6.1, and find the answer is rather 1,000 km. Of course, this is an order of magnitude, not an exact number. Yet, this is good to know to make an informed decision.
- A recent claim found on the web: “In the atmosphere, there are 750,000 million tons of CO_2. Human CO_2 emissions are only 6,000 or 7,000 million tons per year. It is ridiculously small.” To start with, the claim is incorrect because these numbers refer to the amount of carbon in the atmosphere and emitted [6]. Not to the amount of CO_2. But even without this, the conclusion is erroneous. A simple multiplication shows that if you emit 7,000 million tons per year for eleven years, you increase the total amount by 10 %. And we have been doing this for much more than 11 years. In fact, measurements show the CO_2 concentration has gone from 280 to 393 ppm (“part-per-million”[7]) since the beginning of the industrial era. Who would pretend such a 40 % increase is “ridiculously small”?

Most of these calculations are similar to what physicists called “Fermi calculations”, or “back of the envelope” calculations. Enrico Fermi, one of the brightest scientist of the twentieth century and 1938 Nobel Prize winner, liked to ask intriguing questions to his students. The most famous one may be “How many piano tuners are there in Chicago?” Since the solution can be found on Wikipedia,[8] let me propose another one: “How many children are born in Ciudad Real, Spain, each year?” Ciudad Real is the place where I teach, so that students can relate. You can of course adapt the problem to any city. Here is how it goes,

- The city population is 70,000.
- Say half are women. That gives 35,000 women.
- Say 1/3 are neither too young nor too old to give birth. That gives 11,500.
- Each one will have on average 1.5 children in a time window spanning about 20 years. That gives $11{,}500 \times 1.5 = 17{,}250$ children over 20 years, namely $17{,}250/20 = 862$ babies per year.

---

[7] 2012 mean value at Mauna Loa. See www.esrl.noaa.gov/gmd/ccgg/trends. A CO_2 concentration of “1 ppm” means that out of 1 million liters of atmosphere, 1 L is pure CO_2.

[8] See Wikipedia page on “Fermi problem”.

Official statistics[9] tell 874 babies were born in Ciudad Real in 2009. Not bad at all. Another example: "How many tons of CO_2 are emitted each year by Spanish cars?" We can try the following,

- Spain has 45 million inhabitants. We will consider one car for two people, this is, 22 million cars (the exact result is 22.5, but forget about the comma).
- A typical car burns 7 L for 100 km and covers some 10,000 km each year. These are 700 liters/year.
- Oil is mainly carbon. These 700 liters/year then translate to 0.7 tons of carbon *atoms* emitted each year, for each car.
- With 22 million cars, we get to $0.7 \times 22 = 15$ million tons of carbon atoms.
- Each carbon atom combines with two oxygens to make a CO_2 molecule. The molecular weight of carbon is 12, and the one of oxygen is 16. So 1 ton of carbon atoms yields $1 \times (12 + 16 + 16)/12 = 3.6$ tons of CO_2. Spanish cars should then emit about 54 million tons of CO_2.

What are the stats saying? According to the United Nations Framework Convention on Climate Change,[10] Spanish CO_2 emissions from "Transport" were 86 million tons in 2011. Again, not bad. And since the official number also accounts for trucks, our estimate may be quite accurate.

Of course, you cannot expect to pinpoint the exact number through these little exercises. But understanding the mechanism and then doing a back of the envelope calculation always gives a good estimate of the answer.

2.3 Energy Conservation

This book is about energy. One extremely important principle Physics has taught us it that energy is *conserved*. This principle will allow us to perform all sorts of calculations. But before using it extensively, let us try to explain what it means.[11]

Suppose you have been given €1,000,000 on a bank account with a bunch of credit cards. As long as you stick to the three following rules, you can do whatever you want with this money:

1. You are not allowed to invest, borrow or earn any single Euro.
2. You can resell things you will buy, but at the exact price you bought them (your world allows this).
3. You cannot buy anything perishable, such as food, drinks, or flowers.

So you start living out of your bank account. You buy everything money can buy within the limits of the three rules: furniture, cars, clothing…And 50 years later, the

---

[9] See Instituto Nacional de Estadística, www.ine.es.

[10] See www.unfccc.int.

[11] I really recommend in this respect Richard Feynman's illustration in *The Feynman Lectures on Physics* ([7], Chap. 4).

bank account is empty. How much money did you spent? You could go through 50 years of receipts, provided you never threw any, and sum. Chances are you would find a wrong result for it is almost impossible to keep track of every single Euros after 50 years of spending. Yet, you know exactly how much you spent: €1,000,000. Because you were never allowed to change one Euro into something more, the zero at the bottom of your last bank statement necessarily means you spent exactly €1,000,000, even if you do not remember how. But there is more: At any given time during these 50 years, the total amount already spent, plus the available balance on the account, always summed €1,000,000. In short, the total amount of Euros has always been the same. Some were on the bank account, others in your wallet, others on your credit cards account, and still others had been converted into sofas, car, or TV. But the total amount was always the same (remember you are in an ideal world where you can always resell something at the very price you bought it).

Energy conservation is very similar. Defining "energy" is not easy so that we will not enter this subtle topic.[12] But you can easily define its *effects*, saying for example, energy is what allows you to move something from point A to B. To do some work. Physicists have learned to *quantify* it. For example, a car of mass m at velocity v has the *kinetic* energy $E = \frac{1}{2}mv^2$. Kinetic energy is one of the many forms energy can take. But there are more. An object of mass m falling for h meters liberates a *potential* energy equal to $E = mgh$, where g is the so-called gravitational acceleration (9.8 m s^{-2} on Earth, less on the moon). A mass m of liquid water heated by T degrees absorbs the thermal energy $E = mTC$, where C is called the water "heat capacity". And on, and on…We will call "reservoirs" these forms energy can take.

Now, energy is conserved. Always. In the bank account example above, some Euros where in the account, others on your credit cards records, and still others under the form of car, beds, stereo…But the total amount had to sum €1,000,000. In the same way, when a ball falls from h meters, its potential energy mgh progressively switches to kinetic energy $\frac{1}{2}mv^2$, so that the total $mgh + \frac{1}{2}mv^2$ remains constant during the fall. Once it touches the ground, both h and v go to zero. So, where is the energy? Both the ball and the ground have been heated. Here, energy went from potential to kinetic to thermal. And if you find a way to measure the thermal energy produced, you will find it matches exactly the potential energy we had in the first place.

Of course, the law of energy conservation has been extensively tested experimentally. But it is also a consequence of the logical coherency of our world. This coherency echoes in properties that can be expressed in mathematical language. And one famous theorem of mathematical physics, the Noether's theorem, relates the conservation of energy with the invariance of the laws of physics with time [9]. As strange as it seems, stating the laws of physics should be the same tomorrow than today is *equivalent* to stating energy is conserved. The very existence of a particle called "neutrino" has been inferred from the energy conservation principle

---

[12] One of the problems with defining "energy" is that you cannot do it in terms of more fundamental concepts. "Energy" is already a highly fundamental concepts in physics [8].

26 years *before* it was discovered in the laboratory.[13] We have here an extremely well-established physical principle.

One of its consequences is that you cannot *produce* energy. The parallel with the bank account stops there because banks do *create* money. But energy cannot by created, precisely because it is conserved. There is no such thing as an energy "producer," only energy "transformers." Electricity producers do not produce electrical energy from scratch. They just convert the energy contained in, say, coal, to electricity. Oil companies do not produce energy. They just refine the oil they get out of the ground into fuel your car can burn.

The principle of energy conservation is as useful as powerful. When energy comes and goes between various reservoirs during a given process, it allows to derive relations of the type "total energy before = total energy after," *regardless* of the mechanisms involved. In other words, you do not have to know exactly what happened in the meantime. It is irrelevant. Energy had to be conserved anyway. So just sum the energy in the reservoirs before the process started. When it will be over, the total energy in the end reservoirs will be the same. Whether in the climate science or the energy sections, the alliance of energy conservation with orders of magnitude calculations will allow to derive a host of interesting results.

2.4 Some Energy "Sources" are not Sources

Because energy is conserved, there is no such thing as an energy *source*. Energy cannot be created. Like water springing from a source comes from somewhere, the energy springing from an energy source also comes from somewhere. And if nature did not gather the energy for you, you will have to do it yourself. A common mistake precisely consists in forgetting some forms of energies are nowhere to be found in nature. They have to be made out of natural energy sources, namely *primary* sources. Electricity and hydrogen are the best illustrations.

- Can hydrogen solve the energy problem? You certainly heard this many time. It generally goes like this: "Hydrogen is the most abundant element in the cosmos. In addition, it burns without emitting CO_2. It is *the* solution to fossil fuels depletion." It is true that in our universe, out of ten atoms, nine are hydrogen. Still in the cosmos, two atoms of hydrogen often pair up to form an hydrogen molecule, H_2. Our Sun, for example, is mostly made up of hydrogen. It is also true that hydrogen burns very well, reacting with oxygen to form water (which is why it is called hydro-gen, literally, "water generator"). The only problem is that hydrogen is very difficult to find here on Earth. There is almost no hydrogen in the atmosphere because it is so light that Earth' gravity has a hard time confining it. And there

---

[13] Wolfang Pauli hypothesized the existence of this particle in 1930 to ensure conservation of energy (among others) during a particular nuclear reaction [10]. The neutrino was discovered in 1956 [11].

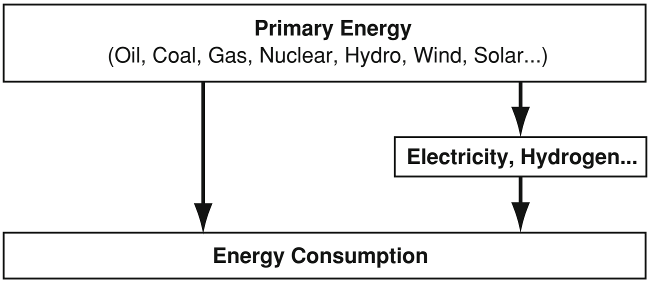

Fig. 2.1 Energy demand is met either directly from primary energy sources or indirectly through electricity, or possibly hydrogen, in the future. Neither electricity nor hydrogen are primary sources

are no natural hydrogen reservoirs like we have methane reservoirs for example.[14] The reason for this is that oil, coal, or gas all originated from organic material. And since organic material are carbon based, they necessarily yield substances with carbon in them, not pure hydrogen H_2.

So hydrogen would be the number one solution, *if* only it existed on Earth. And because it does not, you need to make it, which requires energy. As a matter of fact, R&D investments in hydrogen production (and fuel cell innovation) amounted to 5.6 billion dollars worldwide in 2008 [12]. In summary, hydrogen is a great option to *store* energy (see Chap. 5), not to produce it. If hydrogen is the ultimate answer to our energy problems, then a good bucket is the ultimate answer to the worst droughts.

- Could the electric car solve traffic pollution? This claim is equally frequent in the news. Indeed, an electric car would not emit CO_2 when running. So, why wait? As the movie goes, "who killed the electric car?" Here again, the reasoning would be perfect if only we had natural sources of electricity. But electricity is to be *produced* from another energy source. Electricity is a wonderful energetic vector, not an energy source. So if you want electric energy to power your car, this energy has to come from somewhere. And if most of your electricity is produced burning fossil fuels,[15] you may well emit less CO_2 by burning them directly in the car because each time you convert energy from one form to another, you lose part of it.

Electricity and hydrogen share the common property of *not* being primary sources of energy. As sketched on Fig. 2.1, the energy demand can be met by consuming directly a primary source, like when burning oil in your car. But neither hydrogen nor electricity are primary energy sources. So when you hear about the next energetic miracle, start wondering where the energy comes from.

---

[14] see Sect. 5.3 for a little more on this.

[15] As is the case in most countries but a few like France, where it is 75 % nuclear [13].

Let me finally take advantage of this section to issue a little warning: the confusion between “energy” and “electricity” is quite frequent in mainstream medias. Just an example: On January 15, 2014, the famous Spanish newspaper *El País* published an article entitled “Spain is the first country where wind energy becomes the main source of energy [in 2013].” Yet, a look at the latest available energy stats (the 2012 ones) on the web page of the *Instituto Nacional de Estadística*[16] shows that in 2012, 42 % of Spanish’ Joules came from oil, 22 % from gas, and less than 5 % from wind. Should we then assume wind energy grew spectacularly between 2012 and 2013 to become the first energy provider? Clearly no. It just turns out that in Spain, wind energy became the main source of *electrical* energy in 2013.[17] But the headline omitted the word “electrical.” Here again, next time you hear about the surprising performances of a given source as an energy provider, start wondering whether we are talking energy, or just electricity.

2.5 Energy Reservoirs and Sources

We just found energy can flow from one reservoir to another, while the total amount contained in every possible reservoir is conserved. When it comes to look for energy *sources*, the real issue is therefore to look for *already* filled reservoirs. If an energy source is to truly behave like a “source,” the reservoir holding it must have been filled naturally. If not, you need to fill it, and what you have is not a source. It is a bottle (see Chap. 5).

Finding out exactly the kind of reservoirs we have to look for is a key issue for the world energy problem. As previously stated, “kinetic” energy is one kind of reservoir. Another kind is “potential” energy. And the list stops there. The “thermal” energy previously mentioned is in fact another form of kinetic energy, as the heat held by something is nothing but the sum of the kinetic energy of the particles forming this “something.” We are thus left with kinetic and potential energy reservoirs.

Potential energy is a form of energy that can be liberated through the action of a force. It is there, *potentially* (hence the name), and you need a force to unravel it. When an object is dropped from a height, gravity pulls it down. Because it speeds up, it acquires kinetic energy. But where does this kinetic energy come from? From gravity. This energy was potentially in the object before it was dropped. We just needed to let gravity act on it. The same happens with other kind of forces.

How many kind of fundamental forces are there? Four. This is it. Gravitation is the force holding the Solar System together. Masses attract each other through gravitation. Then comes the electromagnetic force. This is the force of a magnet. Or the force holding the electron and the proton together in the hydrogen atom. Also

---

[16] See www.ine.es.

[17] Even this seems slightly inaccurate. Nuclear energy provided 20.1 % of Spanish’ electricity in 2013, against 19.4 % for wind [14].

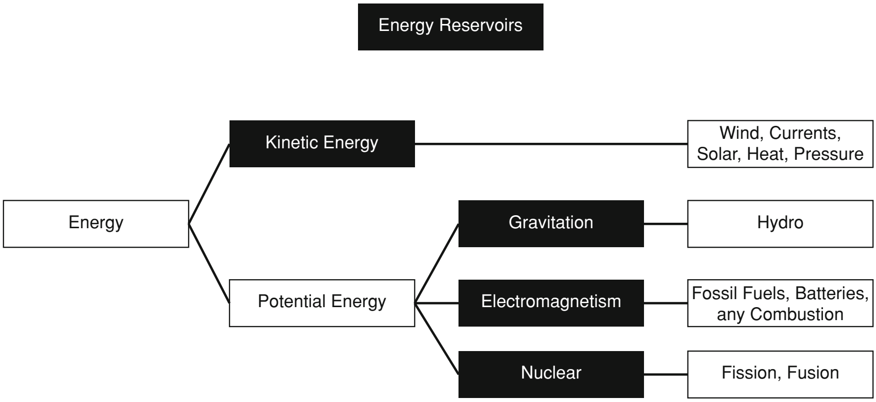

Fig. 2.2 Exhaustive listing of energy reservoirs

the force driving electricity in the cable from the plug to your TV. Then come the nuclear forces, holding the protons together in the nucleus of an atom.[18] Technically, there are two types of such forces, strong and weak, but for our purpose, we shall simply speak of nuclear force. Every single physical process we know so far can be described in terms of these forces.

When searching for an already filled reservoir, it is thus enough to review the ones we just mentioned. Either we find available kinetic energy, something nature has put in motion for us, or we find potential energy reservoirs we can empty.

Figure 2.2 schematically renders the result of this inventory. In the category "kinetic energy," we have wind power or current power, the power that could be extracted from ocean currents. Solar energy is also there, because it simply consists in harnessing the kinetic energy of light.[19]

Turning now to gravitational potential energy, we have to think about something nature has put on a height for us, like water on the mountains. Indeed, there is nothing else falling from the sky. This reservoir has already been widely tapped through hydroelectricity generation.

With electromagnetism, we need to think about chemical reactions liberating energy. A chemical reaction converts a bunch of molecules A into a bunch of different molecules B, as sketched on Fig. 2.3. It is like dismantling a Lego house to make a car. When taking the atoms of molecules A apart, you spend[20] the energy E_A. An amount of E_B energy is then given back to you when assembling molecules B. If

---

[18] The electromagnetic force keeps protons apart from each other's. Without the nuclear force, nucleus would not hold together, and there would be no atoms at all.

[19] Solar energy could equally fit into the "electromagnetic potential energy" box, because it is just the electromagnetic energy of sunlight.

[20] Dismantling a molecule has to cost some energy. It would not be there otherwise, having been destroyed long ago by the slightest bump with an atom.

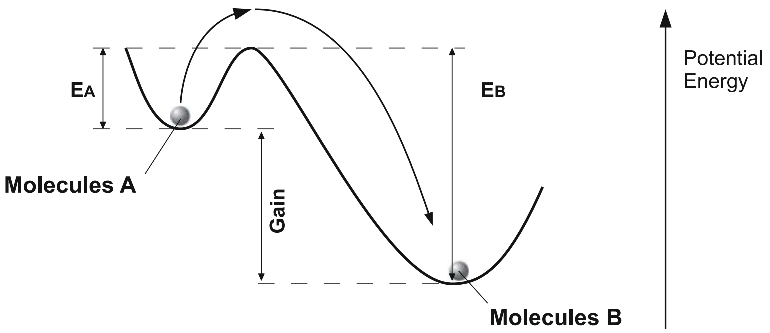

Fig. 2.3 To change molecules A into B, you first need to spend E_A dismantling A. As molecules B are assembled, you are given back E_B. An "exothermic" chemical reaction has $E_B > E_A$. If in addition $E_B - E_A > E_A$, the reaction is self-sustained because one reaction releases enough energy to trigger another one

what you got back is larger then what you spent, you have an energy gain $E_B - E_A$. Such chemical reactions are called "exothermic." All combustion reactions are like this. What you really want indeed is a gain $E_B - E_A$ larger than E_A. This way, one reaction releases enough energy to trigger yet *another* one. This is why you need a match to light a fire, but *only one*. Firewood or fossil fuels burning are definitely there.

Finally, some nuclear reactions are able to release energy following the same pattern than chemical reactions. We will see later in Sect. 6.5 than only two kinds of nuclear reactions can do the job: fission, where a heavy nucleus is divided into smaller ones and fusion, where two light nucleus merge to form a bigger one.

Because there are only four fundamental forces, and because energy is either kinetic or potential, Fig. 2.2 is an *exhaustive* listing of possible energy reservoirs. The last column may not list every single energy source you ever heard about. For example, tide and wave energies do not appear and will only be cursory reviewed at the end of Sect. 6.1. But every possible kind of vessel is there. In this universe, this is all you have. If you were lucky enough to find a reservoir already full, you have an energy source. Otherwise, you may have an energy storage option. At any rate, the solutions to our problems are among these cells. There is no other way.

References

1. A. Cho, Y. Bhattacharjee, First wrinkles in spacetime confirm cosmic inflation. Science **343**, 1296 (2014)
2. J.M. Kovac, E.M. Leitch, C. Pryke, J.E. Carlstrom, N.W. Halverson, W.L. Holzapfel, Detection of polarization in the cosmic microwave background using DASI. Nature **420**, 772 (2002)

3. D. Normile, Hwang convicted but dodges jail; stem cell research has moved on. Science **326**(5953), 650–651 (2009)
4. R. Van Noorden, Science publishing: the trouble with retractions. Nature **478**(7367), 26–28 (2011)
5. J. Giles, Internet encyclopaedias go head to head. Nature **438**(7070), 900 (2005)
6. P. Falkowski, R.J. Scholes, E. Boyle, J. Canadell, D. Canfield, J. Elser, N. Gruber, K. Hibbard, P. Hgberg, S. Linder, F.T. Mackenzie, B. Moore III, T. Pedersen, Y. Rosenthal, S. Seitzinger, V. Smetacek, W. Steffen, The global carbon cycle: a test of our knowledge of earth as a system. Science **290**(5490), 291 (2000)
7. R.P. Feynman, R.B. Leighton, M. Sands, *The Feynman Lectures on Physics* (Addison-Wesley Publishing Company, MA, 1977)
8. E. Brewe, Energy as a substance like quantity that flows: theoretical considerations and pedagogical consequences. Phys. Rev. ST Phys. Educ. Res **7**, 020106 (2011)
9. H. Goldstein, C. Poole, J. Safko, *Classical Mechanics* (Pearson Education, New Jersey, 2002)
10. L.M. Brown, The idea of the neutrino. Phys. Today **31**, 23 (1978)
11. C.L. Cowan, F. Reines, F.B. Harrison, H.W. Kruse, A.D. McGuire, Detection of the free neutrino: a confirmation. Science **124**(3212), 103–104 (1956)
12. PATH. Annual report on world progress in hydrogen. Technical report, Partnership for Advancing the Transition to Hydrogen, June (2011)
13. International Energy Agency, *Key World Energy Statistics* (International Energy Agency, Paris, 2012)
14. Red Eléctrica de España, *The Spanish electricity system preliminary report 2013* (S.A.U,Technical report, Red Eléctrica de España, December 2013)

Fossil Fuels

3

Now that the stage has been set, let us look in more details at our problem. To which extent are fossil fuels limited, and how do we know their usage has an influence on the climate? Such are the questions answered from now on.

According to the International Energy Agency [1],[1] fossil fuels amounted in 2012 to 81.1 % of the world primary energy use. Out of these 81.1 %, oil had 32.4 %, coal 27.3 %, and gas 21.4 %. Although oil will be emphasized more than the others, they all share the same traits: Each one is available in limited quantity, and each one emits greenhouse gases when burning. Let us emphasize that we will only talk of "conventional oil". "Conventional oil" is the liquid one, which gushes out of the ground after the drilling. "Unconventional oil" features the Canadian oil sands, for example, which are quite close to bitumen or tar. Exploiting tar sands is similar to extracting the oil from the bitumen of the road. As a result, unconventional oil is far more expensive (see Sect. 7.1). Our focus is therefore on "cheap oil," to paraphrase the title of a famous article, *The end of cheap oil*, written in 1998 by two petroleum geologists and engineers, Campbell and Laherrère [2].

What we are about to check is that even if there were no climate issues at all, our economy would be in danger as conventional reserves are seriously depleted, while unconventional ones are considerably more expensive to exploit [3]. Indeed, this is the very reason why they were not considered in the first place. As the anthropologist and historian Joseph Tainter puts it in *The Collapse of Complex Societies* ([4, p. 194]),

> To the extent that information allows, rationally acting human populations first make use of sources of nutrition, energy, and raw materials that are easiest to acquire, extract, process, and distribute. When such resources are no longer sufficient, exploitation shifts to ones that are costlier to acquire, extract, process, and distribute, while yielding no higher returns.

When including climate issues in the equation (see Sect. 4.5), the conclusion is it would be wise to leave non-conventional resources alone and find an alternative to fossils even before we burn all of the conventional reserves. How do we know "the

---

[1] Freely downloadable at www.iea.org/publications/freepublications/publication/kwes.pdf.

A. Bret, *The Energy-Climate Continuum*, DOI: 10.1007/978-3-319-07920-2_3

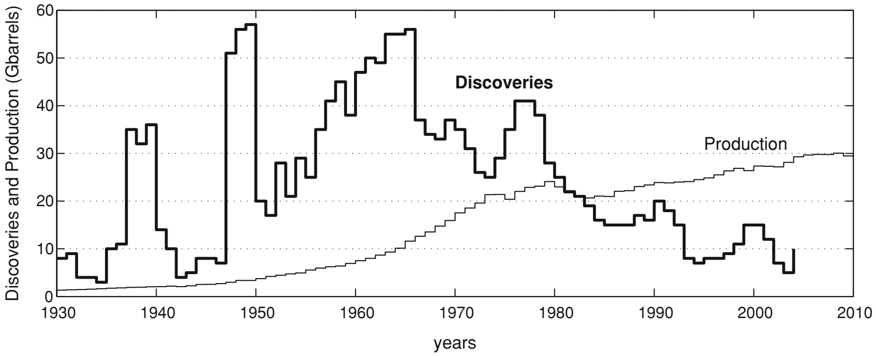

Fig. 3.1 *Bold curve* Oil discoveries worldwide by year in gigabarrels (Gbarrels) since 1930. The peak in 1948 is the discovery of the famous giant Ghawar field in Saudi Arabia. *Light curve* World oil production. Until 2004, 1,802 Gbarrels had been discovered, and 1,237 had been produced until 2011. *Source* Exxonmobil 2002 and Association for the Study of Peak Oil ("ASPO"), Newsletter 100, April 2009

end of cheap oil" in near, and which amount of greenhouse gases have been poured in the atmosphere? This chapter answers these questions.

3.1 Discoveries and Production

Before you burn oil, you need to find it. Are we still finding a lot of oil in 2012, or are we just uncovering some last drops here and there? The first data to look at is the history of discoveries. While remaining reserves are usually fiercely debated, discoveries are just history. The bold curve on Fig. 3.1 shows the evolution of oil discoveries worldwide by year, since 1930. One thing is clear: The big findings are behind us. In spite of a tremendous increase of technology (think about a 1960' computer), discoveries peaked around 1960. Clearly, there is still oil to be found here and there, but the bulk has already been spotted. If you compute the total amount of oil ever found until 2004, you find 1,802 billions of barrels. Accounting for what must be left, we get a very important number representing the total amount of oil that was to be found in the first place: 2,500 billions of barrels, give or take a few hundred billion.

Let us now turn to oil production, which closely mimics oil consumption. This one is necessarily smoother than the discoveries because you do not sell and burn every single drop of an oil field the very year you find it. Indeed, the giant Ghawar field discovered in Saudi Arabia in 1948 still produces about 5 million barrels a day. We thus turn now to the light curve on Fig. 3.1 to note the expected tendencies. The production is much smoother than the discoveries, and shifted in time as a consequence of the time it takes to deplete a field. Computing from these data the

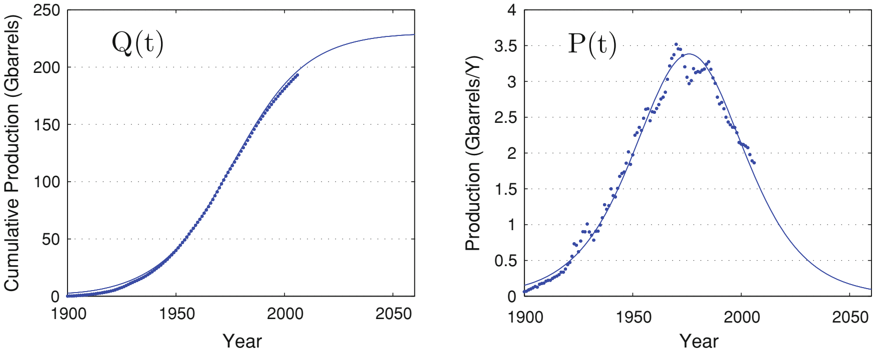

Fig. 3.2 *Plain lines* Hubbert model $P(t)$ and $Q(t)$ defined by Eqs. (3.2) and (3.1) with $a = 17$, $P_m = 13.5$ and centered around the year 1976. *Dots* US conventional oil production and cumulative production. *Source* Energy Information Administration

total amount of oil ever produced until 2011, we find 1,237 Gbarrels, that is, about half of the total available amount we just assessed. This fact is extremely important and explains the plateau in the production clearly visible since 2005 (see below).

Oil production steadily increases from 1930, before it is halted by the 1973 and 1979 oil crises. This first phase of growth, before 1970, is worth emphasizing. As oil flows into society, society adapts and requires even more. It is quite like getting rich. The richer you are, the more you want. When you were still poor, $1,000 were a fortune. Now that you are a millionaire, it takes billions to make you dream. The same pattern can be identified with the number of households equipped with a TV set, a computer, a cell phone, or an Internet connection: The equipment growth rate increases with the number of households equipped, at least at the beginning. Those familiar with math will have identified the hallmark of the *exponential* growth. The more you have, the more you want, as long as supply can keep up.[2]

This initial phase of exponential growth followed by a plateau before a necessary drop to zero are the basic elements of the so-called Hubbert model we now explain.

3.2 The Hubbert Model

Marion King Hubbert became famous for predicting in 1956 the 1975 peak of US oil production displayed on Fig. 3.2-right. His mathematical model is not unrelated to population growth theories. Like oil or Internet connections, rabbits reproduce all the more than they are numerous until they reach some external limit like predators

---

[2] If you plot the production curve of Fig. 3.1 setting a logarithmic scale on the vertical axis, this initial growth phase appears as a straight line, evidencing the exponential growth.

or finite food supply. Hubbert's original work [5] is extremely mathematical, and Kenneth Deffeyes, a former geologist who worked with Hubbert and now Professor at Princeton University, summarizes it nicely in his book *Beyond Oil: The View from Hubbert's Peak* [6]. We shall start with a little mathematics before we switch to the real numbers. To start with, geologists have found the following formula well adapted to describe the total quantity produced up to a given time t,

$$Q(t) = \frac{a P_m}{1 + e^{-t/a}}, \tag{3.1}$$

where P_m is four times the maximum production, t the time, and a the time scale of the production. This function is called the "logistic function" and is known in many fields of knowledge ranging from demography to political science. The production at time t is simply the time derivative of $Q(t)$ and reads

$$P(t) = P_m \frac{e^{-t/a}}{(1 + e^{-t/a})^2}. \tag{3.2}$$

It is for convenience that the maximum production is reached at time $t = 0$, but you can shift this moment as you want without changing anything to the reasoning. Equation (3.2) has all the desired properties. It starts growing exponentially, as was observed for oil production. Then, it reaches a maximum at $P = P_m/4$ before it goes back to zero. The total quantity[3] of extracted oil is eventually $Q_\infty = a P_m$, while the production peak occurs at $t = 0$, when *half* of the total has been extracted. These two curves are plotted on Fig. 3.2 for $a = 17$ and $P_m = 13.5$ together with the real numbers for US oil production. As expected, the cumulative production reaches a plateau at large times, while the production drops to zero.

The Hubbert model has a very interesting property allowing to extrapolate Q_∞ from real data. It is easily checked that

$$\frac{P(t)}{Q(t)} = \frac{1}{a}\left(1 - \frac{Q(t)}{Q_\infty}\right). \tag{3.3}$$

When plotting P/Q in terms of Q, you thus get a strait line starting from $P/Q = 1/a$ for $Q = 0$, before it drops to zero for $Q = Q_\infty$.

3.2.1 The Peak Oil

Let us see how to exploit this with real data. Already in Fig. 3.2, we could check the model adjusts really well to the US production. Using the numbers plotted on Fig. 3.1, we can compute P/Q and Q for the world and plot the former in terms of the latter. The result is displayed on Fig. 3.3 where each dot represents a year. For low values of Q, when cumulative production is still low, fluctuations of the real numbers have an important impact on the ratio P/Q (Q is at the denominator) and the curve departs

---

[3] You can check $\int_{-\infty}^{\infty} P(t)dt = a P_m$.

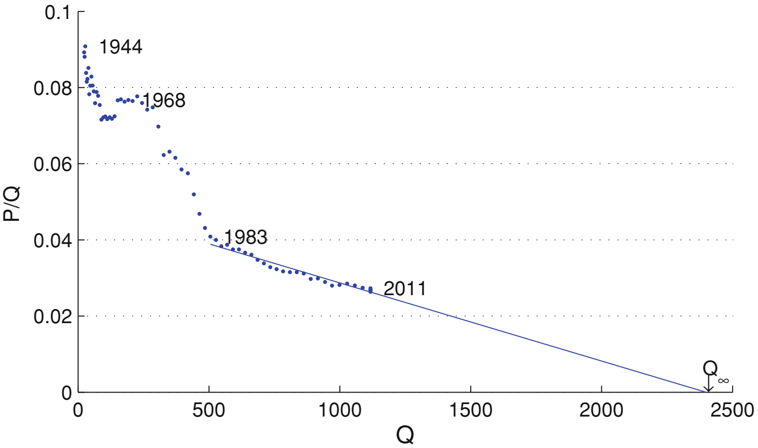

Fig. 3.3 Plot of P/Q versus Q for the real-world production numbers used in Fig. 3.1

significantly from the expected straight line. The halt in the production occurring during the seventies is also visible. Then, from 1980 and onward, the points align pretty well along a line. According to the Hubbert model, this line should intersect the horizontal axis at $Q = Q_\infty$. Of course, we are not there yet, as there is still production going on in 2011. But the extrapolation of the tendency gives $Q_\infty = 2{,}400$ Gbarrels, perfectly coherent with our previous estimate of $Q_\infty = 2{,}500$.

Once Q_∞, the total quantity of available oil, has been assessed, the time of maximum production can be evaluated as the time when cumulative production reaches $Q = Q_\infty/2 = 1{,}250$ Gbarrels. This is almost the number we found in the previous section for the number of barrels historically produced until 2011. The production plateau visible after the year 2005 on Fig. 3.1 is not just one among others. It is *the* plateau, the peak of oil production frequently referred to as the "peak oil." It absolutely does *not* mean we are running out of oil right now. With a production curve roughly symmetric around its peak, it will take at least 100 years for it to come back to zero. But it does mean conventional oil production is bound to decline from now on.

As the peak of world oil production has been reached, it means the same peak is *history* for most of the largest producing countries.[4] In Europe, both Norway and UK have already peaked around 2000. On the American continent, the USA, still the third world producer in 2012, reached its peak in 1970. Both Mexico and Venezuela have peaked, while Brazil is still on the rise. Toward the East, Saudi Arabia and Russia, the two largest world producers, are probably near their peak. For the former, the Hubbert analysis of the production yields a total reserves estimate of less than 250 Gbarrels, while more than 130 (at least half of the total) had been produced until

---

[4] See www.indexmundi.com or BP Statistical Review of World Energy June 2012.

2011. For the latter, the same analysis gives a total amount of oil to recover toward 200 Gbarrels with nearly 90 already produced. At any rate, the peak is near for these two champions.

The question "how many years left until we run out of oil?" is not very meaningful. It gives the sensation that we could be in business-as-usual mode until production vanishes. The truth is that production will vanish only *progressively* over many decades. With countries like China, India, or Brazil on the rise, tensions on oil prices should become extreme as the number of guests coveting a shrinking cake is going up. The important point for us in 2013 is that decline starts now. As of January 2013, Exxon, Shell, BP, and Total all had to admit a declining crude oil production.[5]. In 2011, Shell's CEO Peter Voser declared[6]

> Oil output from fields in production declines by 5 percent a year as reserves are depleted, so the world needed to add the equivalent of four Saudi Arabias or 10 North Seas over the next 10 years just to keep supply level, even before much of an increase in demand…We most probably will see a tightening of the supply-demand balance and hence rising energy prices for the long term. I think we should just get used to that.

The end of cheap oil has definitely arrived.

What we have checked for oil is also true for coal and gas. Both exist in finite quantities, so both are bound to run out one day. For gas, the peak could occur around 2020 [7,8], while for coal, it could be around 2050 [8–10]. Altogether, fossil fuels should peak toward 2060.

The mere finiteness of fossil resources sets a first term for the need to find alternatives. Do we really have some 50 years left to cook some serious substitutes? We will now see that pollution and climate issues do not leave so much time.

3.3 Pollution

Burning fossil fuels would be no problem at all if it were not for pollution. Unfortunately, pollution is intimately linked to the very nature of these fuels. From the atomic point of view, fossil fuels are overwhelmingly carbon. One ton of oil, for example, contains more than 800 kg of carbon atoms.[7] The rest is mostly hydrogen. Could it be otherwise? No, because fossil fuels are nothing but decomposed organic matter, and life is carbon based for some fascinating chemical reasons we cannot emphasize here [11]. Could the carbon in organic matter become something else before oil, or gas or coal, is formed? Again no, because only chemistry acts in the process. From

---

[5] *Le Monde*, January 8, 2013. http://petrole.blog.lemonde.fr/2013/01/08/exxon-shell-bp-total-les-rois-du-petrole-sont-ils-nus-2/

[6] *Financial Times*, September 21, 2011.

[7] See the Wikipedia article on "Petroleum." This is a lower bound; the exact number depends on the kind of oil considered.

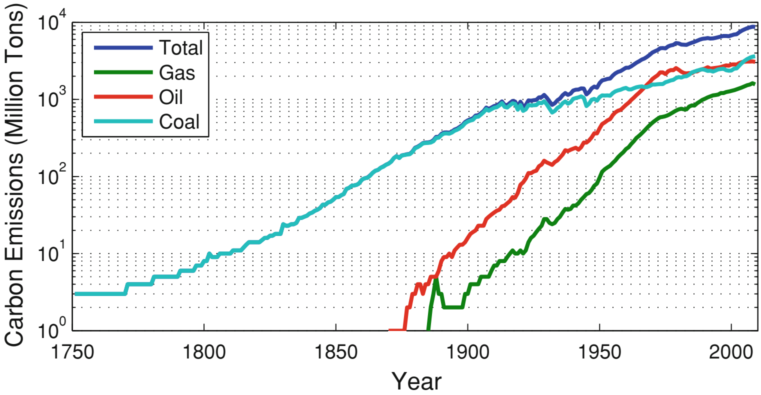

Fig. 3.4 World emissions of carbon per fossil fuel use from 1750 to 2009 (in millions of tons). The logarithmic vertical axis evidences more than 250 years of exponential growth. Because fossil fuels are almost exclusively carbon, emissions and consumption are parallel. *Source* Carbon Dioxide Information Analysis Center, www.cdiac.ornl.gov/

living matter to fossil fuels, chemistry has a lot to do. But chemistry only modifies the molecular composition, not the kind of atoms involved. It takes *nuclear* reactions to do this. Chemical reactions cannot. Therefore, every carbon atom of a decomposing T-Rex makes its way to the fuel it becomes.

Suppose you burn one ton of gasoline in your car. Where goes the carbon? Possibly some of it remains in your engine, but the amount cannot be anything but extremely small as your car is hardly heavier after than before. The only possible conclusion is that carbon comes out of your car, into the atmosphere. Fossil fuel pollution is thus *necessary*. It cannot be otherwise.

The exponential rise of coal, oil, and gas consumption has thus been accompanied by an exponential rise of pollution. And cars are not the only ones involved. It takes fossil fuels to generate 67 % of the world electricity[8] or to run almost every single industrial process. As a result, carbon emissions into the atmosphere have been rising for more than 250 years, as evidenced on Fig. 3.4. Here, the logarithmic scale[9] on the vertical axis makes it clear the increase has been exponential and has yet to find its upper limit. From 1750, coal is found to be the first exploited fossil fuel, triggering the industrial revolution. By the middle of the nineteenth century, oil production emerges in Russia, USA, and Canada, with natural gas as a by-product [12, p. 33]. Pollution, hence energy, comes overwhelmingly from coal combustion until the beginning of the twentieth century. Then, the rise of modern transportation boosts liquid fuel usage. The pace of emission increase is strikingly robust over two centuries and

---

[8] Number for the year 2010, see [1].

[9] On a normal scale, ticks are regularly spaced, as in "1 ton, 2 tons, 3 tons…". On Fig. 3.4, numbers are multiplied by 10 between one tick and the next. As a result, the vertical axis now reads "1 Mt, 10 Mt, 100 Mt…". Such is a *logarithmic scale*.

half. Note that deforestation, another important source of carbon emission,[10] is *not* accounted for here.

Today, about 9 gigatons of carbon are poured in the atmosphere each year, in complete correlation with the 12 Gtep of energy produced a year [1]. Note that this is just the weight on the carbon *atoms*. But since carbon cannot make a molecule alone, it is always found associated with other atoms. Most of the time, it joins two oxygen atoms to form CO_2, or four hydrogen atoms to form a CH_4, methane, molecule. If these gases were harmless, life would be much easier. As oil production declines, we could generate liquid fuel from coal through the so-called Fischer-Tropsch process, keeping our cars and planes running.[11] We could also use every non-conventional resources available. Of course, these non-renewable resources would eventually peak and run out, but we would have plenty (enough?) of time to replace them.

The reason why time is short is precisely because these gases are *not* harmless. Carbon dioxide, CO_2, is one of these so-called greenhouse gases capable of warming up the atmosphere. Still, could anthropogenic emissions be negligible? After all, a few molecules of poison in a glass of water would not kill anyone. There are some 720 gigatons of carbon in the atmosphere, mostly encapsulated in CO_2 molecules [14]. By now, 9 gigatons are added each year, that is, 1.25 % of the total amount. Even if one single year of emission is not a big deal, one hundred years of emission, even at a lower rate, are not negligible at all. From the numbers used in Fig. 3.4, it is straightforward to compute that as of 2009, 355 gigatons of carbon had been emitted since the beginning of the industrial era. Compared to 720 gigatons, this is unequivocally something. Therefore, *if* carbon plays a role in the atmosphere, anthropogenic emissions cannot do anything but altering it. We shall now check that carbon does play a role, a warming role, and that human emissions are definitely detectable.

References

1. International Energy Agency, *Key World Energy Statistics (International Energy Agency 2012)*
2. C.J. Campbell, J.H. Laherrère, The end of cheap oil. Sci. Am. **278**(6), 8A (1998)
3. C.A.S. Hall, K.A. Klitgaard, *Energy and the Wealth of Nations: Understanding the Biophysical Economy* (Springer, Berlin, 2011)
4. J. Tainter, *The Collapse of Complex Societies. New Studies in Archaeology* (Cambridge University Press, Cambridge, 1990)
5. M.K. Hubbert, United States, National Bureau of Standards. Techniques of Prediction as Applied to the Production of Oil and Gas (NBS special publication. National Bureau of Standards, 1982).

---

[10] When you cut a tree and burn it, the carbon it contained is released into the atmosphere.

[11] Having a lot of coal and little oil, Germany used the Fischer-Tropsch process extensively during World War II. Altogether, it provided half of Germany's total oil production during the war ([13, p. 344]).

6. K.S. Deffeyes, *Beyond Oil: The View from Hubbert's Peak* (Farrar, Straus and Giroux, 2006)
7. R.W. Bentley, Global oil and gas depletion: an overview. Energy Policy **30**(3), 189 (2002)
8. G. Maggio, G. Cacciola, When will oil, natural gas, and coal peak? Fuel **98**, 111–123 (2012)
9. S.H. Mohr, G.M. Evans, Forecasting coal production until 2100. Fuel **88**(11), 2059 (2009)
10. Mikael Hook, Werner Zittel, Jorg Schindler, Kjell Aleklett, Global coal production outlooks based on a logistic model. Fuel **89**(11), 3546 (2010)
11. Norman R. Pace, The universal nature of biochemistry. Proc. Nat. Acad. Sci. U.S.A. **98**(3), 805–808 (2001)
12. V. Smil, *Energy Transitions: History, Requirements* (Praeger, Prospects, 2010)
13. D. Yergin, *The Prize: The Epic Quest for Oil, Money, and Power* (Simon & Schuster, New York, 1991)
14. P. Falkowski, R.J. Scholes, E. Boyle, J. Canadell, D. Canfield, J. Elser, N. Gruber, K. Hibbard, P. Hgberg, S. Linder, F.T. Mackenzie, B. Moore III, T. Pedersen, Y. Rosenthal, S. Seitzinger, V. Smetacek, W. Steffen, The global carbon cycle: a test of our knowledge of earth as a system. Science **290**(5490), 291 (2000)

ABC of Climate Science

4

By changing the atmosphere composition, fossil fuel emissions couple humanity energy use to the climate. This chapter will focus on climate science, uncovering the link between climate and anthropogenic greenhouse gases emissions.

Let us start answering an extremely frequently asked question: What is the difference between "climate" and "weather"? How can we forecast climate change 20 years ahead, when it is difficult to forecast the weather 20 days from now? Another question may answer this one: if you live in the Northern Hemisphere, like me, how can you be sure August will be hotter than January? I reside in Southern Spain, where summers are extremely hot. Absolutely no one would bet August might be cooler than January. How can we be so sure? Simply because Spain receives more sunlight in summer than in winter. If more energy enters, temperature has to rise. Likewise, storms are not exceptional in summer. You can thus claim without risk that August will be hotter than January, *and* that there will be a few storms. But it would be extremely hazardous to pinpoint the stormy days.

Climate is easily predicted, weather is not. Climate has to do with what happens *on average*. Weather has to do with what happens *really*. As the climate scientist Mike Hulme simply puts, "climate is what you expect, weather is what you get" [1, p. 9]. For any given place at any given time of the year, average temperature, precipitation, humidity, etc., are known and predictable. But it is impossible to know with certainty whether it will rain or not in Paris, France, one month from now. Such is the difference between climate and weather.

Since this chapter is all about elucidating the link between human emissions and climate change, we shall start taking notice of the change. Even before we understand what is going on, it is useful to notice that "something" is happening. Sea level is rising, global mean temperature is increasing, glaciers are receding. This is all happening right now. The question is not "is there such thing as a climate change?" but rather "what are the causes of the climate change?"

Answering this question requires the ABC of Climate Science. And the "A" of the ABC is the concept of energy balance, namely that all the energy the Earth receives from the Sun eventually goes back to space. Much of the climate science lies there, between how much energy enters, how it enters, and how it leaves. Once this point

A. Bret, *The Energy-Climate Continuum*, DOI: 10.1007/978-3-319-07920-2_4

will be understood, we will see what numerical models, who successfully reproduce past climate evolution, have to tell about the future.

4.1 Something's Happening

A number of measurements performed over the past decades are unambiguous indicators that climate is changing.[1] Though not the best indicator (see below), let us start with global mean temperature. It is rising. What exactly is "global mean temperature"? Before going on vacation, it is easy to check the mean temperature for any given month at any given place. Taking the mean value of all the average temperatures around the globe for a given month, gives the mean *global* temperature for that month. From this *monthly* global temperature, you can derive an *annual* global temperature, simply averaging from January to December. The mean global temperature is therefore an average in space, around the globe, and in time, in general over a month or a year.

For brevity, let us denote our mean global temperature by the symbol T_g. A few general principles regarding mean values may be worth reminding. Suppose observations show T_g is decreasing over two decades. You will deduce the Earth is cooling, in the same way you would deduce summers in Paris, France, are getting cooler if you find out the mean June through August temperature in Paris has been going down over the last years. Note that you would deduce cooling even if some years were hotter than the previous one. You would focus on the *trend*. It is like the evolution of a share in the stock market. Claiming Apple Computer has been on the rise in September does not mean its share went up every single day. It means the overall September trend was rising.

Also, a decreasing T_g does not imply temperature must decrease at every single location on Earth. Consider a classroom with 20 children. The teacher gives a test each month, and after a few of them observes that the mean grade is rising. Does it mean every single kid got better grades, test after test? Not at all. You can perfectly have a rising average grade *and* a few kids receding. The year 2010, for example, got the highest T_g since 1880 (see Fig. 4.1). Yet, 2010 was hotter than the 1971–2000 average in Canada, but *cooler* than the same average in Scandinavia.[2]

To summarize, T_g is an average in time and space. The important is the trend over a few years, not the evolution from one year to the next. As an average in space, every locations do not need to mimic the evolution of T_g. Some of them can even go against. This is simply mathematical.

---

[1] As early as 1859, John Tyndall found out carbon dioxide greenhouse properties. Mike Hulme's book *Why We Disagree About Climate Change* [1] contains a great exposition of the discovery of climate change.

[2] See www.noaa.gov.

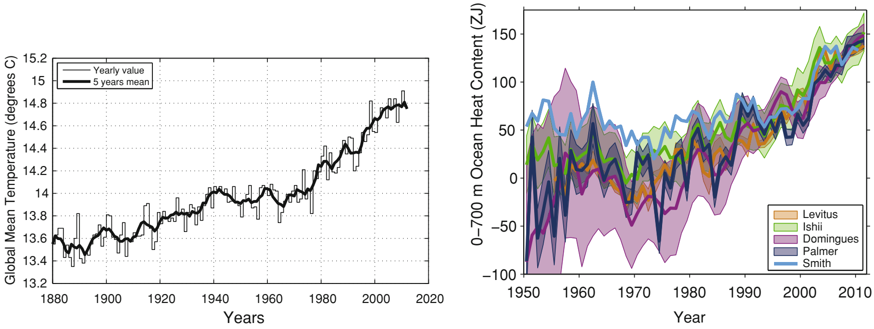

Fig. 4.1 *Left* Global mean temperature in °C since 1880. *Source* Hansen, J.E., R. Ruedy, M. Sato, and K. Lo, NASA Goddard Institute for Space Studies. Data available at http://cdiac.ornl.gov/. *Right* Oceans heat content between 0 and 700 m from various studies, in ZJ (1 ZJ $= 10^{21}$ J). *Source* Climate change 2013: the physical science basis. Working group i contribution to the fifth assessment report of the intergovernmental panel on climate change, Fig. 3.2a p. 262. Cambridge University Press [2]

Turn now to Fig. 4.1-left that pictures the evolution of T_g from 1880. The overall trend is obviously to the rise as more than one degree has been gained between 1880 and 2012. The yearly value fluctuates significantly, and even the 5-year mean does not increase steadily. The warming is thus appreciable over, say, 10-year-long periods of time.[3]

The atmosphere is warming, so do the oceans. It is quite logical as both are in close contact. Figure 4.1-right shows the upper (0–700 m) oceans heat content evolution from various studies. Here also, the trend is unequivocal.

As a consequence of the observed warming, land and sea ice extensions are shrinking. In the Northern Hemisphere, the portion of the Arctic Ocean covered by ice is receding while Greenland ice sheet is losing mass. In the South, the amount of ice accumulated over Antarctic is equally decreasing. Everywhere on the continents, glaciers are also losing mass. Figure 4.2 evidences these trends. As a consequence of the ice loss, sea level has been raising for the last decades.

Regarding this last effect, two points are to be made. First, only melting land-ice contributes to the rising. It is easy to check that an ice cube melting in a glass of water does *not* raise the level, simply because once it is melted, the cube occupies exactly the volume of ice below water at the beginning. Therefore, only glaciers, Greenland, and Antarctic melting, contribute to sea-level rise. Arctic sea ice does not have anything to do with it. Second, sea level rise originates only in part from the melting. The other part comes from water dilatation due to the warming evidenced on Fig. 4.1-right [2, p. 1151]. Though less famous, probably because most of us do not sense it directly, oceanic warming accounts for 90 % of the global heat increase [2, pp. 8, 265]. No wonder James Lovelock wrote [5, p. 42],

---

[3] The reasons why T_g fluctuates around its trend are discussed in Sect. 2.7 of Ref. [2].

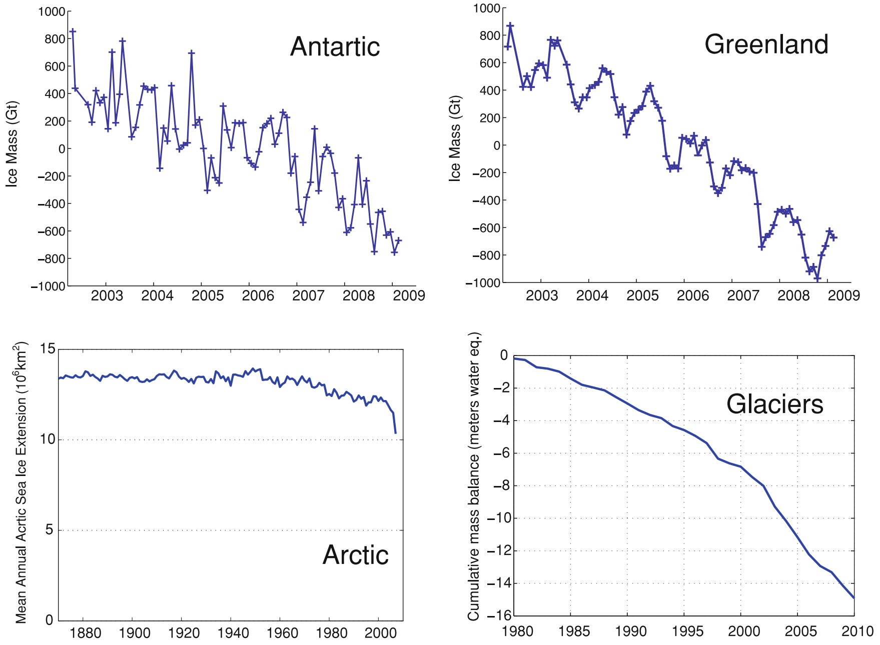

Fig. 4.2 Ice loss in Antarctic [3], Greenland [3], Arctic and world glaciers. *Sources Arctic* [4]. World glaciers: world glacier monitoring service, www.wgms.ch/

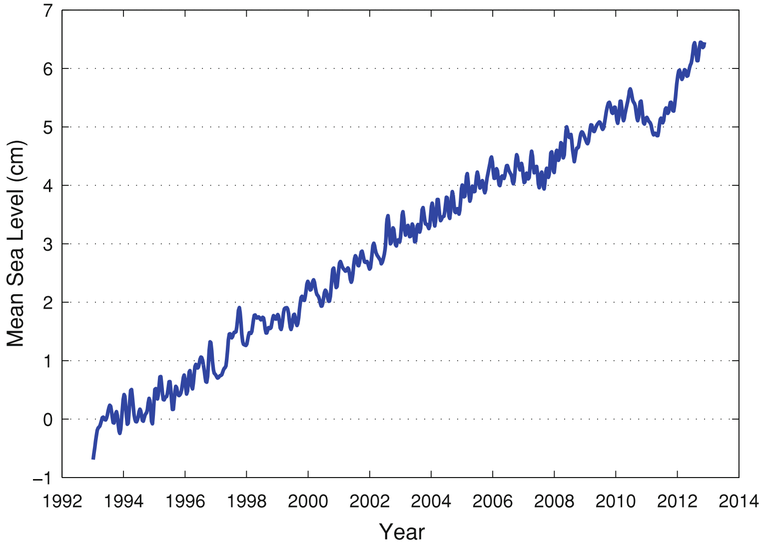

Fig. 4.3 Satellite measurements of the mean sea-level rise since 1993. The observed trend is 3.16 mm/year. *Source* CLS/Cnes/Legos, www.aviso.oceanobs.com/msl

> Sea-level rise is the best available measure of the heat absorbed by the Earth because it comes from only two main causes. The melting of the glaciers on land and the expansion of the ocean as it warms—in other words, sea level is a thermometer that indicates the true global warming.

Figure 4.3 displays some satellite measurements of the mean sea-level rise since 1993. The year 1993 is taken as the reference. An overall rising trend corresponding to 3.16 mm/year is observed. Something, definitely, is happening. The cryosphere, a word that now designates the portion of our world where water is solid, is melting. Global temperature and sea level are rising. Let us now try to understand what is happening, starting with the crucial concept of energy balance and the corresponding equation.

4.2 Energy Balance

A surface oriented toward the Sun on the Earth orbit receives from the Sun about $C_S = 1{,}370\ \text{W/m}^2$ (see calculation in Sect. 6.2). The Earth radius R_e being 6,400 km, it intercepts the total solar power,

$$P_S = \pi R_e^2 C_S = 1.76 \times 10^{17}\ \text{W}. \tag{4.1}$$

In just one second, the Earth receives 1.76×10^{17} Joules. And it has been like this for some 4.5 billion years. How is it that the Earth is not burning? How is it that the Earth has not been vaporized yet? We find here an instance where the law of energy conservation (see Sect. 2.3) becomes tangible and yet, enigmatic. It is obvious that energy arrives every second from the Sun. If energy conservation is true, where does it go?

Like cars entering a parking (where do they go after?), the problem has only two possible solutions. Either Sun's energy gets stored somehow on Earth, or it eventually comes back to space. Let us start examining the first option.

The problem under scrutiny is therefore: to which extent could the Earth store the energy it receives from the Sun? Regardless of the timescales and mechanisms involved, it could be stored under the form of chemical energy in plants and trees, or fossil fuels. Another possible reservoir could be the heat of the oceans. We will now perform a series of order of magnitude calculations to quantify, even loosely, the capacity of these reservoirs.

4.2.1 Capacity of Forests as a Reservoir

One meter square of Earth receives[4] on average $P_S/4\pi R_e^2 = C_S/4 = 342$ W. Considering photosynthesis can exploit at best 5 % of it ([6], [7, p. 140]), a growing forest can absorb 17 W/m^2. Assuming it reaches maturity after 100 years,[5] it will

---

[4] We forget here about the "albedo." See Sect. 4.3.

[5] Regarding these 100 years, see the calculation performed in Sect. 5.5.

eventually contain at most

$$17 \times 100 \times 365 \times 24 \times 3600 = 53 \ \ \mathrm{GJ/m^2}. \tag{4.2}$$

Let us now assume (certainly exaggerating) that 50 % of dry land is made of forest. Since dry land is 30 % of the Earth surface, forests amount to some 77×10^6 km^2. Multiplying this surface by the energy density previously derived, we come to the conclusion that the amount of energy stored in vegetation is about,

$$E_V = 53 \ \mathrm{GJ/m^2} \times 77 \times 10^6 \ \mathrm{km^2} = 4.16 \times 10^{24} \ \mathrm{J}. \tag{4.3}$$

It is now worth comparing this number to the total power received from the Sun derived in Eq. (4.1). Dividing the former by the later, one finds the Sun irradiance “fills” the vegetation reservoir in just 273 days! Because we are talking billion years, this reservoir is obviously inadequate. Let us now turn to the energy oil can store.

4.2.2 Capacity of Oil as a Reservoir

This calculation can obviously be made for gas, or coal, as the result will prove this kind of reservoir equally inefficient. The conclusion is here even more straightforward. According to the most optimistic estimates of the oil industry, the total amount of conventional oil ever present in the ground was about 3×10^{12} barrels, of which some 1×10^{12} have already been extracted.[6] With a 160-liters barrel, and considering a density of $\sim$1 g/cm^3, this amounts to 4.8×10^{14} kg of oil. Since the combustion of 1 kg of oil releases some 42 MJ, the overall reservoir contains,

$$E_O = 2.16 \times 10^{22} \ \mathrm{J} \ = \ 34 \text{ hours of Sun}. \tag{4.4}$$

Here again, we find the reservoir far too small to play a role in containing the Sun energy received by the planet during the last billion years. The number itself shows that adding unconventional oil, coal or gas to the calculation will not solve the problem.

4.2.3 Capacity of the Oceans as a Reservoir

Let us now check how much energy could be stored in the oceans. The volume of water they contain is about 1.3×10^9 km^3. Considering a heat capacity of 4.2 kJ/kg/K, we find the energy absorbed by the oceans when gaining 1 K,

$$E_W = 5.43 \times 10^{24} \ \mathrm{J} \ = \ 356 \text{ days of Sun}. \tag{4.5}$$

This third reservoir is equally found wanting. Even if an increase of 1 K can capture almost one year of Sun energy, the process cannot proceed for more than 100 years.

---

[6] See Chap. 3. The $3 \times 10^{12} = 3{,}000$ Gbarrels are a little more optimistic than the 2,500 we found.

4.2.4 Conclusion: The Energy Balance

These three Fermi-like calculations make it clear that the power from the Sun cannot be stored on Earth on a billion year timescale. Indeed, we just checked that given its consequences, the imbalance time in 4.5 billion years must be smaller than ~ 1 year, which amounts for some 10^{-10} of the total. Returning to the image of a parking facility, we find some 10^{10} cars (the energy) entered, while there is room for just one car. The only solution is that the number of cars leaving the parking in (almost) any amount of time, is (almost) exactly the number of cars entering it.

At this stage, the conclusion is inescapable: If there are no long term storage solutions, the energy coming in *must* eventually come out. Now, there are three ways of transporting energy: You can put it inside some container, and take the container away. This is convection. You can also heat one side of an object and have heat propagate. This is conduction. Finally, you can have light carry away the energy for you. This is radiation. Because Earth is surrounded by virtually nothing, you cannot get rid of the energy through convection nor conduction. The only way out is *radiation*. Assuming an average temperature T_e, the Stefan-Boltzmann law tells the radiated power per meter square is σT_e^4, where $\sigma = 5.67 \times 10^{-8}$ W/m^2/K^4 is the Stefan-Boltzmann constant.[7] Equating this quantity with the amount of power received, we find,

$$C_S/4 = \sigma T_e^4. \tag{4.6}$$

Though the evaluation of the reservoirs capacity is highly approximate, the orders of magnitude involved are so disparate that there is no way to escape the need for an energy balance. Accounting for unconventional oil reserves such as "tar sands", or for a higher photosynthesis yield, cannot yield some reservoir large enough to retain a significant portion of the energy poured by the Sun over billions of years.

4.3 Elements of Climate Modeling

4.3.1 Elementary Model

Equation (4.6) is the starting point of climate modeling. It relates the temperature to the amount of energy received from the Sun. Now, T_e has to be an average temperature, as every place on Earth does not receive the same amount of sunlight. If our planet were a single point, T_e would be the temperature of this point. Let us start examining this "zero dimension model," as Kendal McGuffie and Ann Henderson-Sellers name it in *A Climate Modeling Primer* [8].

Our Eq. (4.6) needs some tuning in order to account for two kinds of processes. First, part of the incoming energy never really enters. Sunlight enters the atmosphere as visible light. It gets absorbed by the Earth, which in turn emits radiation in the

---

[7] In terms of fundamental physical constants, $\sigma = \pi^2 k_B^4 / 60\hbar^3 c^2$ where k_B is the Boltzmann constant, $\hbar$ the Planck constant h divided by 2π, and c the speed of light.

infrared range, which is *not* visible. How is it then that astronauts could take pictures of the Earth from the Moon? Because part of the Sun visible radiation bounces back to space as soon as it hits the Earth. The bounced back percentage is called the "albedo" and is conventionally labeled by the Greek letter α. Therefore, the power that really comes in and has to be re-emitted is not $C_S/4$, but $(1-\alpha)C_S/4$. With $\alpha = 30\,\%$ (see Table 4.1), the average power received is not 342 but 240 W/m^2.

Second, the planet may have an atmosphere (it does not have to be the Earth) that could be opaque to some radiations. We all know how x-rays may see through our body, while visible light cannot. This is why we cannot see behind someone while x-ray radiography allows to monitor broken bones. The thing is, some materials are transparent to some wavelengths, and opaque to others. The radiation a planet emits to outer space consists in various wavelengths. And depending on its composition, an atmosphere can be opaque to some wavelength, and transparent to others. In the absence of atmosphere, the amount of energy carried away by all the emitted wavelengths is σT_e^4. But if the atmosphere blocks some of them, the amount of energy eventually escaping is lower and can be written $\varepsilon\sigma T_e^4$, where ε is smaller than unity. This phenomenon ends up increasing the temperature, because if the number of wavelengths energy can "ride" is reduced, temperature must rise for the authorized wavelengths to carry out the same amount of energy. This mechanism is exactly the one operating in greenhouses, where incoming radiation is trapped inside a glass-like room. This is why it is called the "greenhouse effect". The new energy balance equation then reads,

$$(1-\alpha)C_S/4 = \varepsilon\sigma T_e^4, \tag{4.7}$$

which gives directly the temperature

$$T_e = \left(\frac{(1-\alpha)C_S}{4\varepsilon\sigma}\right)^{1/4}. \tag{4.8}$$

The value of C_S will be calculated later in this book, when talking about solar power in Sect. 6.2. Borrowing its expression from Eq. (6.7), we find a very simple expression for the average temperature of a planet orbiting at distance D from the Sun,

$$T_e = T_S\left(\frac{1-\alpha}{\varepsilon}\right)^{1/4}\sqrt{\frac{R_S}{2D}}, \tag{4.9}$$

where T_S is the Sun surface temperature, and R_S its radius.

While an increasing albedo α cools the planet (it receives less), the greenhouse parameter ε warms it all the more that it is small. Figure 4.4 may help illustrate this point. Our planet needs to balance the incoming power adjusting its $\varepsilon\sigma T^4$ emission. For lower values of ε, the $\varepsilon\sigma T^4$ curve gets lowered as well. But because the incoming power has not changed, it takes a higher temperature to give it back to space. Note that every single Watt received is eventually sent back. It just takes a higher temperature to do it.

The mechanism through which temperature automatically adjusts to its equilibrium value is quite simple. Suppose temperature is too low. Then, we see on Fig. 4.4 that the amount of energy out is lower than what comes in. There is a net energy gain,

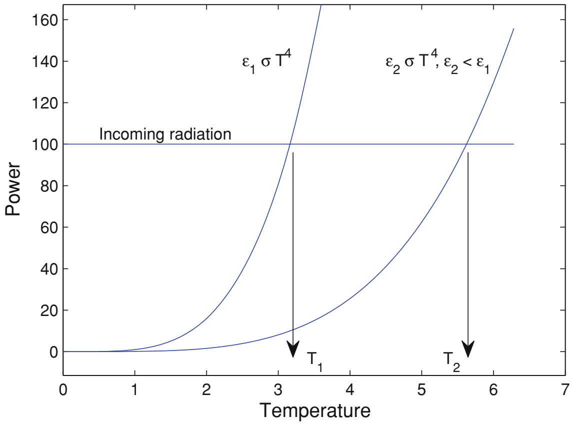

Fig. 4.4 The temperature balancing the incoming and outcoming power increases when the greenhouse coefficient decreases. Units are arbitrary

Table 4.1 Parameters entering Eq. (4.9) for the planets of the solar system

Planets	D (10^6 km)	Albedo	T measured	T from Eq. (4.9)
Mercury	58	0.068	440	436
Venus	108	0.9	737	183
Earth	150	0.3	288	253
Mars	228	0.25	208	208
Jupiter	779	0.34	163	109
Saturn	1,434	0.34	133	80
Uranus	2,873	0.3	78	58
Neptune	4,495	0.209	73	48
Pluto	5,870	0.5	48	37

Temperatures, all in degrees Kelvin, have been computed setting $\varepsilon = 1$ in Eq. (4.9). *Source* NASA Planetary Fact Sheet, http://nssdc.gsfc.nasa.gov/planetary/factsheet/

and temperature rises. Suppose now temperature is too high. The same figure shows energy out now surpasses the incoming one. We now have a net energy loss, and temperature falls. Like a marble in a bowl comes back to the bottom, temperature spontaneously comes back to its equilibrium value.

Since there is more than one planet in the solar system, why do not we test our formula on some of them? Table 4.1 gathers the parameters involved in Eq. (4.9) for the planets of the solar system, with the theoretical temperatures given by this same equation when neglecting greenhouse effect (i.e., setting $\varepsilon = 1$ in the equation). In order to visualize the agreement between the measured temperatures and the computed ones, Fig. 4.5 plots both quantities for each planet in terms of the planets' distance to the Sun. Several comments are appropriate.

- First, our little toy model is not that wrong. Even forgetting about greenhouse effect, we get the correct orders of magnitude and capture the trend $T \propto D^{-1/2}$.

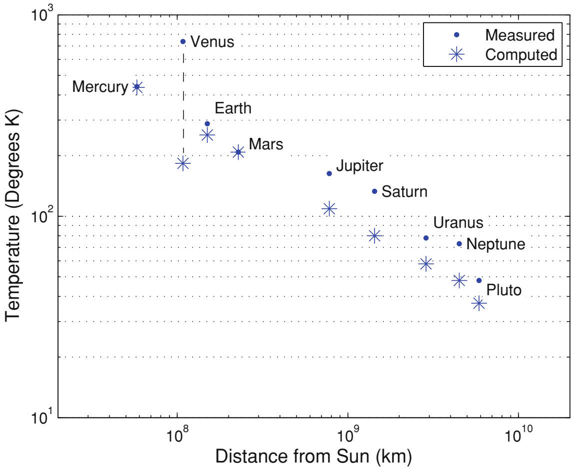

Fig. 4.5 Plot of the measured and computed temperatures listed in Table 4.1. The dashed line linking the Venus data is just an eye guide

- Second, the measured temperatures are always *higher* than the computed ones. This is because setting $\varepsilon = 1$ implies we systematically miss the greenhouse warming factor (see Fig. 4.4).
- Third, for the planets with almost no atmosphere, namely Mercury, Mars and Pluto, the agreement is very good. Note that the logarithmic scale amplifies the discrepancy for Pluto, while the error is only 22 %. For the others, the greenhouse effect operates through their atmosphere and warms them. Yes, such effect is not specific to Earth and operates throughout the Solar System.
- Fourth, Venus data are striking. Here, the actual temperature is four times the greenhouse-less one. Venus is 737 K hot (464 °C) and would be only 183 K (−90 °C) without greenhouse effect.[8] What happens there? It turns out that CO_2 amounts for 96.5 % of Venus' atmosphere [9]. And CO_2 is a notorious greenhouse gas.

Without greenhouse effect, Eq. (4.9) gives a mean temperature equal to 253 K, −20 °C, for the Earth. Quite cold indeed. The reason why we experience a mild average temperature of about 15 °C is the greenhouse contribution. Setting $\varepsilon = 0.6$ in Eq. (4.9) readily gives $T_e = 288$ K, or 15 °C. Without greenhouse effect, it would be far too cold down here.

4.3.2 Beyond the Elementary Model

Our basic climate model is therefore able to provide the average temperature on any planet, once its albedo and greenhouse parameters are known. How can we go further that this? We would like now to describe a real planet Earth, and have something to say about the average temperature in Africa or Asia for example. A complete

---

[8] Such a low temperature without greenhouse effect is due to Venus' extremely high albedo $\alpha = 0.9$.

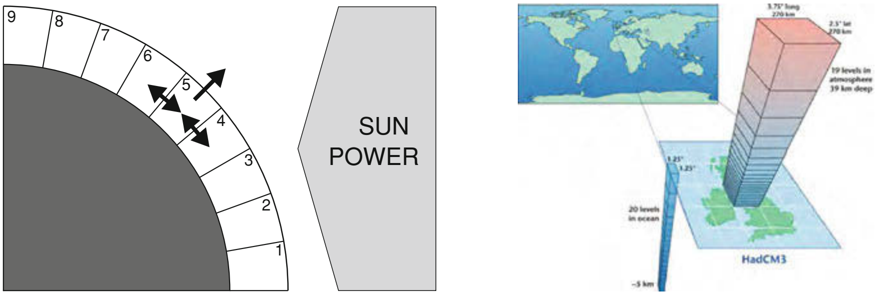

Fig. 4.6 *Left* Basic principles for a more elaborated climate model. Each cell receives Sun power, radiates to space and exchange energy with its neighbors. Not to scale. *Right* Cell structure of the "HadCM3" global climate model. *Source* [12, p. 30]

exposition of contemporary climate modeling clearly goes beyond the scope of this book, and we refer the reader to excellent treaties on this topic [8,10,11]. Yet, it is useful to give a flavor of how a more complete model can be constructed from the physical basis we just exposed. We thus now describe how to elaborate a still simple 1D climate model. It is not a full fledged 3D model yet, but it can help figuring out how to get there.

Consider a 2D disk-like planet with a 1D atmosphere. It means we do not care so far about climate differences with altitude (state of the art models do). Figure 4.6-left represents a quarter of the disk. The planet surface is here divided into 9 cells, but a computer treatment of the problem would let you chose much more. The basic idea is to write an energy balance equation for each cell. Consider cell number 5 for example. The Sun power entering it will read $(1-\alpha_5)C_{S5}$. Note that both the albedo and the incoming Sun power appear with the subscript "5" because these quantities are now cell-dependent. Land, sea, or ice do not have the same albedo, and incoming Sun power varies with latitude. Cell 5 also radiates energy out, as $\varepsilon_5\sigma T_5^4$. Here again, greenhouse parameter and temperature are cell-dependent, hence the subscript "5". Finally, cell 5 exchanges energy with cells 4 and 6. The energy exchange can be modeled in terms of the temperature difference between adjacent cells, like $\delta_{5,4}(T_5-T_4)+\delta_{5,6}(T_5-T_6)$ where the δ's are coefficients that may vary from cell to cell. The energy balance equation for cell 5 eventually looks like,

$$(1-\alpha_5)C_{S5} = \varepsilon_5\sigma T_5^4 + \delta_{5,4}(T_5-T_4) + \delta_{5,6}(T_5-T_6). \tag{4.10}$$

If $T_5 > T_4$, cell 5 gives energy to cell 4 so that $\delta_{5,4}(T_5-T_4) > 0$ appears on the "loss" side. What has been done for cell 5 can obviously be done for every cell. The result is a system of 9 equations with 9 T_i's unknown. It can be solved provided the physical parameters (α_i, C_{Si}, ε_i ...) are known for each cell i. Because these parameters usually depends on temperature (for instance, sea becomes ice for $T < 0\,^\circ\mathrm{C}$, which changes the albedo), numerical calculation is required.

Such division of the outer disk of a 2D planet can be performed on the surface of a real, 3D planet. Modern "Global Climate Models" divide the Earth surface into N cells, N being as large as your computer power allows. On the top of each cell, more cells sample the atmosphere. And on the bottom of each ocean cell, even more cells dive into the sea to render its evolution. The "Hadley Centre Coupled Model 3" (HadCM3), developed at the Hadley Centre in the United Kingdom, implements the kind of grid displayed on Fig. 4.6-right, allowing it to model the coupled evolution of the atmosphere and the ocean.[9]

4.3.3 Testing the Models

Before we ask them about the twenty-first century, what do models have to tell about the twentieth? This is obviously the first question to ask. Do they reproduce correctly what already happened? Yes. Global climate models successfully reproduce *past* Earth climate, which allows to trust them for the future.

For example, they correctly render the mean global temperature over the twentieth century, including the drops due to major volcanic eruptions [13, p. 600]. Beyond global data, *local* climate variations already observed are equally depicted faithfully [2, pp. 18, 930]. Indeed, "Evaluation of Climate Models" is the title of the ninth chapter of the IPCC report *Climate Change 2013, The Physical Science Basis* [2].

Interestingly climate models have been found efficient at modeling Mars [14] or Venus [15] climates as well. Such is one of the many benefits of Solar System exploration. There is only one Earth, and only one Earth history. The number of benchmarks Earth climate models can pass is thus limited. By gathering in situ data from Mars and Venus, the physics and the modeling can be thoroughly tested, resulting in increasingly trustworthy forecasting tools.

4.4 So, What's Happening?

These elements of climate modeling show that global mean temperature results from a balance between the incoming solar power and the outcoming radiation. Therefore, if the Earth is warming, as it has been observed in Sect. 4.1, it can be only for two reasons. Either there is more energy coming in, or radiation coming out does it differently.

4.4.1 It Is Not the Sun

Sun activity is obviously the first suspect in this matter. It has been known for long that cyclical variations in the Earth' orbit and inclination, the "Milankovitch cycles",

---

[9] The French "Institut Pierre Simon Laplace" has posted on YouTube a great video on climate simulations at www.youtube.com/watch?v=ADf8-rmEtNg.

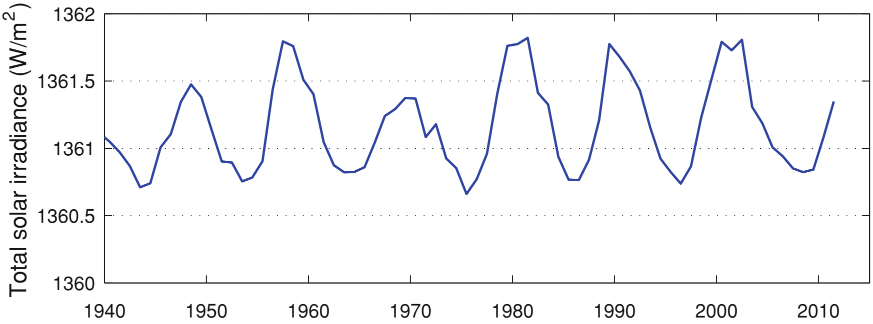

Fig. 4.7 Total solar irradiance since 1940. This is the C_S of Eqs. (4.1, 4.7). *Source* Solar radiation and climate experiment

result in climatic cycles which aftermaths have been detected[10] in ice cores records [8, 17]. The problem is that the shortest is about 19,000 years long, so that they cannot be held accountable for the recent 100 years or so warming trend.

Are there shorter cycles more appropriate to the present problem? Yes. Our Sun presents an 11-year activity cycle worth noticing (similar cycles have been detected for other stars [18]). Figure 4.7 displays the evolution of the total solar irradiance measurements since 1940. This is the C_S of Eqs. (4.1, 4.7). Though frequently called the "solar constant", we can check it is only nearly constant as it fluctuates by 0.1 %. Displaying on the vertical scale numbers from 0 to 1,362 W/m^2 would give an uninteresting flat line. Equation 4.8 shows, after a little math,[11] that a 0.1 % change in C_S should produce a $\frac{1}{4}0.1$ % change of the mean temperature. Putting the numbers gives a temperature shift of only 0.1 K. We miss a factor 10. Variations of the solar constant are indeed so faint that their influence on the climate is difficult to quantify [19]. In addition, there is hardly any correlation between the evolution of C_S observed here, and the trends displayed on Figs. 4.1, 4.2 and 4.3.

Moreover, the 11-year cycle is linked to the internal Sun dynamic [20]. As such, it has been there for a very long time. How could such an 11-year cycle suddenly drive the CO_2 concentration beyond 400 ppm,[12] when it has remained[13] below 300 ppm at least for the last 800,000 years [21]?

---

[10] The French glaciologist Claude Lorius tells how he got the idea in 1965 that ancient air bubble could be trapped in ice cores: "It was when I saw these bubbles bursting when an ice cube melted in a glass of whiskey that I had the feeling they could be reliable and unique indicators of the composition of air, something we subsequently proved was correct". In vino veritas… [16].

[11] Just compute dT_e/dC_S.

[12] See definition in Appendix A.

[13] By the way, this very objection holds against the Milankovitch cycles as well. Besides their improper timescale, how would they suddenly produce something they never did during the last million years?

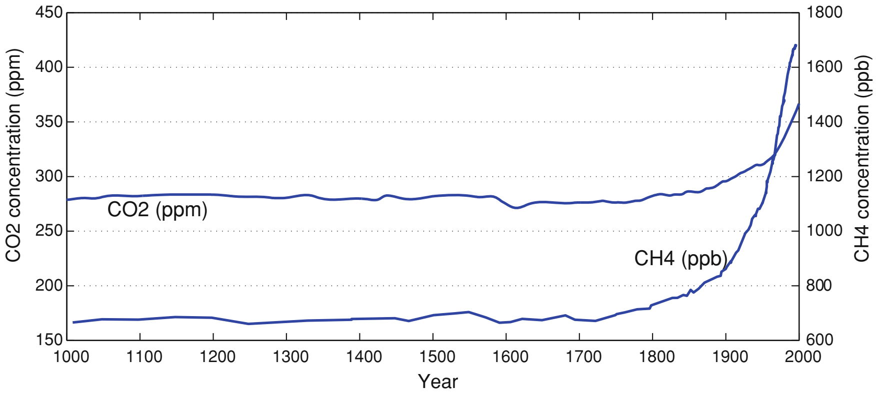

Fig. 4.8 Evolution of the CO_2 (*left scale*, "ppm" = part per million) and CH_4 (*right scale*, "ppb" = part per billion) average annual concentrations during the last 1,000 years. 2012 values are about 390 ppm and 1,800 ppb for CO_2 and CH_4 respectively. *Sources* For CO_2, www.ncdc.noaa.gov/paleo/icecore/antarctica/law/lawdata.html—For CH_4, http://cdiac.ornl.gov/trends/atm_meth/lawdome_meth-data.html

4.4.2 It Is the Atmosphere

If recent warming cannot be attributed to the amount of energy coming in, then the problem must be in the way it comes out. The time has come for greenhouse gases to enter the scene. Sun' radiation makes its way to the ground because the atmosphere is roughly transparent to the wavelengths involved (visible). This energy heats the Earth which in turn re-emits it. But the re-emitted light, or radiation, is in the infrared range.

Now, greenhouse gases interact strongly with infrared light, not with the visible. As already mentioned, temperature has to rise if the same amount of energy is to be expelled to fulfill the energy balance. The most efficient greenhouse gas in the atmosphere is water vapor. Anthropogenic emissions in this respect are so far negligible, and the increase of water vapor detected in the atmosphere simply stems from the fact that warmer air can hold more vapor [2, p. 666]. The second most efficient greenhouse gas in CO_2. Remember Sect. 3.3, where it was established that as of 2009, 355 gigatons of carbon had been added to the atmosphere since the beginning of the industrial era, while 720 gigatons represents the total amount in the atmosphere today. Here, human emissions are not negligible at all.

During the last 800 thousand years and until 1800, CO_2 concentration has been oscillating between 200 and 280 ppm [2, p. 400]. Then, suddenly, concentration rises like pictured on Fig. 4.8. And methane, CH_4, the third most efficient greenhouse gases, follows exactly the same trend.

The expected drop in the outgoing infrared emissions is more than a conjecture. Satellite measurements of the radiation the Earth emits to space have definitely confirmed a decreased of infrared emissions. And the depleted wavelengths do correspond to the ones absorbed by CO_2 and CH_4 [22,23].

But how can we be sure we are responsible for the increase in CO_2 and CH_4 up there? After all, they could originate from somewhere else. Three facts leave almost no doubt:

- First, if carbon emissions come from combustion reactions, then the amount of oxygen in the atmosphere should drop because each time you generate a CO_2 molecule through such reaction, you pair up a carbon atom with an O_2 molecule. Is it observed? Definitely. Atmospheric oxygen concentration is decreasing by the expected amount [2, p. 51].
- Second, carbon on Earth can be found under 3 forms. The "usual" carbon-12, with 6 protons and neutrons in its nucleus, amounts for 99 % of the carbon population. Then, the nuclear isotopes carbon-13 and carbon-14, still with 6 protons, but 7 and 8 neutrons respectively. Carbons 12 and 13 are stable. Carbon-14 is not. It is continuously produced in the upper atmosphere by cosmic rays collisions, and decays to nitrogen with a half-life of 5,730 years.[14] Now, because carnivores eat herbivores and herbivores eat plants, organic matter has the carbon composition of plants. It turns out that photosynthesis, which absorbs atmospheric carbon for the plants, is less efficient with C-13 [24]. If organic matter is poor in C-13, fossil fuels as well because they are made of organic matter. As a result, burning fossil fuels results in massive emission of carbon with less C-13 than normal. Like pouring alcohol free beer in normal beer results in a mixture with less alcohol, the atmosphere C-13 concentration should therefore decrease. Is that observed? Yes, and in the expected proportion [2, p. 51].
  Moreover, fossil fuels are deprived of C-14 since they have been buried for millions of years.[15] Anthropogenic emissions are therefore expected to lower the atmospheric C-14 concentration for the same reason. This was foreseen in 1955 [25] and is definitely observed, again in the expected proportions [26].
- Third, Fig. 4.9 has interesting lessons to teach. The left panel represents the evolution of the CO_2 concentration measured at Hawaii, averaged over a month and a year. A one year long cycle is clearly superimposed over a growing trend. This yearly cycle pertains to the vegetation cycle: because most of it is in the Northern Hemisphere, it "dies" *together* from fall, to get back to life from spring. As trees lose their leaves before growing them again, they release CO_2 through the decomposing leaves, before they absorb it to generate new leaves. Looking at the amplitude of the oscillation, you could deduce the amount of CO_2 emitted and absorbed and check it fits very well the total amount of leaves. What we see here is nothing but the respiration of the Earth biosphere.

---

[14] Suppose you have 1,000 carbon-14 atoms before you. Wait 5,730 years, half of them, will have turned to nitrogen. Wait another 5,730 years, and half of the remaining carbon-14 decay. Every 5,730 years, half of the carbon-14 decay. Until there is no more left.

[15] The number of C-14 atoms is divided by 2 every 5,730 years. So in 1 million years, it is divided (1 000,000/5,730) times by 2, which means divided by $2^{174} = 2.4 \times 10^{52}$. So even if you started with 10^{50} of them, the number of atoms on Earth according to *Wolfram Alpha*, there is not any single one left after 1 million years (the number 10^{50} can be easily checked, order of magnitude wise, knowing the Earth' mass and assuming it is made up of iron).

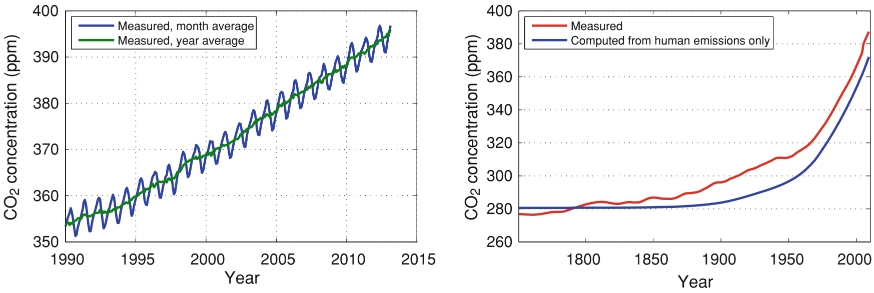

Fig. 4.9 *Left* Monthly and annual mean carbon dioxide measured at Mauna Loa Observatory, Hawaii. *Source* http://noaa.gov. *Right* Measured and (loosely) computed CO_2 concentrations. *Source* Same as Fig. 4.8

Now, what about the upward trend? Its steady pace does not fit punctual natural events like volcanic eruptions for example. But it does fit very well steady human emissions. We can even check the numbers: We know from Fig. 3.4 the amount of carbon emitted since 1750. About 55 % of it stays in the atmosphere, and the rest goes into the oceans ([2, p. 467]). Also, there were about 600 Gt of carbon in the atmosphere before the industrial era [2, p. 471]. Knowing what was before, and what has been added, we can loosely compute the amount of carbon up there from 1,750, hence CO_2 concentration,[16] accounting *only* for human emissions. Why don't we compare now our calculation to the *measured* CO_2 concentration? This is done on the right panel of Fig. 4.9. We cannot expect perfect a fit as our calculation is quite rough and deforestation not accounted for, but the agreement is noteworthy.

Let us summarize what we have so far: We have an observed warming, starting circa 1,800. From the physical basis of climate science, we know such warming must come either from an increased solar flux, or a change in the way the Earth radiates its energy. Looking at the Sun' behavior, we can discard the first hypothesis. Turning now to the second hypothesis, the best candidates to alter energy radiation to space are greenhouse gases. The most efficient, water vapor, has not moved much in the last 200 years. But the second and third of these gases, carbon dioxide and methane, have seen their atmospheric concentration rising tremendously during the last 200 years, in response to fossil fuels burning. Both the expected effect and time window perfectly fit observations. Anthropogenic emissions of these gases are definitely the ideal suspects. Finally, Global Climate Models based on basic physical principles, are very efficient at reproducing what is already known on Earth, Mars and Venus climates.

---

[16] One ton of carbon gives 3.67 t of CO_2 by virtue of the atomic weights of carbon and oxygen. For the calculation, we also need the volume of the atmosphere, 4×10^9 km^3, and the CO_2 density, 1.96 kg/m^3.

4.5 Men and Greenhouse

4.5.1 Climate Models and Recent Years

Based on the suspicions we now have, we can ask climate models to quantify the consequences of human emissions. Granted, they fit the expected time window and they go into the right, warming, direction. But this is not enough. Suppose calculations tell human emissions could have produced +0.1 degrees since 1880. Then, we would have to find another culprit because the observed value on Fig. 4.1 is rather 10 times higher. We wrote previously climate models correctly render the mean global temperature over the twentieth century. Let us give some more details about how they do so.

To simulate past climate, models need some inputs like the amount of solar irradiation, the timing of volcanic eruptions which send ashes into the atmosphere, and human emissions evolution. In short, inputs consist in a mix of natural factors (Sun, volcanoes…) and human ones. Now, models successfully reproduce past climate evolution all the way to 2011 only when accounting for natural *and* human factors. When switching-off the latter in the calculation, simulations and observations clearly *diverge* during the second half of the last century [2, pp. 18, 930]. The *quantitative* test is therefore successful. At this junction, let us simply quote a paragraph from the 2013 IPCC report,

> Human influence has been detected in the major assessed components of the climate system. Taken together, the combined evidence increases the level of confidence in the attribution of observed climate change, and reduces the uncertainties associated with assessment based on a single climate variable. From this combined evidence it is *virtually certain* that human influence has warmed the global climate system. Anthropogenic influence has been identified in changes in temperature near the surface of the Earth, in the atmosphere and in the oceans, as well as changes in the cryosphere, the water cycle and some extremes. There is strong evidence that excludes solar forcing, volcanoes and internal variability as the strongest drivers of warming since 1950. (emphasis mine).
> *Climate Change 2013: The Physical Science Basis. Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, p. 871. Cambridge University Press* [2].

Within this IPCC reports terminology, “virtually certain” means more than 99 % confidence [2, p. 36]. Already in the 2007 report, and confidence has grown since then, one could read “it is *extremely unlikely* [<5 %] that the global pattern of warming during the past half century can be explained without external forcing, and *very unlikely* [<10 %] that it is due to known natural external causes alone” ([13, p. 86] emphasis mine). Granted, the confidence level is not 100 % straight, and will never be. But elements are definitively in place to pay attention to models predictions.

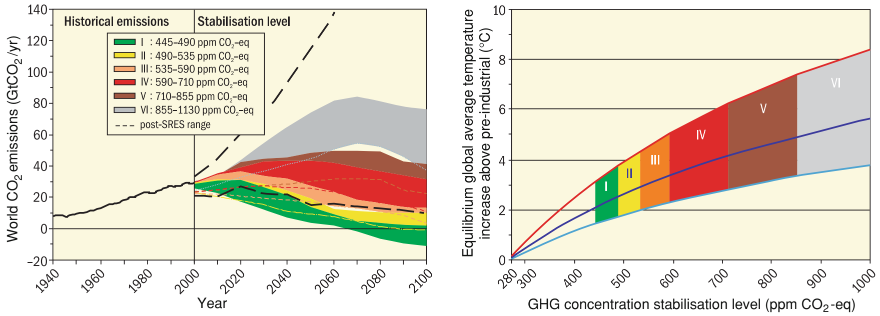

Fig. 4.10 *Left* CO_2 emissions scenarios, from global successful thrive to cut emissions (I), to business-as-usual (VI). *Right* Corresponding long term atmospheric level of greenhouse gases and global average temperature increase above pre-industrial. *Source* Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Fig. 5.1, p. 262. IPCC, Geneva, Switzerland [27]

4.5.2 Climate Models and the Future

When it comes to forecasting climate evolution for the twenty first century, natural *and* human factors again need to enter the equation. On the natural side, future volcanic activity is an unknown quantity which can be modeled assuming an activity similar, on average, to the twentieth century. Other modalities are possible and explored, and we refer the reader to Refs. [2, 13] in this matter. Still, "the eruptions that produce climatologically significant forcing represent just the extremes of global volcanic activity" [13, p. 797]. On the human factors side, the IPCC considers various emission scenarios briefly explained below.

Figure 4.10 can be considered as the climax of this first part, as it gathers all the issues and the questions raised so far. The left part displays various emissions scenarios, from number I where efficient emissions cut policies are globally implemented, to number VI where every single gram of fossil fuels is burnt. Note the peak of emissions in scenario VI around 2060, corresponding to the overall peak of fossil fuels.[17] For each scenario, the right panel shows the equilibrium global average temperature increase above pre-industrial, versus the greenhouse gases (GHG) concentration stabilization level in ppm CO_2 equivalent.[18]

Simply put, scenario VI yields a most probable temperature increase of +5 °C. Not a big deal, one could think. But do not forget we are talking global mean temperature. In this respect, it is sobering to know that some 20,000 years ago, during

---

[17] See a full description of the scenarios in [13] p. 18. Figure 4.10 comes from the 2007 IPCC report. Similar information can be derived from figures SPM.7 & TS.19 of the 2013 document [2], pp. 21 & 94.

[18] CO_2 is not the only greenhouse gas. Methane (CH_4), for example, is another one. All GHG emissions are therefore converted to "CO_2 equivalent" according to rules we will not detail here (see [2, p. 710]). This allows to represent the full amount of GHG emissions with a single number.

the last Glacial Maximum, global mean temperature was only 3 to 8° cooler than now [2, p. 405], with a northern polar ice sheet covering Northern Europe down to Moscow, Berlin and the North of France, and coming as low as New York in North America. So +5°C are definitely a very big deal [28].

Is it about "saving the planet"? Not necessarily. Near-tropical forests could grow in Antarctica some 50 million years ago (early Eocene), at a time where average temperature in winter down there would surpass 10 °C [29]. CO_2 concentration was probably beyond 4,000 ppm [30], and obviously, no ice was to be found on Earth. So high temperature, lots of CO_2 and no ice are not a problem for the Earth. It already happened, and it is still there. But a sea-level rise of 10 m would definitely be a problem for a world where more than 60 % live within 150 km of the coast [31].[19]

Suppose we want to limit warming to 2 to 3° maximum. According to the right panel of Fig. 4.10, we need to stick to scenarios I or II. No more. Turning now to the left panel, we see both scenarios peak around 2020. In other words, fossil fuels renouncement would have to start *tomorrow*. With coal resources that could peak as late as 2050 (see Sect. 3.2), the message is clear: even if there is plenty left, we cannot afford the comfort of fossil fuels anymore. We need to turn away from them even before they are over. The price to pay to postpone 40 years the search for alternative could simply be too high. Let us now review the possible alternatives.

References

1. M. Hulme, *Why We Disagree About Climate Change: Understanding Controversy, Inaction and Opportunity* (Cambridge University Press, Cambridge, 2009)
2. IPCC. Climate Change 2013—The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge (2014)
3. I. Velicogna, Increasing rates of ice mass loss from the greenland and antarctic ice sheets revealed by grace. Geophys. Res. Lett. **36**, L19503 (2009)
4. J.E. Walsh, A data set on northern hemisphere sea ice extent. world data center—A for glaciology (snow and ice). Glaciological Data, Report GD-2, 1:49–51 (1978)
5. J. Lovelock, *The Vanishing Face of Gaia: A Final Warning* (Basic Books, London, 2009)
6. R.E. Blankenship, D.M. Tiede, J. Barber, G.W. Brudvig, G. Fleming, M. Ghirardi, M.R. Gunner, W. Junge, D.M. Kramer, A. Melis, T.A. Moore, C.C. Moser, D.G. Nocera, A.J. Nozik, D.R. Ort, W.W. Parson, R.C. Prince, R.T. Sayre, Comparing photosynthetic and photovoltaic efficiencies and recognizing the potential for improvement. Science **332**(6031), 805–809 (2011)
7. F.A. Armstrong, K.M. Blundell, *Energy...Beyond Oil* (Oxford University Press, Oxford, 2007)

---

[19] The complete melting of Greenland and Antarctica ice sheets would result is a sea-level rise of $7 + 58 = 65$ m [2, p. 321]. Just take their volume, divide by the surface of the oceans, and you find the good order of magnitude. A +5 °C temperature rise could submerge the home of 600 million people, together with 150 of the 981 UNESCO world heritage sites [32]. For more on the impact of climate change, see the 2014 report of the IPCC Work Group II, *Climate Change 2014: Impacts, Adaptation and Vulnerability* (www.ipcc.ch).

8. K. McGuffie, A. Henderson-Sellers, *A Climate Modelling Primer* (Wiley, London, 2005)
9. A.P. Ingersoll, News & views, Venus: Express dispatches. Nature **450**(November), 617–619 (2007)
10. J.T. Houghton, *Global Warming: The Complete Briefing* (Cambridge University Press, Cambridge, 2004)
11. J.D. Neelin, *Climate Change and Climate Modeling* (Cambridge University Press, Cambridge, 2010)
12. J.M. Murphy, D.M.H. Sexton, G.J. Jenkins, B.B.B. Booth, C.C. Brown, R.T. Clark, M. Collins, G.R. Harris, E.J. Kendon, R.A. Betts, S.J. Brown, K.A. Humphrey, M.P. McCarthy, R.E. McDonald, A. Stephens, C. Wallace, R. Warren, R. Wilby, R.A. Wood. UK Climate Projections Science Report: Climate Change Projections. Meteorological Office Hadley Centre, Exeter, UK, June 2009. Report available to download at: http://ukclimateprojections.defra.gov.uk/media.jsp?mediaid=87851&filetype=pdf
13. IPCC. Climate Change 2007—The Physical Science Basis: Working Group I Contribution to the Fourth Assessment Report of the IPCC. Cambridge University Press, Cambridge, (2007)
14. C. Leovy, Weather and climate on Mars. Nature **412**(6843), 245–249 (2001)
15. H.F. Parish, G. Schubert, C. Covey, R.L. Walterscheid, A. Grossman, S. Lebonnois, Decadal variations in a venus general circulation model. Icarus **212**(1), 42–65 (2011)
16. CNRS. Claude Lorius biography (2002)
17. J.R. Petit, J. Jouzel, D. Raynaud, N.I. Barkov, J.M. Barnola, I. Basile, M. Bender, J. Chappellaz, M. Davis, G. Delaygue, M. Delmotte, V.M. Kotlyakov, M. Legrand, V.Y. Lipenkov, C. Lorius, L. Pepin, C. Ritz, E. Saltzman, M. Stievenard, Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. Nature **399**(6735), 429 (1999)
18. R.A. García, S. Mathur, D. Salabert, J. Ballot, C. Régulo, T.S. Metcalfe, A. Baglin, CoRoT Reveals a Magnetic Activity Cycle in a Sun-Like Star. Science **329**, 1032 (2010)
19. J.D. Haigh, The sun and the earth's climate. Living Reviews Solar Phys. **4**(2) (2007)
20. P. Charbonneau, P.K. Smolarkiewicz, Modeling the solar dynamo. Science **340**, 42–43 (2013)
21. D. Luthi, M. Le Floch, B. Bereiter, T. Blunier, J.-M. Barnola, U. Siegenthaler, D. Raynaud, J. Jouzel, H. Fischer, K. Kawamura, T.F. Stocker, High-resolution carbon dioxide concentration record 650,000–800,000 years before present. Nature **453**, 379–382 (2008)
22. J.E. Harries, H.E. Brindley, P.J. Sagoo, R.J. Bantges, Increases in greenhouse forcing inferred from the outgoing longwave radiation spectra of the earth in 1970 and 1997. Nature **410**, 355 (2001)
23. H.M. Worden, K.W. Bowman, J.R. Worden, A. Eldering, R. Beer, Satellite measurements of the clear-sky greenhouse effect from tropospheric ozone. Nat. Geosci. **1**, 305 (2008)
24. G.D. Farquhar, J.R. Ehleringer, K.T. Hubick, Carbon isotope discrimination and photosynthesis. Ann. Rev. Plant Physiol. Plant Mol. Biol. **40**(1), 503–537 (1989)
25. H.E. Suess, Radiocarbon concentration in modern wood. Science **122**, 415–417 (1955)
26. I. Levin, K.O. Munnich, W. Weiss, The effect of anthropogenic CO_2 and C-14 sources on the distribution of C-14 in the atmosphere. Radiocarbon **22**(2), 379–391 (1980)
27. L. Bernstein, R.K. Pachauri, IPCC, A. Reisinger, Climate Change 2007: Synthesis Report. Intergovernmental Panel on Climate Change (2008)
28. M. Lynas. *Six Degrees: Our Future on a Hotter Planet*. National Geographic Society (2008)
29. J. Pross, L. Contreras, P.K. Bijl, D.R. Greenwood, S.M. Bohaty, J.A. Bendle, U. Röhl, L. Tauxe, J.I. Raine, C.E. Huck, T. van de Flierdt, S.S.R. Jamieson, C.E. Stickley, B. van de Schootbrugge, S. Schouten, C. Escutia, H. Brinkhuis. Persistent near-tropical warmth on the Antarctic continent during the early Eocene epoch. Nature **488**, 7377 (2012)
30. M. Huber, R. Caballero, The early Eocene equable climate problem revisited. Climate Past **7**, 603–633 (2011)
31. D. Hinrichsen, Coasts under pressure. People Planet **3**(1), 6–9 (1994)
32. B. Marzeion, A. Levermann, Loss of cultural world heritage and currently inhabited places to sea-level rise. Env. Res. Lett. **9**, 034001 (2014)

Part II

Elements of Solution

5 Energy Storage, Carbon Sequestration, and Geoengineering

Each winter, when you are cold, everyone in Southern Spain thinks the same: If only we could store just a little of the summer heat for the winter! For sure, we would not have to use any radiator. Although our main problem is finding new sources of energy, finding efficient ways to store it can be part of the solution. A bottle is useless if you have no water. But it can be very useful to distribute or store it. Most of the alternative energies we will find in Chap. 6 are not like oil, coal, or gas. Their production cannot be controlled easily. In such cases, storage could help tremendously, which explains why our review of the solutions starts here.

How can you store energy? As explained in Sect. 2.5, energy has to go into designated reservoirs. It has nothing to do with technological limitations or human laws, but with the laws of physics. When it comes to storing energy, storage options cannot do anything but follow the same laws. Any energy vessel has to fit into one of the categories of Fig. 2.2. This section will *not* be devoted to a review of technological storage solutions. Instead, the focus will be on the fundamental physical capabilities of each kind of reservoirs. The outcome allows us to understand why storing energy is not trivial and why fossil fuels are exceptional resources.

Suppose we want to store 42 MJ, the energy contained in 1 L of oil. What can you expect from the reservoirs listed in Fig. 2.2, namely kinetic energy and gravitational, electromagnetic, or nuclear potential energies? We will now see what Physics has to tell on this.

5.1 Kinetic Energy Storage

So you want to store 42 MJ in kinetic energy of something in motion. A first idea would be to place them in an object of mass m at velocity v. It would then have a kinetic energy $E = \frac{1}{2}mv^2$. Which mass and velocity would you need? There is no unique solution, because the equation $\frac{1}{2}mv^2 = 42 \times 10^6$ can be fulfilled for an infinite numbers of couples (m, v). But probing a few of them allows to grasp the problem. For example, considering $v = 1$ m/s (3.6 km/h) implies $m = 84 \times 10^6$ kg

A. Bret, *The Energy-Climate Continuum*, DOI: 10.1007/978-3-319-07920-2_5

which are 84,000 tons. No, there is no calculation mistake. Consider now $v = 10$ m/s (36 km/h). This is the average speed of an athlete running 100 m in 10 s. Then, you need a mass of "only" 840 tons. This gives an idea of how much are 42 MJ, compared to the little liter of oil it takes to own them.

Clearly, storing energy in an object moving straight is not convenient. Let us try a spinning disk. The kinetic energy it holds is now given by $E = \frac{1}{2}I\omega^2$, where I, the so-called moment of inertia, behaves like a mass for such rotative motions. Also, ω is the rotation frequency and has to come in radians/s in the formula (multiply by $30/\pi$ to get the rotation speed in rounds per minute). Considering a disk of mass m and radius R, the moment of inertia reads $I = \frac{1}{2}mR^2$. The denser the disk, the smaller it will have to be. So let us try lead, which has a density of 11.2 tons per m^3. The result is that you would need a 10-m-wide, 1-m-thick lead cylinder spinning at 27 rounds per minute, to get your 42 MJ of kinetic energy. Even if the solution is much more practical, the numbers remain staggering.

We now look at thermal energy. Is it still of the kinetic type? Yes, because from the microscopic point of view, the amount of heat contained in a medium is nothing but the kinetic energy of the particles composing it. Here, a key parameter is the so-called heat capacity which measures the amount of energy required to increase the temperature of 1 kg of matter by 1 K. The heat capacity varies from one material to another, and also with temperature. As a first approximation, let us forget about this latter dependency to make some quick calculations. Water heat capacity is $C = 4.2 \times 10^3$ J/kg/K. It would thus take 42 MJ to increase by 10 degrees the temperature of 1 ton of water. In other words, if you could cool 10° 1 ton of water and collect all the energy, you would recover 42 MJ.

Numbers are less impressive with thermal storage. A ton of water occupies only 1 m^3, and you can heat it by more than 10°. Note that although oil heat capacity is less than that of water, it is already used for energy storage because it does not boil beyond 100 °C. Like water, it is not uncommon, but you can heat it far more in the liquid, hence compact, phase.[1] Of course, once the energy is in, it is impossible to fully recover it. There are always losses. These numbers only give the best possible performances you can expect.

Finally, thermal storage could be realized with gas rather than liquid. Gases also have their heat capacity. But to vary, let us shortcut this notion and work directly at the microscopic scale. The "kinetic theory of gases" teaches each particle of a gas at temperature T has on average the kinetic energy $\frac{3}{2}k_B T$, where $k_B = 1.4 \times 10^{-23}$ m^2 kg s^{-2} K^{-1} is the Boltzmann constant. At ambient temperature and pressure, 1 L of gas contains about 2.7×10^{22} particles. At 20 °C, $T = 293$ K, these particles hold in total $2.7 \times 10^{22} \times \frac{3}{2}k_B T = 165$ J. This means that in order to get a storage capacity comparable to oil, you will need to compress your gas because if 1 L only holds 165 J, it will take $42 \times 10^6/165$ L, namely 254 m^3, to hold 42 MJ. Compressing 700

---

[1] This is the reason why besieged soldiers would throw boiling oil instead of water on their assaulters. You cannot throw 200 °C water, because it is vapor. But you can do so with *liquid* oil.

times brings these 254 m^3 down to 364 L, still at 20 °C. Getting the energy in and out efficiently is the topic of many current researches.

5.2 Potential Energy Storage: Gravitation

We come to the second category of energy reservoirs reviewed in Sect. 2.5. Here, energy is encapsulated, and it takes a fundamental force to reveal it. One of these fundamental forces is gravitation. The potential energy of gravitation held by a mass m at height h is $E = mgh$, where $g = 9.8$ m s^{-2} is the acceleration of gravity. To be more accurate, this is the gravitational energy released when dropping the mass by h meters. Considering 10 tons of water, you need $h = 428$ m if you want $mgh = 42$ MJ. We understand why dams are such huge infrastructures. If local geography only lets you exploit 100 m of free fall, then you will need to extract the gravitational energy of 43 tons of water to get as much as 1 L of oil. Yet, pumping water in the upper reservoir of a dam is a widely used practice to store electricity surpluses.

The sizes involved are not without logic. The amount of space you need to store the potential energy of a fundamental force varies with the intensity of this force. Gravity is far weaker than the electromagnetic and nuclear forces.[2] Think, for example, that a little magnet lifting a piece of iron wins against the gravity of the whole earth. The reason why 1 L of oil holds as much energy as 43 tons of water 100 m high, is because gravity is extremely faint compared to the electromagnetic force. Let us see how this latter holds energy.

5.3 Potential Energy Storage: Electromagnetic Force

The electromagnetic force is strong enough to reorganize molecules. It can, for example, take hydrogen and oxygen to make water. It changes molecules composition, but it does not change the atoms themselves. Comparing atoms to bricks, the electromagnetic force can undo two small houses to make a big one, but it cannot change the bricks themselves.

We start calculating an order of magnitude of the energy density we can expect here. Let us take an example: To separate the 2 hydrogen atoms forming the hydrogen molecule, the electromagnetic force has to provide 4.5 electron volts, or 7.2×10^{-19} J. These are not a lot of Joules,[3] but it is just one single molecule. One of them weights 3.2×10^{-27} kg, so that you need $1/3.2 \times 10^{-27} = 3.1 \times 10^{26}$ molecules to get 1 kg of

---

[2] This relative weakness of gravity is one of the greatest enigmas of contemporary theoretical physics. See the Wikipedia article on the “hierarchy problem”.

[3] $7.2 \times 10^{-19} = 0.0 \ldots 16 \text{ zeros} \ldots 072$.

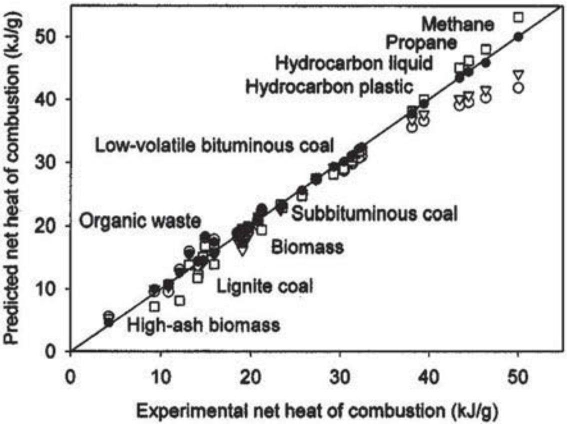

Fig. 5.1 Measured heat of combustion for various fuels, versus the predicted values. The "kJ/g" is equivalent to "MJ/kg". From Ref. [1]

molecular hydrogen. Dismantling this kg would therefore require the electromagnetic force provide $3.1 \times 10^{26} \times 7.2 \times 10^{-19} = 225$ MJ, more than 5 times the energy of our kg of oil. This is getting much better.

Of course, you will never get that much energy out of 1 kg of chemical reactive because a chemical reaction does not consist in liberating *all* the potential energy. Instead, these reactions reorganize atoms from a bunch of molecules to form others molecules. Hydrogen combustion, for example, reads

$$2H_2 + O_2 \rightarrow 2H_2O \tag{5.1}$$

so that 2 molecules of hydrogen and 1 of oxygen have their atoms reorganized to form two molecules of water. The energy released is thus the difference between the potential energy before and after.[4] Still, you can in general expect a fraction of these 225 MJ. Oil, for example, is a mix of many molecules. To describe its combustion, we would have to line up various equations like the one above. But the energy potential difference between "after" and "before" is eventually 42 MJ/kg, a number fitting very well the expected order of magnitude from first physical principles.

5.3.1 Firewood

Another widely used combustion reaction is the combustion of firewood. Wood is mostly made of cellulose, a long molecule made of carbon, hydrogen, and oxygen. Its combustion reaction is similar to the one of hydrogen, though more involved. But here again, the energy release is computed looking at the potential energies before and after the reaction. The result is that burning 1 kg of cellulose releases about 13 MJ of heat [1]. We thus expect all kinds of woods to lie around this value. Figure 5.1, from Ref. [1], shows the measured heat of combustion for various fuels, versus the values predicted by a simple equation given in the reference. Firewood ("organic

---

[4] Closely related to what chemists call "enthalpy of combustion."

waste" to "biomass" on the graph) lies where expected, between 10 and 20 MJ/kg. It takes therefore between 2 and 4 kg of organic material to release the energy of 1 kg of oil. Gaseous fossil fuels (propane and methane) are more energetic because of the combustion reactions involved. At any rate, the overall energy scale still lies within a fraction of the 225 MJ calculated above.

5.3.2 Batteries

What about batteries? Here again, electromagnetism is at work. Batteries deliver electrical energy from selected chemical reactions. When you are told a car battery delivers "12 V, 40 Ah," it means it can provide a current intensity $I = 40$ A with a tension of $U = 12$ V during 1 h. After that, it will be completely empty. Under these circumstances, the energy delivered by the battery in 1 s is UI. The energy out in 1 h is therefore $E = 3{,}600 \times UI$. With the numbers of our example, we find $E = 1.7$ MJ. Since it probably weights about 15 kg, we get an energy density of $1.7/15 = 0.11$ MJ/kg. Our 42 MJ in 1 kg of oil requires 370 kg of batteries. Gasoline is really great! Of course, our example is not representative of the most recent researches in this field. Still, as of 2011, the best batteries hardly reach 0.5 MJ/kg [2]. It would then take 4.2 tons of these to carry the energy held by a 50-L gasoline tank. Tomorrow's electric cars are unlikely to be equivalent to today's vehicles,[5] at least autonomy wise.

5.3.3 Hydrogen

Let us finish this section about electromagnetic storage emphasizing the case of hydrogen. Why is it interesting? Because unlike most of the things you can burn, you can *make* hydrogen quickly. You can burn oil, wood, or coal, but you cannot make them out. It implies you cannot use them for energy storage. Equation (5.1) above features the hydrogen combustion reaction. Burning 1 kg of it releases 148 MJ, almost 4 times as much as 1 kg of oil. The only problem is that hydrogen is a gas, and 1 kg occupies more than 11 m^3. This is why they always talk of *compressed* hydrogen. In an hydrogen tank with hydrogen compressed 700 times, these 11 m^3 would be reduced by the same factor, leaving only 16.6 L. The 42 MJ from 1 L of oil eventually fits in 4.7 L of 700 bar hydrogen.

In case you worry about carrying a 700 bar reservoir, you can opt for *liquid* hydrogen. Like every substance, hydrogen can be found under gas, liquid, or solid forms, or "phases." The phase it adopts results from two opposite tendencies. On

---

[5] Something may help though: The efficiency of an electric motor is far better than the one of a gasoline engine (about 90 vs. 25 %; see Wikipedia page on "Internal combustion engine"). The former gets the most out of the batteries energy content, while the latter wastes most of the gasoline energy.

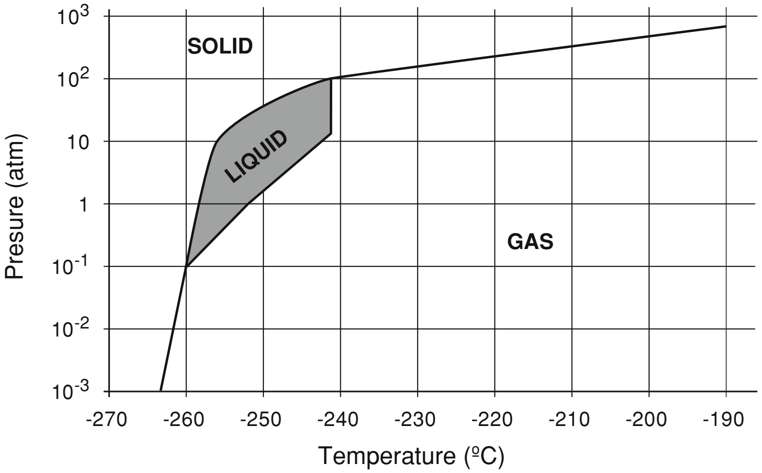

Fig. 5.2 Phase diagram of hydrogen H_2 at low temperature. At atmospheric pressure (1 atm), hydrogen is liquid between −259 and −253 °C. *Source* Adapted from [3]

the one hand, temperature tends to have molecules jiggling around, keeping them apart from each other. On the other hand, pressure squeezes them against each other. This is why water goes from solid ice to liquid and then vapor as you heat it. Under normal atmospheric pressure, water boils at 100 °C. But on the top of Mount Everest, pressure is less than half its ground level value, and water vaporizes around 70 °C. Figure 5.2 shows the "phase diagram" of hydrogen. It tells you which phase hydrogen adopts in terms of the temperature and pressure. You can check hydrogen becomes liquid under atmospheric pressure, between −259 and −253 °C. You can extend the upper limit to −241 °C compressing it 10 times. The advantage is that 1 kg of liquid hydrogen occupies only 14 L.

So you can choose between 4.7 L at 700 bar, and 14 L at −255 °C. Both will hold 1 L of oil energy. It is the very reason for the hydrogen success. It can be made quickly, and its energetic content by volume is quite close to oil. Even if the total energy balance is not that nice (you lose energy when you make it, and when you compress or freeze it), there is nothing better in the chemical world.

Is there really no molecular hydrogen at all here on Earth? Not completely. Natural sources of hydrogen have been found, which have been so far considered too diffuse to have commercial value [4]. The French "Institut Français du Pétrole, Énergies nouvelles" launched in 2013 a research program to assess the worldwide potential of these sources.[6] Yet, even according to optimistic expectations, these sources could only contribute locally to the future energy mix.[7] So stay tuned, but do not hope too much for global options on this side.

---

[6] See the April 11, 2013, press release on www.ifpenergiesnouvelles.fr, or [5].

[7] *Le Monde*, Pierre le Hir, April 12th, 2013.

5.4 Potential Energy: Nuclear Forces

The word “storage” has been removed from the title in this section, because there is no way (so far?) to “store” energy using this fundamental force. Energy can be stored lifting up water, or synthesizing hydrogen. But how can you synthesize an atomic nucleus? As far as energy issues are concerned, all we can do so far is splitting heavy nuclei.

Nuclear force and its physics will be explained in Sect. 6.5. It is nevertheless interesting to take advantage of this chapter to compare the energy densities deriving from this force, with the others. We already saw energy “storage” is all the more efficient that it derives from a powerful fundamental force. And nuclear forces are the best at this game. The mere fact that they successfully stick protons together in the nucleus, while the electromagnetic force repels them, shows nuclear forces are far much stronger.

In contemporary nuclear power plants, the fission of one nucleus of uranium-235 (Ur-235) provides 202×10^6 electron volts, that is, 3.24×10^{-11} J. One Ur-235 atom weights 3.7×10^{-25} kg. The energy liberated by the fission of 1 kg is therefore $1/3.7 \times 10^{-25} \times 3.24 \times 10^{-11} = 86{,}170{,}213$ MJ. Here, the 42 MJ of 1 L of oil can be generated by the fission of 0.0005 g (not kg) or Ur-235. This is by far the largest energy density reviewed so far, simply because it stems from the strongest force.

Last but not least, there is another way to extract energy from nuclear reactions. Instead of splitting a heavy nucleus, merge two light ones, like deuterium (1 proton + 1 neutron) and tritium (1 proton + 2 neutrons) for example. The result is an helium nucleus, a neutron, and 17.6 MeV of energy. The fusion of 0.05 mg of deuterium with 0.07 mg of tritium gives the 42 MJ. Fusion power is yet to be developed and will be outlined as a potential future energy source in Sect. 6.6.

Our review of the possible energy reservoirs is over. It had to be finite because the number of reservoirs is finite. Table 5.1 summarizes this chapter. Hydrogen clearly stands out in terms of energy density. Even if energy losses have to occur whether you encapsulate energy in hydrogen or extract it, it should definitely play an important role in energy storage. Nuclear forces offer incredible energy densities, explaining why so many efforts have been poured in developing fission or fusion energy. Finally, oil stands out as an energetic champion: large energy density, available almost for free, easy to exploit (just burn it), easy to transport and store…Too bad it is finite and emits greenhouse gases.

Let us now look at something else that we could store: carbon.

5.5 Carbon Sequestration and Absorption

The principle is simple: if we cannot avoid fossil fuels in the midterm, why do not we try to cut carbon emissions by keeping them for ourselves, or absorbing them? It would give us some extremely needed extra decades to switch away from fossil fuels.

Table 5.1 Energy reservoirs summary

Reservoirs	Requirements to hold/release 42 MJ
Kinetic energy	84,000 tons at 36 km/h
	10 m wide lead disk, 1 m thick, at 27 rpm
	1 ton of water losing 10°
	364 L of gas at 700 bar and 20 °C
Gravitation	43 tons of water falling from 100 m
Electromagnetic force	
Oil combustion	1 kg
Wood combustion	3 kg
Batteries	84 kg (best state-of-the-art technology)
Hydrogen @ 700 bar	4.7 L
Hydrogen @ −255 °C	14 L
Nuclear forces	Fission of 0.5 mg of Ur-235
	Fusion of 0.05 mg of D with 0.07 mg of T

Requirements to store 42 MJ of energy, i.e., 1 L of oil. “D” stands for deuterium, “T” for tritium

Carbon sequestration would thus consist in capturing our emissions, when possible. Regarding absorption, planting trees is the first option one can think about.

5.5.1 Carbon Sequestration

The idea is to store carbon emissions to keep them from polluting the atmosphere. Of course, once the carbon is in, you want it to stay there forever. Good candidates for storage could be, for example, exhausted oil and gas wells. After all, we had to drill to get them out, where they had been waiting for us a few million years. According to geologists, burying it and forgetting about it should definitely be possible [6,7].

Let us check to which extent this technique could solve our problems. The key point here is that only *localized* emissions are easy to sequester. How could you retain the carbon emitted through deforestation? Or how to capture the carbon emitted by millions of cars and trucks? In turn, capturing the one getting out of an electricity power plant seems feasible.

Figure 5.3 shows the repartition of global anthropogenic greenhouse gas emissions in 2004. CO_2 is clearly the leader, followed by CH_4, N_2O, and F-gases.[8] CO_2 is primarily emitted through fossil fuels burning. Deforestation comes second, before

---

[8] Fluorinated gases, used in aerosols, and banned in 1987 because of their effect on this ozone cap. Their usage has steadily decreased since then.

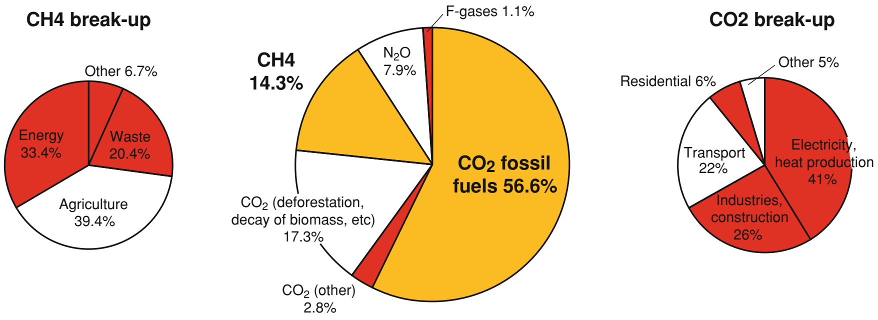

Fig. 5.3 Breakup of global anthropogenic greenhouse gas emissions. The red sections are considered sequestrable. *From* [8], *except International Energy Agency 2010, for the* CO_2 *emissions break-up*

"others," which stands for cement production and natural gas flaring.[9] In red are the emissions sequestration could cut. N_2O emissions could not because they mainly stem from the use of fertilizers in agriculture. CH_4 and CO_2 from fossil fuels need a second look, which is why they appear in orange. At this stage, we already have a $1.1 + 2.8\ \%$ cut.

A split of the methane emissions shows 60.5 % could be sequestered. Regarding CO_2, we come to 73 %. The proportion of greenhouse gases involved is thus

$$1.1 + 2.8 + 56.6 \times 0.73 + 14.3 \times 0.605 = 53.9\,\%,$$

that is, a good half. Will we be willing to pay the extract costs and will there be time to implement it globally? This is another story way beyond the scope of this book.

5.5.2 Planting Trees

Apart from storing the carbon we emit, we could catch what is already in the atmosphere. The simplest idea consists in planting trees instead of cutting them. So let us calculate. A tree 10 m high and 2 m wide has a volume about 30 m^3. As its mass comes mainly from carbon, it holds some 30 tons of it. Suppose we plant trees every 20 m in all directions. That gives us $1/20^2$ trees per meter square, namely 25 per hectare. Multiplying by the amount of carbon each one contains, we get 750 tC/ha. This is the good order of magnitude as forests in temperate latitudes typically hold 500 tC/ha [10].

We see on Fig. 3.4 that 10 Gt of carbon are now emitted each year. Which amount of forest would be needed to offset this? Just divide 10 Gt by 500 tC/ha. The result is 200,000 km^2, nearly the area of UK (243,000 km^2). Though considerable, these

---

[9] When drilling for oil, you frequently get gas as well. In case you do not want it, you just burn it. Yes, this is a complete waste of energy [9].

are numbers we can deal with. As a bad but illustrative example, Brazil has cut 485,000 km^2 of tropical forest from 1990 to 2007.[10]

Another issue here is time. It took Brazil 17 years to chop nearly one Spain area of forest. But it takes much longer to *grow* a forest. Or better said, to let it grow. Here again, the law of energy conservation can give an idea of the numbers. Our typical forest hosts 500 tons of wood per hectare. As such, Table 5.1 tells it carries 42 MJ for 3 kg, under the form of electromagnetic potential energy. All in all, we get 7×10^{12} J/ha in store. Where did this energy come from? From the Sun. There is no other source around. We saw in Sect. 4.3 that the earth receives on average 240 W/m^2, that is, 2.4×10^6 W/ha or 7.5×10^{13} J/ha over a year. Photosynthesis converts only a small part to energy. Its average efficiency for the whole flora is around 0.2% [11], far lower than that of the crops used for biofuels (see Sect. 6.2).

So you need to accumulate 7×10^{12} J/ha. To do so, you have a source of 7.5×10^{13} W/ha/y, with a 0.2 % factor. How many years does it take? The arithmetic gives 47 years. Studies on Appalachian pines trees, for example, showed they take about 100 years to reach maturity [12]. Our estimate is quite correct.

If it takes 50 years for a 200,000-km^2 forest to offset one single year of our carbon emissions, then we can hardly rely on this solution in the short term.

5.6 Geoengineering

Suppose we cannot cut carbon emission fast enough, nor capture them or absorb them efficiently enough. Are there options left to avoid catastrophic warming? Maybe. Geoengineering would be a deliberate, large-scale action to counter global warming, like placing a giant screen in space to block part of the solar radiation, or injecting large amounts of aerosols in the atmosphere (see [13] for a review). The word "aerosol" comes from the contraction of *aero*, standing for air, and *sol*ution.[11] They are fine solid or liquid particles in suspension in the air, emitted by a number of human and natural activities. Their net effect on the energy balance discussed in Sect. 4.2 is negative ([14], p. 13). In other words, their action is similar to an increase of albedo, with a resulting global *cooling* effect.

Climate scientists are quite cautious about these options because of their potential unknown side effects. The climate machine is extremely complicated, and as is the case with the human body, medication side effects are difficult to predict. For example, a recent study suggests massive aerosol injections in the stratosphere could trigger severe droughts in some parts of the world [15]. James Lovelock recently wrote in this respect [16],

---

[10] See www.fao.org.

[11] The word here refers to a chemical mixture, not to a fix.

> I suggest here that we regard the earth as a physiological system and consider amelioration techniques, geoengineering, as comparable to nineteenth-century medicine.

Given our current knowledge of the climate system, much work is still needed to make sure geoengineering strategies would have *only* the desired effects. Yet, nineteenth-century medicine eventually became twenty-first-century one, and the good sides of geoengineering are so promising that an increasing amount of research resources is currently poured into it [17,18].

Now that storage options have been reviewed, let us tour the potential non-fossil energy sources.

References

1. M. Dietenberger, Update for combustion properties of wood components. *Fire Mater*. **26**(6), 255–267 (2002)
2. B. Dunn, H. Kamath, J.-M. Tarascon, Electrical energy storage for the grid: a battery of choices. Science **334**(6058), 928–935 (2011)
3. A. Züttel, Hydrogen storage methods. Naturwissenschaften **91**, 157–172 (2004)
4. R.M. Coveney, E.D. Goebel, E.J. Zeller, G. Dreschhoff, E.E. Angino, Serpentinization and the origin of hydrogen gas in Kansas. AAPG Bull. Am. Assoc. Petrol. Geol. **71**(1), 39–48 (1987)
5. V. Beaumont, C. Vacquand, E. Deville, A. Prinzhofer, Hydrogen generation during serpentinisation in ophiolite complexes: a comparison of H2-rich gases from Oman, Philippines and Turkey. Geophys. Res. Abstr. **15**, EGU2013–5553 (2013)
6. Richard Van Noorden, Carbon sequestration: buried trouble. Nat. News **463**(7283), 871–873 (2010)
7. R. Stuart, Haszeldine. Carbon capture and storage: how green can black be? Science **325**(5948), 1647–1652 (2009)
8. B. Metz and IPCC Working Group III, in *Climate Change 2007 - Mitigation of Climate Change: Working Group III Contribution to the Fourth Assessment Report of the IPCC*. Climate Change 2007 (Cambridge University Press, Cambridge, 2007)
9. Jeff Tollefson, Oil boom raises burning issues. Nature **495**(7441), 290 (2013)
10. Heather Keith, Brendan G. Mackey, David B. Lindenmayer, Re-evaluation of forest biomass carbon stocks and lessons from the world's most carbon-dense forests. Proc. Natl. Acad. Sci. **106**(28), 11635–11640 (2009)
11. D.O. Hall, K.K. Rao, *Photosynthesis*, Studies in Biology (Cambridge University Press, Cambridge, 1999)
12. B. Husch, T.W. Beers, J. John, A. Kershaw, *Forest Mensuration*. Ecology (Wiley, New York, 2002)
13. N.E. Vaughan, T.M. Lenton, A review of climate geoengineering proposals. Clim. Change **109**, 745–790 (2011)
14. IPCC, *Climate Change 2013—The Physical Science Basis: Working Group I Contribution to the 5th Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press, Cambridge, 2014)
15. J.M. Haywood, A. Jones, N. Bellouin, D. Stephenson, Asymmetric forcing from stratospheric aerosols impacts sahelian rainfall. Nat. Clim. Change **3**, 660–665 (2013)
16. James Lovelock, A geophysiologist's thoughts on geoengineering. Philos. Trans. Royal Soc. A **366**(1882), 3883–3890 (2008)

17. D. Keith, *A Case for Climate Engineering*, Boston Review Books (MIT Press, Cambridge, 2013)
18. E. Kintisch, Dr. Cool. Science **342**(6156), 307–309 (2013)

Non-fossil Energy Sources

6

Non-fossil energy sources will have to be found among the energy reservoirs described in Sect. 2.5. This is exactly where fossil fuels can be found. Unlike with storage options, these reservoirs must be found *already* filled, if they are to earn the “source” label. This is why there will be no mention of electricity or hydrogen here. We will now go through the most probable candidates to the succession of the oil-coal-gas Triumvirate.

For each one of them, the physical basis will be explained and a few orders of magnitude calculations performed. The objective of this last point is to provide an idea of the dimensions involved when considering a global implementation of each solution. In this respect, our elements of comparison will be on the one hand, when relevant, the annual production of a typical 1 GW electrical power plant, and on the other hand, the 2010 annual world energy production of 12,717 Mtoe [1]. Converted to joules units, these are 3.1×10^{16} and 5.3×10^{20}, respectively. Clearly, no alternative is likely to become the sole energy producer, but these numbers will make it easy to figure out a 10 or a 40 % share, for instance.

6.1 Wind and Water Turbines

The strategy consists in capturing the kinetic energy of naturally streaming fluids. Air and water immediately come to mind, through wind and currents. These are definitely energy “sources” since we did not do anything to make them move. The Sun did. Let us now analyze the mechanisms at work to evaluate how much energy we can get this way.

6.1.1 Wind Turbines

Once the wind kinetic energy has been transferred to a rotating device, a turbine converts the mechanical energy into electricity. This simple picture allows to derive

A. Bret, *The Energy-Climate Continuum*, DOI: 10.1007/978-3-319-07920-2_6

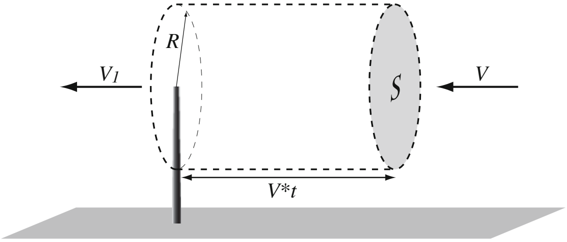

Fig. 6.1 Wind turbine in a wind at constant velocity V

the available power in terms of the radius of the machine and the mean wind speed at the location.

Consider a wind turbine like the one pictured on Fig. 6.1 with a rotor of radius R, capturing the kinetic energy of a wind at constant velocity V (we will account for variable wind later). During a time t seconds, which amount of wind passes through the rotor section? It is straightforward that all the air contained within the cylinder of section S and length Vt pictured on the figure is intercepted by the rotor during this amount of time. Its volume is SVt. If ρ is the air density, the intercepted mass is therefore $M = \rho SVt$, and its kinetic energy reads $\frac{1}{2}MV^2 = \frac{1}{2}\rho SV^3t$. Dividing by t yields the available power,

$$P = \frac{1}{2}\rho SV^3, \tag{6.1}$$

with here $S = \pi R^2$. The power varies like the cube of the wind velocity and the square of the rotor radius, hence the huge windmills we see today.

Can the windmill capture 100 % of the available kinetic energy? No. Simply because if all the kinetic energy is captured, it means the wind stops right behind the machine and blocks the rest of the flow. This is the simple reason why a turbine cannot reach a 100 % efficiency. No amount of R&D will change this. For the present case, there is a best theoretical yield called the "Betz limit," after Albert Betz who derived it in 1920. The calculation of the extractable energy during a year, in terms of the machine radius and the mean wind velocity at a given location, is quite technical and is reported in Appendix B. The result is

$$E_y = 22.7\ R^2V_m^3\ \text{MJ}, \tag{6.2}$$

where V_m is the mean wind speed at the turbine location. The rotor radius is up to you. The largest wind turbine[1] in 2012 had $R = 82$ m. The average wind velocity only depends on the location. Wind atlases are available,[2] mapping the average wind speed in terms of the site. Off-shore and top of the hill winds are usually higher than the rest, which is why many wind farms are located on such sites. Typical values range from $V_m = 10$ m/s on windy coasts to $V_m = 5$ m/s inland.

Before we proceed, it is interesting to compare the predictions of Eq. (6.2) with real cases. Table 6.1 lists a number of existing wind farms. For each, the total number

---

[1] The "Vestas V164," see www.vestas.com.

[2] See, for example, www.windatlas.dk for the world, or Ref. [2] for part of the USA.

Table 6.1 Comparing the measured energy produced E_y^m per year, with predictions from Eq. (6.2) E_y, for various wind farms

Wind farms	N	R	V_m	E_y^m	E_y	E_y/E_y^m
Whitelee (Scotland)	140	49	8	740	1,085	1.5
Horse hollow II (USA)	130	49	8.5	687	1,209	1.8
Horns rev (Denmark)	80	40	9.7	600	737	1.2
Almodovar II (Spain)	36	23	8.5	55	74	1.3
Silan (Spain)	20	23	9	30	49	1.6
Middelgrunden (Denmark)	20	38	7.2	89	68	0.8

Units are R (m), V_m (m/s), E_y^m, and E_y (GWh). The first column gives the number N of turbines in the farm. *Source* www.thewindpower.net, Wikipedia

of turbines, their radius, and the average wind speed at the location are given. Then, the measured annual production is compared to the predictions of Eq. (6.2). Energy productions are here expressed in "gigawatt hour" (GWh), a frequently used unit for electricity. One "watt hour" is the energy produced by a source of 1 W during 1 hour, namely 3,600 J. One gigawatt hour amounts therefore to 3.6×10^{12} J. The numbers derived from the formula fit quite well the measurements. Average wind speeds have been deduced from a wind atlas and may generate some uncertainties. The orders of magnitude are nevertheless completely captured.

From this point, several basic calculations are possible. The first one may be the evaluation of the number N of wind turbines required to replace a 1 GW power plant during one year. Forgetting about the energy loss due to the storage needed to smooth the electricity production, we simply write

$$22.7\ R^2 V_m^3 \times 10^6\ N = 3.1 \times 10^{16} \quad \Rightarrow \quad N = \frac{1.36 \times 10^9}{R^2 V_m^3}, \tag{6.3}$$

where R and V_m must be expressed in meters and m/s, respectively. Figure 6.2 plots the number of machines required in terms of their radius and of the average wind at the chosen location. The order of magnitude goes from 1,000 to 10,000. To reduce the number of machines, it is much more efficient to choose a windier place than a larger rotor. This is the direct consequence of the R and V_m scalings in Eq. (6.3).

The next question is clearly how much room does it take.[3] To give it a beginning of an answer, let us consider two typical configurations: aligned (1D) and spread out (2D). Both options have received much attention with respect to the optimum space between the machines. Clearly, lined up wind mills need to maintain at least 2 rotor radii between them. But leaving too much room necessarily ends up being a waste of space as the number of turbines per km decreases. So if too close and too far are

---

[3] Contrary to a solar farm which monopolizes all the ground devoted to it, a wind farm leaves usable space between the turbines. While its impact is certainly more than the mere footprint of the wind mills, it can share agricultural lands. More on the Wikipedia article on "Environmental impact of wind power."

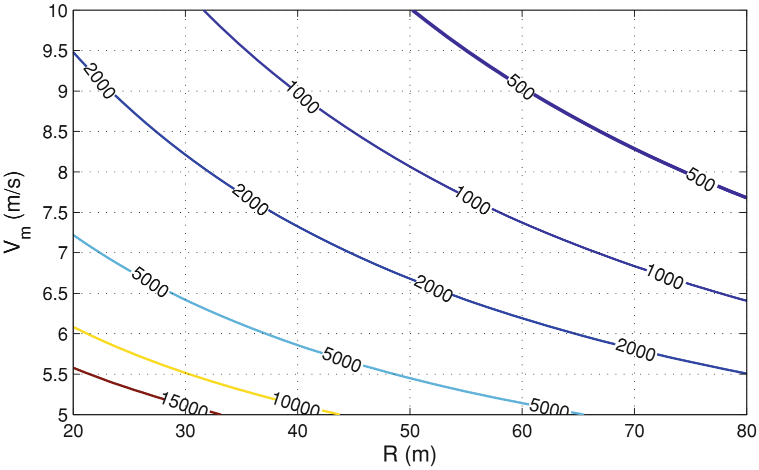

Fig. 6.2 Number of windmills required in terms of their radius and of the average wind to replace a 1 GW power plant

not good, what is the optimum? Studies show it could lie toward $s_1 = 6$ radius. The same holds for a 2D configuration. In such case, machines side-by-side have to be some $s_2 = 10$ radius away. But what if the next row is too close behind the first? It gets poor wind as the first one slows it down. Here again, there is an optimum toward $s_2 = 10$ radius. Such parameters are rather at the low end of the numbers considered [3,4]. But the optimum spacing could be much larger (Ref. [5, p. 430]). The Danish Hors Rev wind farm mentioned in Table 6.1, for example, has $s_2 = 14$.

Keep in mind that once you have found the right number, packing up more turbines hoping for more energy production is useless because we are already talking *optimum* packing. As a consequence, placing more turbines per km^2 than the optimal number will result in *less* energy yield, not more.

For the 1D, row case, N machines in a row occupy a length $L = (N-1)s_1 R$. The total amount of energy produced a year is N 22.7 $R^2 V_m^3$ MJ. So the energy produced per unit length is

$$\frac{N\ 22.7\ R^2 V_m^3}{(N-1)s_1 R} \sim \frac{22.7\ R V_m^3}{s_1} = 3.8\ R V_m^3\ \text{ MJ/m}, \tag{6.4}$$

where we have set $(N-1)/N \sim 1$ because large numbers are involved. Note that the density is now only proportional to the turbine radius instead of its square because a larger radius implies fewer machines per meters.

For the 2D case, suppose we have N turbines in one direction, and M in the other. The surface covered is $(N-1)s_2 R \times (M-1)s_2 R$. We have NM of them, so the total amount of energy produced a year is NM 22.7 $R^2 V_m^3$ MJ. The energy produced by unit area is therefore

$$\frac{NM\ 22.7\ R^2 V_m^3}{(N-1)s_2 R \times (M-1)s_2 R} \sim \frac{22.7\ V_m^3}{s_2^2} = 0.2\ V_m^3\ \text{ MJ/m}^2, \tag{6.5}$$

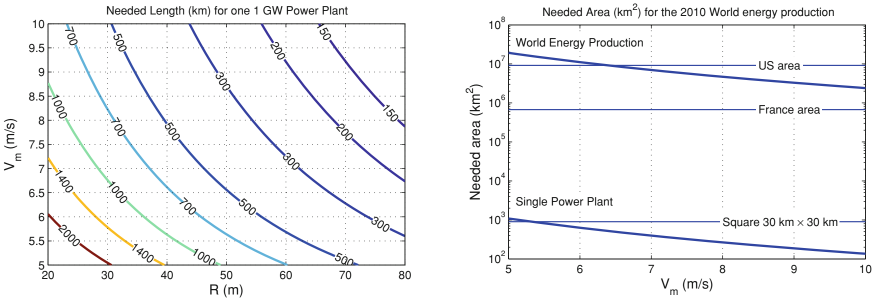

Fig. 6.3 *Left* length required to replace one single 1 GW power plant. *Right* area required to replace a 1 GW power plant or the world 2010 energy production

where the radius disappeared because the number of machines per unit area is now inversely proportional to R^2.

Figure 6.3 displays the length required to replace one 1 GW power plant in terms of the turbines radius and the wind speed (left). The order of magnitude is 1,000 km. The right panel shows the area needed for a 1 GW power plant and for the 2010 world energy output. Horizontal lines have been added to indicate where the US area stands, together with France and a square 30 × 30 km large. For an average wind at 6 m/s, the area needed equals the full US territory. The full French territory would generate less than 10 % of the total.

Clearly, when such large surfaces are involved, finer calculations are required to account, for example, for the wind velocity variations over the very surface. The numbers above are thus only expected to provide the correct order of magnitude.

6.1.2 Water Turbines

A word now about *water* turbines. Equation (6.1) is valid regardless of the fluid. Instead of using air, why not using water? With a density ρ a thousand times higher (830, to be accurate), the available power could be immense. Our water turbine would be located within a water current, capturing part of the flowing kinetic energy.

Nevertheless, a quick calculation shows this option is unlikely to play a role on a *global* scale. Consider one of the world largest oceanic current: the Gulf Stream. Starting off the coasts of Florida, it goes north-east along the USA before crossing the Atlantic. It is about $L = 100$ km wide and $h = 1$ km deep, flowing at about $v = 2.5$ m/s [6]. Applying Eq. (6.1) with $S = Lh$ and $\rho = 10^3$ kg/m^3, we find an available power of 7.8×10^{11} W. Multiplying by the number of seconds in 1 year, we get the kinetic energy that could be extracted per year assuming a 100 % efficiency: 2.5×10^{19} J. As incredible as this number can be, it is only 4.6 % of the 2010 world energy production (5.3×10^{20} J).

Capturing 10 % of the Gulf Stream power[4] with a 50 % efficiency would only provide 0.2 % of the world energy production. Even if interesting energy outputs can be generated locally, a global energy solution will not come from there.

Without entering into details, tides and waves are worth mentioning. Tides originate from gravity. As the sea rises and lowers, it generates streams which kinetic energy can be captured by appropriately located turbines. Most waves originate from the wind friction over the sea.[5] As they have the sea surface oscillating, it is possible to extract energy from the motion of a floating body.

The frontier between kinetic and gravitational potential energy sources is not clear cut. Indeed, tides energy could sit next to hydropower in Sect. 6.4. At any rate, calculations for tides and waves energies are conducted in David McKay's book *Sustainable Energy: Without the Hot Air* [8]. They show that as is the case for sea currents, these sources cannot play a significant role on a global scale. This of course, does not prevent them from being valuable allies locally.

We are therefore done with kinetic energy capture. Let us now switch to what can be done with the kinetic energy of sunlight.

6.2 Solar Power, Biofuels, and Biomass

What are biofuels doing here with solar power? The combustion taking place in your car engine does not care about the origin of the burnt molecules. Whether they came from oil or crops is even. Now, when you burn 1 L of bioethanol in your car, where did the energy come from in the first place? From the Sun. From the corn field to your engine, there is no other primary source of energy around. Some authors even name biofuels and biomass "biological solar energy" [9]. We thus paired-up solar power and biofuels because most of the calculation we will do for the former will be useful when discussing the latter. Let us then start with solar.

6.2.1 Solar Power

Computing the amount of energy the Sun sends to the earth is a good start. The so-called solar constant C_S was already mentioned in Sect. 4.2 in connection with the earth energy balance. Here, we compute it. To do so, we follow the energy path from the Sun to the earth. As indicated on Fig. 6.4, the surface of the Sun is at temperature $T_S = 5{,}800\,\mathrm{K}$. Each meter square of the Sun radiates a power given by the Stefan–Boltzmann law σT_S^4 (see Sect. 4.2). Labeling the Sun' radius R_s so that

---

[4] As a part of the so-called thermohaline circulation, or meridional overturning circulation, this current plays a very important role in the global climate system. Stopping it to avoid pollution would have dire consequences (see, for example, [7, p. 1115]).

[5] Tsunami waves are a counterexample.

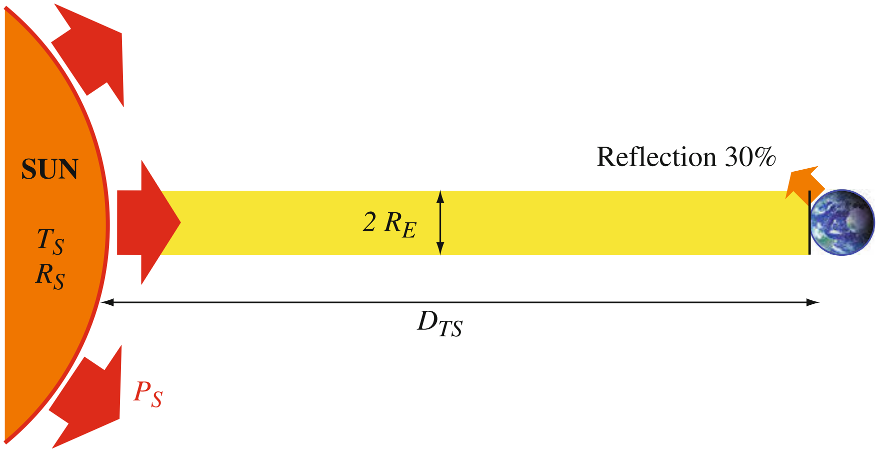

Fig. 6.4 Computing the Sun power received by the earth. Parameters are $T_S = 5{,}800$ K, $R_S = 6.9 \times 10^5$ km, $D_{TS} = 1.49 \times 10^8$ km, and $R_E = 6{,}400$ km

its surface is $4\pi R_S^2$, we find the total power emitted by the Sun,

$$P_S = 4\pi R_S^2 \sigma T_S^4. \tag{6.6}$$

This power is emitted isotropically in space. If D_{TS} is the Sun–Earth distance, one meter square of surface oriented toward the Sun at this distance receives,

$$C_S = 4\pi R_S^2 \sigma T_S^4 \, \frac{1}{4\pi D_{TS}^2} = \sigma T_S^4 \left(\frac{R_S}{D_{TS}}\right)^2. \tag{6.7}$$

Taking the numbers indicated on Fig. 6.4, we find $C_S = 1370$ W/m^2, the so-called solar constant. All the power intercepted by the earth disk of radius $R_E = 6{,}400$ km is captured. How much is it a year? We first calculate the power intercepted and multiply by the number of seconds in a year,

$$\pi R_E^2 C_S \times 3600 \times 24 \times 365 = 5.6 \times 10^{24}\mathrm{J}. \tag{6.8}$$

This number largely surpasses the 5.3×10^{20} J of world energy production. In fact, world production is only 0.01 % of the total amount of solar energy hitting the earth by year. It seems we could have a promising candidate here. A word of caution however: another 200 years of 1,000-fold increase of energy consumption (see Chap. 1) would bring it at 10 % of a year of Sun. This fact alone shows the next two centuries will not be, at least energy wise, like the last two.

To obtain the average power available on Earth, we need first to divide by the earth surface and second, to remember from Sect. 4.2 that the earth' albedo is $\alpha = 30\,\%$. The end result is

$$P = \frac{\pi R_E^2 (1-\alpha) C_S}{4\pi R_E^2} = 245\ \mathrm{W/m^2}. \tag{6.9}$$

Such is the power we can harness. When integrated over a year, you get $I = 7.7 \times 10^9$ J/m^2, or 2.1 MWh/m^2. A Google search on "sun radiation maps" provides a host of color-coded maps, indicating the measured available power at any location. Typical values go from $I = 2.7$ MWh/m^2 in the Sahara driest places, to 2 MWh/m^2 in southern Spain or 1 MWh/m^2 in the UK.

Suppose now you have an area of S m^2 to build a solar farm. Given the annual irradiation I at your place, you could hope for an energy production $E = IS$ per year. The end result would be less because you cannot convert all the solar energy. To start with, whatever your converters maybe, they will not cover the ground in its totality. You will need maintenance lanes between them, for example. And even the light hitting the converters will not be completely converted. The surface needed to replace a typical 1 GW power plant is then determined by,

$$3.1 \times 10^{16} = \eta I S \quad \Rightarrow \quad S = \frac{8.6}{\eta I \ (\mathrm{MWh/m^2})} \ \mathrm{km}^2, \tag{6.10}$$

where η is the conversion efficiency and I is in MWh/m^2. Covering 90 % of the ground with 15 % efficiency[6] solar cells gives $\eta = 0.9 \times 0.15 = 0.13$. With a farm located in Sevilla, southern Spain, $I = 2$ MWh/m^2 gives $S = 33$ km^2. In UK, $I = 1$ MWh/m^2 would double the needed surface with $S = 66$ km^2. On the one hand, this seems everything but small. The area of Paris,[7] France, or the Manhattan island, is 87 km^2. On the other hand, most of the cities ground is already occupied by building (this is nearly the definition of a city), and these buildings have roofs where solar energy could be collected.

What about the world energy production? Here, the formula is simply

$$5.3 \times 10^{20} = \eta I S \quad \Rightarrow \quad S = \frac{0.14}{\eta I \ (\mathrm{MWh/m^2})} 10^6 \ \mathrm{km}^2. \tag{6.11}$$

With an efficiency $\eta = 0.13$, numbers now come in million km^2, that is, in a couple of countries such as France or Spain.

6.2.2 Biofuels

The combustion which takes place in your car engine is a chemical reaction between oxygen and long hydrocarbon molecules. Right now, they mostly come from oil. The basic idea of biofuels is to derive these molecules from crops. Biofuels, namely plants generated fuels, could be a solution as 1/plants can last forever, providing you use each year only what grew this very year, and 2/ they absorb when growing the carbon they emit when burning.

A rough assessment of biofuels efficiency is straightforward from here. The available solar energy for an area S with annual solar irradiation I is $E = \eta I S$, where η is

---

[6] As of 2013, this is the typical efficiency for commercial cells. In the laboratory, the record is more than 43 % [10].

[7] Note for the "connaisseur": I take out the Bois de Vincennes and Boulogne from the Paris surface.

Table 6.2 Typical yield in liters per hectare for a few biofuels

Fuel/Crop	Yield (L/ha)	S_W (10^6 km^2)	S_T (10^6 km^2)
Ethanol			
Sugar beet (France)	6,671	19	3.6
Sugarcane (Brazil)	6,185	21	3.8
Cassava (Nigeria)	3,830	33	6.2
Sweet sorghum (India)	3,494	36	6.8
Corn (US)	3,307	38	7.2
Wheat (France)	2,588	49	9.2
Biodiesel			
Oil palm	4,746	27	5
Coconut	2,149	59	11
Rapeseed	953	133	24.9
Peanut	841	151	28.2
Sunflower	766	166	30.9
Soybean	523	243	45.3

Energy used in production and refining is *not* accounted for. S_W = surface needed to provide the 2010 world energy production. S_T = surface needed to generate the energy used for 2010 world transportation.The US territory is 9.8×10^6 km^2. *Sources* Yields are from Ref. [12, p. 34]

the overall converter efficiency. In the case of biofuels, the converter is a plant which captures solar energy through photosynthesis. Photosynthesis energy yields is at the *very best* 5 % [9, p. 140], [11]. You cannot capture all the solar power because your field needs parallel alleys to access it. We set the amount of covered ground to say, 50 %. Then, only half of the plant or so will be used to extract fuels. Because the plant had to use the solar energy it collected to grow 100 % of itself, this is another 50 % lost. We eventually get to an efficiency coefficient $\eta = 0.05 \times 0.5 \times 0.5 = 1.2\,\%$. And still, we forget about the energy needed to cultivate the field and to extract the fuel from the crops (see Sect. 7.1).

Which amount of fuel can we hope to extract from one hectare? We just have to express the numbers for one hectare in tons oil equivalent (toe). This is the beauty of energy conservation. You do not have to worry about the mechanisms involved. All you care about is the energy in and out. So we come back to $E = \eta I S$, and set $S = 10^4$ m^2 (this is one hectare). For $I = 1$ MWh/m^2 and $\eta = 1.2\,\%$, we now have $\eta I S = 4.32 \times 10^{11}$ J/year for one hectare of field. Converting to toe, with 1 toe $= 42 \times 10^9$ J, we come to,

$$E_{\text{bio}} = I\ (\text{MWh/m}^2) \times 10\ \text{toe}. \tag{6.12}$$

A field located in a region with $I = 1$ MWh/m^2 should thus give you about 10 tons of biofuels a year per hectare. How does this estimate compare with real numbers? Table 6.2 gives the actual yields from a number of crops [12]. Our rough assessment of 10 toe is definitely confirmed and appears as an upper limit. Real numbers could be about 50 % of the ones given in the Table [13]. The same analysis indicates that the real bottleneck is photosynthesis. Table 6.2 also displays the area required to generate the 2010 World energy production, 12,717 Mtoe, and the 2010 World transports energy consumption, 2,369 Mtoe [1]. The numbers are worth comparing to the 13.8×10^6 km^2 of the world arable lands [14].

As staggering as these numbers may appear, biofuels are still one of their kind regarding their energy density: Imagine the post-fossil world. How do you propel a jet capable of flying a few 1,000 km without refueling? The Boing 730–600 some airlines use to take you from Paris to New York, can carry 26,000 liters of fuel, and fly up to 132 passengers 6,000 km straight.[8] The numbers reported in Table 5.1 show other electromagnetic options than liquid fuel would require almost 5 times the same volume to hold the same energy. The tank would just not fit in the plane. In this case, the only alternative to liquid fuel…is another liquid fuel. And if you no longer have coal to make some, the only option, energy wise, is biofuel. It is just a matter of energy density. Because technology will not change the law of energy conservation, the only hope would be to design a plane spending 5 times *less* fuel. A formidable challenge for sure. But who knows?

6.2.3 Biomass

We end this section assessing the potential of biomass. We just saw car engines could burn molecules that did not originate from fossil fuels. More generally, we now look for material to burn outside those fuels. Like trees, for example.[9] As long as we chop in a year what grows in a year, not more, the operation is sustainable and carbon neutral.

Here again, the energy released when burning wood can be eventually traced back to the Sun. A notable difference with biofuels is that when it comes to forest, we can consider the trees intercept 100 % of the sunlight. Also, the portion of the tree you burn is virtually 100 %. In turn, photosynthesis efficiency can get as low as 0.2 % [9, p. 141], [16, p. 5]. We thus gain a factor 4 and lose a factor $5/0.2 = 25$ in photosynthesis. The expected energy for one hectare of exploited forest is thus 4/25 times that of Eq. (6.12), namely

$$E = I\ (\text{MWh/m}^2) \times 6.8 \times 10^{10}\ \text{J}. \tag{6.13}$$

Let us check this number with Sweden. Taking $I = 1$ MWh/m^2, the equation above gives an expected energy per hectare,

$$E_{\text{exp}} = 6.8 \times 10^{10}\ \text{J}. \tag{6.14}$$

What are the stats saying? According to the Food and Agriculture Organization of the United Nations (FAO), Sweden had 28 million hectares of forest in 2010,

---

[8] See www.boeing.com.

[9] Ethanol can also be generated from trees, such as poplars [15].

of which 20.8 (74 %) were used for wood production. Still according to the FAO, Sweden produced 8.6×10^7 m^3 of wood in 2005. Considering a density of order unity and taking 3 kg of wood for 42 MJ from Table 5.1, we find this wood production is equivalent to 1.2×10^{18} J. The measured energy yield per hectare for Sweden is therefore,

$$E_{\text{meas}} = \frac{1.2 \times 10^{18}}{20.8 \times 10^6} = 5.8 \times 10^{10} \text{ J}, \tag{6.15}$$

quite close indeed to our estimation (6.14).

Having checked our formula, let us finally assess the global potential of forest as energy providers. As of 2005, forests occupied 40 million km^2, or 4 billion hectares.[10] Multiplying this number by the energy yield (6.13) with $I = 1.5$ MWh/m^2 on average gives the global energetic potential,

$$E = 1.5 \times 6.8 \times 10^{10} \times 4 \times 10^9 = 2.7 \times 10^{20} \text{ J}, \tag{6.16}$$

namely, 51 % of the 2010 world energy production. It would certainly be difficult to dedicate *all* forests to energy production,[11] but the number above shows woodfuel could play a role on a global scale.

6.3 Geothermal Energy

We conclude the inventory of kinetic energy sources by geothermal energy (biofuels and biomass have been treated here by virtue of their direct connection with solar energy). As previously stated, the heat of a body is nothing but the kinetic energy of the molecules or atoms it is made of.

Geothermal energy consists therefore in harnessing the heat that comes from the earth core about 5,700 °C hot. This heat originates partly from the radioactive decay of uranium-238 & 235, thorium-232, and potassium-40 [17]. The other part is simply the remnant of the heat generated when the earth was formed.[12] Indeed, it is, together with solar power and nuclear energy, the only truly primary energy source on Earth. Fossil fuels are nothing but organic materials which energy content can be traced back to the Sun. Wind is powered by the Sun. Rain also, and hydropower as well. But inner Earth radioactivity does not rely on the Sun. For some planets, such as Jupiter or Saturn [19], it has to be accounted for in the energy balance we saw on Sect. 4.2.

---

[10] See www.fao.org/forestry/fra/fra2010.

[11] Still, in 2005, 30 % were exploited, half of the wood production being dedicated to woodfuel.

[12] Again, energy conservation was at work here: the earth formed by gravitational condensation of rocks and dust orbiting the Sun. Doing so, they had to get rid of their gravitational and kinetic energy, which ended up into heat. By detecting the neutrino emitted by radioactivity, scientists could recently estimate that 23–38 % of the heat flux comes from radioactivity. The rest is very old leftovers of the initial heat [18].

On the earth' surface, the heat flux from within is typically $P_E = 0.087$ W/m^2 [17, p. 136]. This is far less than the 245 W/m^2 from the Sun. Integrating P_E over the full Earth surface and over one year gives the annual energy $E = 1.4 \times 10^{21}$ J.

Though superior to the worldwide 2010 production of 5.3×10^{20} J, such amount of energy is in practice extremely difficult to access. On average, far from tectonic plates boundaries, underground temperature increases by 7 °C per km until 200 km [17, p. 187]. It takes therefore a 14 km drilling to reach the 100 °C zone able to generate vapor.

Uncertainties over the amount of energy recoverable generate a large disparity in global potential assessments. An article from the International Geothermal Association opportunely entitled *What is geothermal Potential?* reviewed the literature in this respect as of 2003 [20]. Potential estimates ranged from 5×10^{20} to 138 less, namely 3.6×10^{18} J. The first number nearly covers the 2010 world energy production and represents 35 % of the number we found integrating the heat flux P_E over the full globe. It is very close indeed to the potential found integrating over all land surfaces (30 % of the globe).

The second and much smaller estimate perfectly fits an integration over the volcanic areas *only*, as they cover 1 % of the full globe [21, p. 217]. This latter estimation would prevent geothermal energy from playing a global role. Still, it could definitely be part of local solutions in well-located countries such as Iceland, El Salvador, or Philippines where 25, 22, and 17 % of the electricity is already produced this way [22].

We can put our orders of magnitude technique to the test with Iceland. Seated on top of the Mid-Atlantic Ridge, Iceland is the volcanic place *par excellence*. Suppose Icelanders want to harness 100 % of the geothermal energy coming through their land. How much would they get? The country is 100,000 km^2 large. Multiplying this by the world average geothermal heat flux P_E, and by the number of seconds in a year gives an approximated potential of 76 TWh/year.

Turning now to the real world, the total heat flux across Iceland is estimated at 30 GW [23]. Dividing by the area of the country, we find an average of 0.3 W/m^2 which is 3.5 times larger than P_E. How high can geothermal energy realistically go in this country? Part of the heat goes through volcanoes, where you cannot capture them for obvious reasons. Out of these 30 GW, the estimated harnessable energy current is 7 GW [23]. Again multiplying by the country area, we find an evaluated potential of 61 TWh, quite in line with of our 76 TWh estimate.

Iceland generated 7 TWh of geothermal energy in 2008, out of which 4 TWh went to electricity [23]. It is thought electricity generation could climb up to 20 TWh. At any rate, our quick estimate is definitely confirmed.

6.4 Hydropower

We now turn to energy sources originating from harnessing gravitational potential energy. We here need to find something high, and let it down. But this something must have been brought on a height by nature. Not by us. Rain falling on mountains is the perfect, if not the only, candidate. As it is channeled down through rivers, dams are built to retain it. All you have to do then is put a turbine on the bottom of the reservoir, and let water flow when you need electricity. Note that the same turbines are often made reversible so that in case there is too much electricity in the grid, you can use it to pump up water. This is a clever option for electricity storage.

It is therefore obvious that a significant hydroelectricity production demands both mountains *and* rain. Belgium has a lot of rain. A lot. But as the famous Belgian artist Jacques Brel was singing in his song "The Flat Land," "cathedrals are the sole mountains" there.[13] As a result, its hydroelectricity production is condemned to remain close to zero.[14]

From this understanding of hydropower, we can compute the potential of any country. Suppose yours has mountains occupying an area S_M, and that it rains r meters/m^2 of water a year. The volume of water falling on mountains is thus $V_M = S_M r$ and its mass $M_M = \rho V_M$, where ρ is the density of water. Then, you need to let it fall. The higher, the better. We will say an average dam has water falling $h = 100$ m before it goes through the turbine. Then, the potential energy of gravitation available is simply

$$E = M_M g h = \rho S_M r g h = S_M r \text{ J}, \tag{6.17}$$

where S_M and r have to appear in m^2 and m, respectively.

Let us try with Spain, which has a lot of mountains, and a fair amount of rain in the north. According to the *Instituto Nacional de Estadística*[15] (*INE*), the total length of Spanish mountains (Pyrenees, sierras…) is about 4,000 km. We will give them a typical width of 50 km. We thus have $S_M = 4000 \times 10^3 \times 50 \times 10^3 = 2 \times 10^{11}$ m^2. The *INE* tells it rained on average $r = 0.68$ m of water per year on the Spanish territory, between 1995 and 2010. Our formula (6.17) gives

$$E = 2 \times 10^{11} \times 0.68 \text{ J} = 1.36 \times 10^{17} \text{ J} = 37 \text{ TWh}, \tag{6.18}$$

where 1 terawatt hour (TWh) is 10^{12} Wh. Still according to the *INE*, the average hydroproduction between 1991 and 2011 was about 30 TWh. Here again, a crude estimate from the physical principles gives a very good order of magnitude.

As for Spain, production has nearly reached saturation. In other words, all the dams that could be built have been so. And the worldwide situation is quite similar. About 70 % of the installations considered in a purely wind/water/sun scenario for 2030 are already in place [24]. As of 2010, hydroelectricity represented 16 % of the world electricity production. In terms of energy production, these 16 % amounted to 2.3 % of the world energy production [1]. Studies found it could be tripled in the future, taking the hydropower share to some 10 % of the 2010 energy production [25, p. 273]. And this is about all we will ever get. Hence, while hydroelectricity is likely to play a role *locally*, it should have but a minor role in any *global* solution.

---

[13] In French, "des cathédrales pour uniques montagnes"—Jacques Brel, *Le Plat Pays* (1962).

[14] Thanks to some "mountains" in the south-east, 1.7 TWh in 2009. Compared to 62 for France or 30 for Spain. *Source*: www.iea.org.

[15] See www.ine.es.

6.5 Nuclear Energy: Fission

We now conclude our inventory of potential energy based sources by nuclear energy, which harnesses nuclear potential energy. Doing so, we jump directly from the last section on gravitational potential energy. We therefore bypass the electromagnetic potential energy category. Oil, coal, and gas are the main representatives of this category. Regarding the post-fossil fuels world, biofuels and biomass would fit in there too. Yet, they were treated in Sect. 6.2 as kinetic energy based sources, due to their direct connection with solar energy.

Nuclear reactions do not emit greenhouse gases by design. They do not have anything to do with combustion reactions at the molecular level. Here, we do not deal with the electrons around the atom nucleus. We deal with the very nucleus. The numbers reported on Table 5.1 are another motivation to pursue this option. Because nuclear forces are by far the strongest ones, they hold, by far, the higher energy density.[16] In case you are unfamiliar with nuclear physics, you can flip to Appendix C for a crash course on the basics. There, we explain, among other, why the only way to get energy out of the nuclear force is to split a big nucleus, or merge two light ones. The first option is *fission*. The other is *fusion*. Let us start with fission.

The table of nuclides represented on Fig. 6.5 displays all the known nuclei. It shows nuclei beyond 126 neutrons and 83 protons are fragile. They are simply too big to be at ease with themselves. Too many protons repel each other inside them. They are radioactive and display the full spectrum of decay types. Some of them, such as uranium-235, have the ability to split into two smaller nuclei when struck by a neutron. Here, we have one of the reactions capable of releasing energy: we start from an heavy nucleus and end up with smaller ones. Suppose our heavy weight has a total of N nucleons, with more than 100 neutrons and 80 protons. From Fig. C.1 in Appendix C, we see its total binding energy should be around $E_B = N \times 7.5$ MeV. After fission, each fragment will be about half the size of the original. With some 50 neutrons and 40 protons, Figure C.1 gives $E_B \sim 8.5$ MeV. The energy balance "after–before" reads,

$$8.5\frac{N}{2} + 8.5\frac{N}{2} - 7.5N = 1 \times N \text{ MeV}. \tag{6.19}$$

The fission of a nucleus with N nucleons should therefore release some N MeV. The 435 power plants running worldwide in 2012 "burn" uranium-235 (143 neutrons, 92 protons). Its fission releases a total of 211 MeV, which fits very well our estimate of N MeV with $N = 235$. Uranium-235 is said "fissile" because it breaks up into two smaller nuclei when hit by a neutron.

Now, where do you find your neutrons? We saw in Sect. 2.5 that it takes energy to trigger a chemical combustion reaction, but that the same reaction releases enough energy to trigger another one. This is why you need only *one* match to light a fire. Nuclear fission of uranium-235 follows the same pattern. You need to provide the first neutron to split the first nucleus. But the very fission process frees between

---

[16] About 1 million times higher than the electromagnetic force.

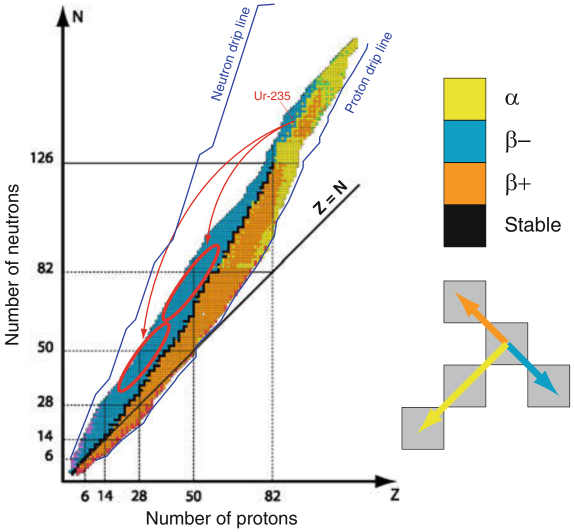

Fig. 6.5 The table of nuclides. Each cell of the graph represents a known nucleus. Only black cells are stable. The red ellipses locate very schematically the fission products of uranium-235 (see discussion in Sect. 7.3). Drip lines (see Appendix C) are schematically drawn

2 and 3 neutrons. This is the basis for the famous "chain reaction." One fission event generates a few neutrons which generate more fissions, generating even more neutrons, etc. Here again, the "fire" is self-maintained. The formidable strength of nuclear forces eventually results in the energy densities reported on Table 5.1. The 42 MJ released by the combustion of 1 L of oil hold in just 0.5 mg of uranium-235, less than the weight of a mosquito.

Nuclear fission would not deserve the label "element of solution" if it were only for uranium-235. Like oil, coal, or gas, the amount of uranium-235 available on Earth is finite. If there is a peak oil, there must be a peak uranium-235 in exactly the same way there is a peak for whatever non-renewable resource.[17] The question is not "will there be a peak," but "*when* will it be." With uranium-235, the big problem is that it amounts for only 0.72 % of the extracted uranium ore. Almost all the rest is uranium-238, which is *not* fissile.[18] As of 2009, worldwide uranium-235 reserves were estimated at $R = 5.3$ Mt while annual demand was $D = 63{,}875$ t [27]. The ratio R/D gives 83 years. Anything but "renewable."

But again, in the same way that there is not one single combustion reaction, there is not one single nuclear fission reaction. Uranium-238, for example, making up most of the uranium ore, can absorb a neutron to become plutonium-239. And plutonium-239 can fission releasing the same amount of energy as uranium-235. Since for one nucleus of uranium-235 extracted, we recover indeed 99 of uranium-

---

[17] Copper production, for example, could peak around 2040 [26].

[18] 0.72 % is too low a percentage for a power plant (∼4 % required), or a weapon (∼90 %). The uranium ore needs therefore enrichment before it can be used. Technologically, this is a difficult task since uranium-235 and uranium-238, with the same number of protons and electrons, have nearly identical chemical properties. See Wikipedia on "Enriched uranium."

238, our ratio R/D suddenly jumps to $99 \times 83 = 8{,}217$ years. Thorium-232 also can absorb a neutron to become the fissile uranium-233. It is even more abundant than uranium-238 and would then give another 10,000 years or so [27,28].

Nuclear fission represents today only 5.7 % of the world energy production [1]. Thus, uranium-238 and thorium-232 could potentially power the world for one millennium. This is not renewable *sensu stricto*, but long enough to earn a section in this chapter. Let us now turn to the only other way of harnessing nuclear power: nuclear fusion.

6.6 Nuclear Energy: Fusion

Nuclear fusion is just the contrary of fission. You start with a very low number of protons and neutrons on Fig. 6.5, and you jump up the hill on Figure C.1. Suppose you start with two really small nuclei bearing N nucleons and a binding energy per nucleon around 2 MeV. Once they are merged, the final result is a nucleus with $2N$ nucleons and a binding energy of roughly 4 MeV per nucleon. Your energy balance "after–before" now reads,

$$4 \times 2N - 2 \times N - 2 \times N = 4N \text{ MeV}. \tag{6.20}$$

Let us look at a few fusion reactions with their energy yield and the place where they occur,[19]

$\mathrm{p} + \mathrm{p}$	$\rightarrow \mathrm{D} + e^{+} + \nu_e$	0.42 MeV	Sun
$\mathrm{D} + \mathrm{p}$	$\rightarrow \text{He-3} + \gamma$	5.49 MeV	Sun
$\text{He-3} + \text{He-3}$	$\rightarrow \text{He-4} + 2\mathrm{p}$	12.86 MeV	Sun
$\mathrm{D} + \mathrm{T}$	$\rightarrow \text{He-4} + \mathrm{n}$	17.6 MeV	Fusion Reactor

Our energetic rule of thumb above is quite accurate but for the first, as it gives energetic gains of 4, 4, 12 and 12 MeV, respectively. The first three occur at the center of the Sun [29]. Just these three (there are more) release 18.78 MeV: Nuclear fusion is the source of the Sun power.[20] Without it, no shining Sun nor life on Earth. The fourth one is the one physicists have been trying to exploit in vain for more than 60 years. In contrast, fission was discovered in 1938 and the first reactor-generating electricity was operated in 1951.

---

[19] D = deuterium = p + n, T = tritium = p + 2n, helium-3 = 2p + n, helium-4 = 2p + 2n, e^{+} = positron, ν_e = electron neutrino, γ = photon.

[20] Among the products of these 3 reactions going on at the center of the Sun, only the neutrinos ν_e escape the star because they interact poorly with matter. From the late 1960s, physicists tried to detect these neutrinos in order to check solar fusion reaction rates. To their surprise, experiments were detecting about 1/3 of the expected number [30,31], a result which inaugurated the "neutrino problem." The puzzle was solved when it was found that neutrinos oscillate periodically between 3 different types. Since the first experiments were only sensitive to 1 type, they only detected 1/3 of the neutrinos. The experimental confirmation of this fact solved the problem [32], and earned the 2001 Nobel Prize in Physics to its discoverers.

Why are scientists so eager to pursue fusion? Because it is incredibly promising. Table 5.1 shows it could generate the energy of one liter of oil out of only 0.05 mg of deuterium (1 proton + 1 neutron) and 0.07 mg of tritium (1 proton + 2 neutrons). In addition, the fuel is virtually inexhaustible. Here on Earth, one seawater hydrogen atom out of 6,700 has a deuterium nucleus [33]. Tritium is radioactive, with a 12.3 years half-life. As such, it does not exist in nature. But it could be bred from lithium (3 protons and neutrons) in power plants, and oceans host about 250 Gt of it [34]. All in all, there is enough fuel to provide more than 36 million years of the 2010 world energy production.

Why is fission so easier to harness than fusion? In fission, fissile heavy nuclei "want" to split. Once the first one has done it upon absorbing a neutron, it releases more neutrons in the fission process. All you have to do then is make sure other fissile nuclei are not too far apart so that they can enjoy your newly born neutrons and split in turn. With fusion, light nuclei need to come close enough to merge. Here, the "close enough" is the problem because while they are not close enough, they repel each other because of the electromagnetic interaction between the protons of each nuclei. While they are "far," the dominant interaction is not the nuclear force, but the electromagnetic Coulomb force. And it keeps protons apart. Nuclear force takes the lead only at very, very close distances like 10^{-15} m. There is no such thing as Coulomb repulsion with fission because the neutron about to split your Ur-235 is *neutral*. It does not care about Coulomb and can make its way right to the uranium nucleus, without any hurdles.

It takes a lot of energy to merge two light nuclei. Granted, it will be given back to you, with interests, once fusion is achieved. But in the meantime, you need to invest. How much? If we represent 1 electron volt by one meter, we can picture a fusion event by the climbing of the Coulomb hill pictured on Fig. 6.6. You need first to climb a hill 10,000 m high before you fall at the bottom of a well some 10 million meters deep. In physical terms, you need to give 10 keV to receive 10 MeV or so.

There is more. If we just want a few single fusion events, we can go to a particle accelerator, smash nuclei against each other's and merge them. But the end energy balance would be a disaster because the few MeV we would get are nothing compared to the energy needed to run the accelerator. In order to get more energy than we have put it, we need to merge a lot of nuclei. We cannot just throw two at each other. We need a place where fusion reactions occur on a regular basis. In the same way, combustion releases energy when you burn a macroscopic number of molecules, namely 10^{23} or so, we need here to "burn" a macroscopic number of nuclei.

A branch of physics called statistical physics has a lot to say on macroscopic numbers of nuclei. For example, in such a population, the average kinetic energy E_K of the particles is related to the temperature T of the gas by $E_K = \frac{3}{2}k_B T$ (k_B is the Boltzman constant). If particles are to be energetic enough to come close enough and merge, then E_K must be about 10 keV, the height of the Coulomb hill. What is then the corresponding temperature? Around 100,000,000 K (or °C. At this stage, ±273 will not change much anyway).

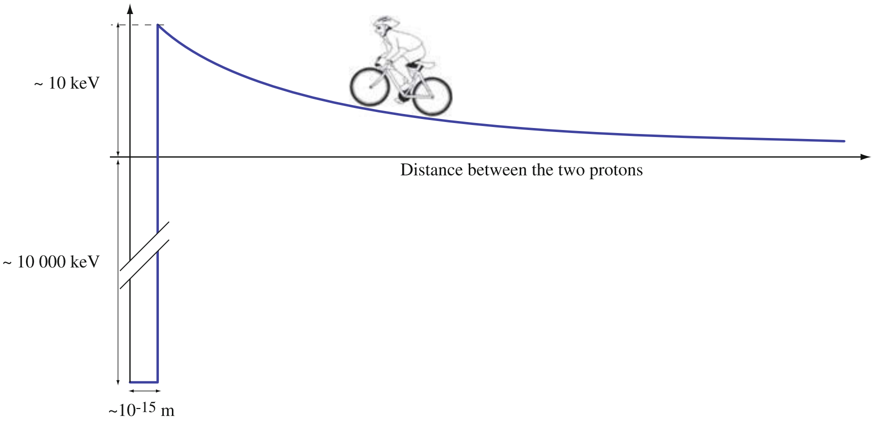

Fig. 6.6 The fusion Coulomb hill. If 1 eV = 1 m, you start from sea level, climb 10,000 m before falling 10,000 km down

6.6.1 The Lawson Criterion

We are starting to understand the beginning of the problem. One hundred million degrees is no cool place. But it is still not enough. This temperature only guarantees a great number of fusion events can occur. But how do you know they will last? Your fireplace is able to warm your living room because the combustion is self-sustained. On the one hand, it loses energy heating the room, but on the other hand, exothermic chemical reactions continuously feed power in. On the contrary, fire would die out quickly. Likewise, a fusion gas loses energy by radiation. If the internal energy input provided by fusion is lower than the losses, the fusion flame will quickly vanish. Analyzing the problem, John Lawson showed in 1957 that fusion reactions compensate losses provided [35],

$$n\tau > 2 \times 10^{20} \text{ s/m}^3, \tag{6.21}$$

where n is the gas density in particles per m^3, and τ the so-called confinement time which can be considered as the time the gas spends together at such density, and above the required temperature.

Putting numbers together, the domain (n, τ) fulfilling the Lawson criterion features the upper part of Fig. 6.7. Of course, an immense challenge is to hold a 10^8 degrees gas. In the Sun, gravity does the job and confines it at the center.[21] But how to achieve this in laboratory? No material on Earth can stand such temperature. It is thus necessary to maintain the gas away from any surface.

---

[21] The temperature at the Sun's core is "only" 1.5×10^7 degrees. Fusion can happen, but the time needed to achieve it is enormously longer than at 10^8 degrees. We should be thankful for this, since were the temperature to rise suddenly to 10^8 degrees, the sun would quickly burn out!

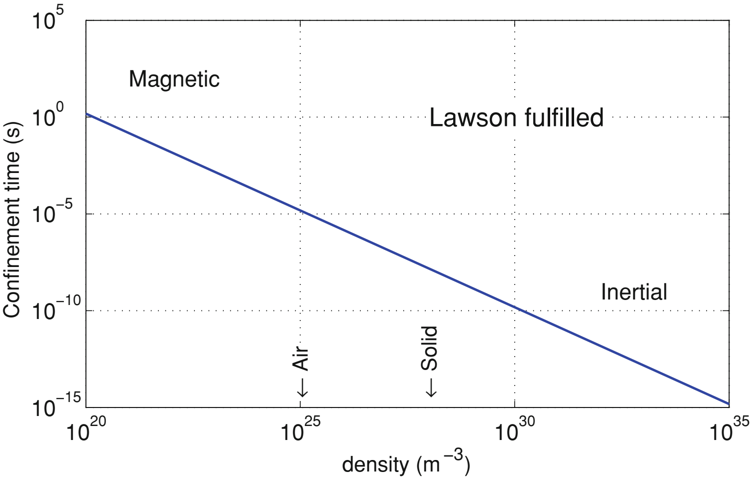

Fig. 6.7 Fusion releases more energy than losses if the gas parameters are above the line defined by the Lawson criterion (6.21). In addition, temperature must be larger than 10^8 degrees. Typical air and solid densities are indicated for reference

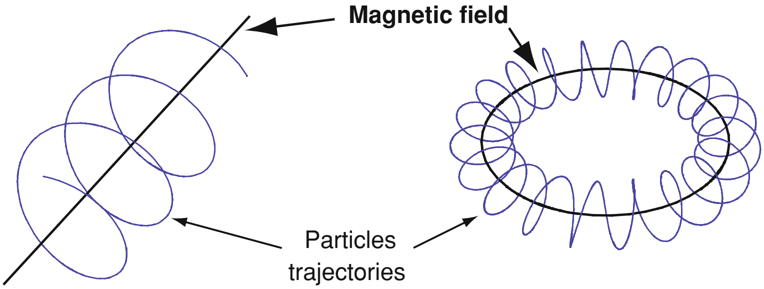

Fig. 6.8 In the presence of a magnetic field, here pictured by the *bold lines*, particles circle around. By closing the *field line*, particles are confined

One option consists in doing everything so quickly, at the center of a spherical reaction chamber, that the gas simply has no time to reach the surface before all the nuclei that have to merge do so. This is called "inertial confinement," with a confinement time τ of a fraction of nanosecond (10^{-9} s). Figure 6.7 shows how the fulfillment of the Lawson criterion demands in turn extreme densities.

Any slower option requires holding the gas. The only possibility is to confine it to a closed region of space by means of a powerful magnetic field. It turns out that at such temperatures, atoms have lost all their electrons. The result is known as a "plasma," namely, a charged gas. As such, it can be manipulated by magnetic fields. For reasons we shall see below, this is only possible at densities like the ones displayed on Figure 6.7 near the label "magnetic." This second option has been called "magnetic confinement."

6.6.2 Magnetic Confinement

The basic idea of magnetic confinement is that if you picture a magnetic field like the line drawn on Fig. 6.8, charged particles circle around that line. So if you close the line, making it a loop, particles circle around the loop. And since the loop is closed, they are spatially confined inside a donut-like shape. But as they form a gas together, pressure tends to drive them away from the donut. How do you keep them inside? Plasma physicists have found a magnetic field produces a “magnetic pressure” opposing gas pressure (see, for example [29, p. 47]). For a confinement field of amplitude B_c tesla, it reads $P_B = B_c^2/2\mu_0$, where $\mu_0 = 4\pi 10^{-7}$ is the vacuum permeability.[22] Since the gas pressure reads $P = nk_B T$, we need

$$B_c > \sqrt{2\mu_0 n k_B T}, \tag{6.22}$$

where T must be larger than 10^8 K while the density n remains constrained by the Lawson criterion. On the one hand, choosing a low density to keep the magnetic field low as well, imposes an ever increasing confinement time through the Lawson criterion (see Fig. 6.7). On the other hand, large densities require large B_c fields which are difficult to generate. The typical density pictured on Fig. 6.7 for magnetic confinement results from a trade-off between these two masters. Setting $n = 10^{21}$ m^{-3} in the equation above gives $B_c > 1.86$ tesla. This is already 100,000 larger than the earth magnetic field. How do you generate this? It is well known that a current I passing through a ring-like circuit of radius r generates a field along the ring axis given by,

$$B = \frac{\mu_0 I}{2r}. \tag{6.23}$$

Here again, a trade-off is to be made. The current ring will have to be outside the donuts. We would like it to be as large as possible to leave room for the hot plasma. But maintaining the same B with a large r requires an ever increasing current. Choosing $r = 1$ m and $B_c = 2$ tesla imposes $I = 3.2$ mega-ampere (MA). Even if your ring circuit is made up of 100 windings, we still need 32 kilo-ampere per winding, which is considerable.

The resulting machine is schematically represented on Fig. 6.9. Invented by Russians physicists, among whom stands Andrei Sakharov, the famous 1975 Nobel Peace Prize Russian physicist, it bears the Russian name of “Tokamak.” Progresses have been slow but rather steady in magnetic fusion. The largest machine built so far, the “Joint European Torus” (JET) successfully triggered DT fusion reactions in 1991.[23] On JET, the donut was $2R = 6$ m wide in diameter, with a torus radius $a = 1.25$ m. JET could not experiment long duration discharges for various reasons. One of

---

[22] The connection between this confinement by magnetic pressure, and the confinement through spiraling trajectories explained in Fig. 6.8 is not straightforward. The latter refers to the motion of individual particles, a *microscopic* perspective. The former has to do with the behavior of the full gas, a *macroscopic* perspective. Though puzzling, magnetic pressure is a macroscopic result of the microscopic effect of the field (see [36, p. 231]).

[23] See www.efda.org/jet/history-anniversaries/ or [37].

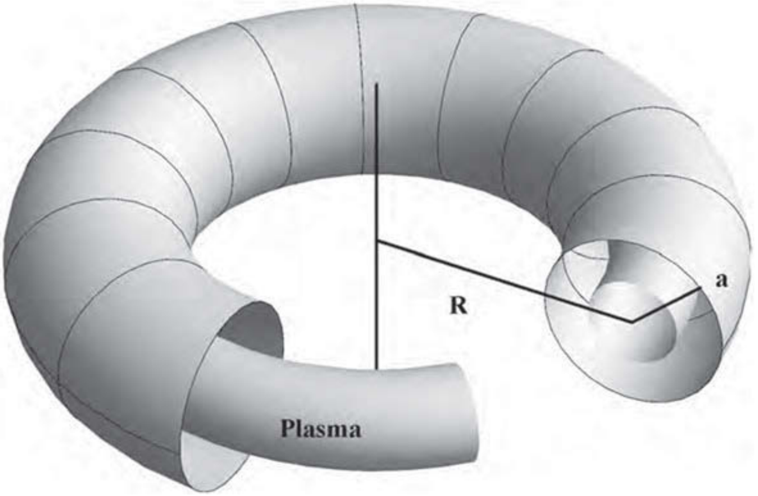

Fig. 6.9 Schematic representation of a Tokamak. The coils are the *black lines circling* the donut. The section of a real machine is not exactly circular

them is that the mega-amperes necessary to sustain its 3.4 T magnetic field would have melted the coils quickly. This issue was dealt with in a slightly smaller machine ($R = 2.4$ m, $a = 0.72$ m) baptized “Tore Supra”. Equipped with superconducting coils, long duration experiments could be run without worrying about coils heating and melting. In 2003, a 17 million degrees plasma was maintained for more than 6 min [38].

The International Thermonuclear Experimental Reactor (ITER[24]) is currently under construction in the south of France. One could write “JET + Tore Supra = ITER.” Like JET, ITER will operate with deuterium and tritium (Tore Supra did not), and like Tore Supra, superconducting coils will allow long duration experiments. In addition, ITER will be larger than his fathers, with $R = 6.2$ m and $a = 2$ m. One of its goals is to achieve 500 MW of fusion power from 50 MW of injected power, for more than 5 min [39]. Completion of the construction is scheduled for 2019. The first DT experiments for 2027 [40].

ITER should be the last experiment before DEMO, a DEMOnstration Power Plant. It could be the first prototype generating electricity, possibly operating from 2037 [40]. Note that scientists are not the only ones responsible for such time dilatation. With respect to the ITER project, for example, Ronald Reagan and Mikhail Gorbachev agreed on a joint effort to pursue fusion in 1985. It took more than 20 years of politics to sign an agreement in Paris on November 21, 2006. Yet, politics notwithstanding, technical challenges are considerable.

---

[24] See www.iter.org.

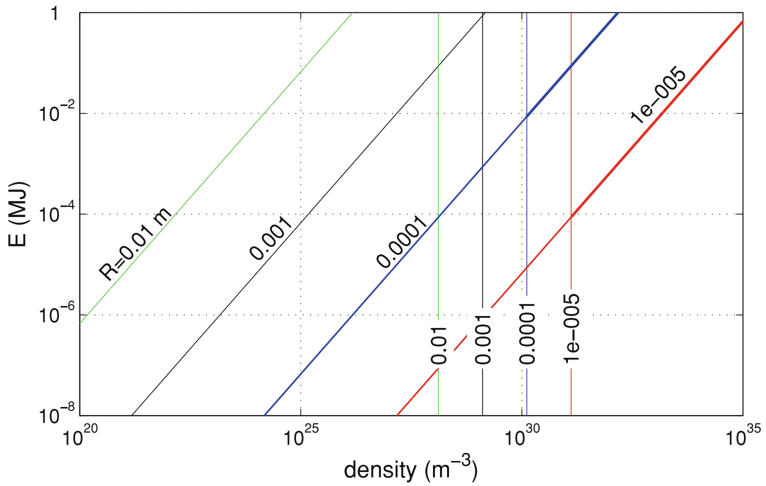

Fig. 6.10 Constraints set by Eqs. (6.24, 6.25) for inertial confinement fusion. Oblique lines pertain to Eq. (6.25) for 4 values of R. Vertical lines come from Eq. (6.24)

6.6.3 Inertial Confinement

We are now in the lower right corner of Fig. 6.7. In a plasma at temperature T, particles' velocity is about $\sqrt{k_B T/m}$ (m/s), where m is the particles' mass. If your gas in enclosed in a region of space of size R and you just let it go, it will stay together for a time $\sim R/\sqrt{k_B T/m}$. Such is now our confinement time τ. Here again, we have two masters to please. The first one is the Lawson criterion. Reminding we still need $T > 10^8$K and setting $\tau = R/\sqrt{k_B T/m}$, we now get from the Lawson criterion (6.21) a requisite on the density,

$$n > 2 \times 10^{20} \frac{\sqrt{k_B T/m}}{R} = 1.3 \frac{10^{26}}{R} \text{ m}^{-3}, \tag{6.24}$$

where m has been set to the deuterium mass.

The second one is the amount of energy we can pour in. In order to trigger fusion, we need to bring in energy in a limited region of space. Suppose this region is a sphere of radius R and volume $V = \frac{4}{3}\pi R^3$. If the gas inside is at density n and temperature T, the sphere contains nV particles, holding the total energy

$$E = n\frac{4}{3}\pi R^3 k_B T, \tag{6.25}$$

still with $T > 10^8$ K.

For any given R, Eq. (6.24) gives a minimum density to achieve. Still for any given R, Eq. (6.25) gives the amount of energy to bring in, in terms of the density. And it must be realistic. Figure 6.10 allows to visualize these constraints all together. Equation (6.25) has first been plotted for 4 values of R, yielding the 4 oblique lines. Then, the lower density limits set by Eq. (6.24) gives 4 vertical lines for the same

4 values of R. For a given radius, only the density range to the right makes sense, as the rest does not fulfill Lawson's criterion. Consider $R = 10^{-5}$ m, for example. Lawson criterion imposes $n > 1.3 \times 10^{31}$ m^{-3}. This means only the bold part of the oblique line for this radius is meaningful. As a result, the minimum energy to put in is 100 J. For $R = 10^{-4}$ m, the threshold density is 1.3×10^{30} m^{-3} and the minimum energy jumps to 10 kJ.

Why is the vertical scale limited to 1 MJ? For technological reasons. You may have noticed the radii involved are extremely small. Up to now, we reviewed what happens for 10 and 100 microns. How can you inject 100 or 10,000 J in a region 10 or 100 microns large? It takes an extremely accurate energy deposition. One way is to use a laser or a particle beam. As of 2013, there is only *one* MJ class laser in the world. And it is 3 football fields large (see below). Regarding particle beams, no installation on Earth is remotely capable of doing the job.[25] This is why there is no need to extend the vertical scale beyond 1 MJ. As a consequence, the graph shows $R = 1$ mm requires 1 MJ, and 1 cm targets will not work. It would require too much energy.

The final radius is eventually set by the properties of deuterium and tritium. Solid DT has a density close to 3×10^{28} cm^{-3}. We see from Fig. 6.10 that such density imposes a radius which demands too much energy. We will thus have to compress our solid DT in order to bring it down to a density yielding an affordable energy. A one hundredfold compression gives a compressed density of 3×10^{30} m^{-3}, with a corresponding compressed radius of $R \sim 0.04$ mm. The un-compressed, initial radius is therefore $0.04 \times 100^{1/3} \sim 0.2$ mm. The target is finally some 1 mm wide because it is not 100 % made of solid DT. If you wish to know more, Ref. [42] is one of the must read on this topic.

Magnetic fusion has its big machines and projects. So does inertial fusion. The "National Ignition Facility" (NIF) is the 3 football fields size laser already mentioned. The laser itself is a technological masterpiece perfectly delivering the 1.8 MJ it was designed to [43]. Yet, "ignition," namely the fulfillment of the Lawson criterion, is yet to achieve. Basic physics issues remain unexplained when it comes to understand the details of the laser plasma interaction. Temperatures of more than 3 million Kelvin have been produced [44]. More than 10^{15} fusion events have been generated in one shot [45,46]. But the Lawson criterion remains in an hopefully near, future.[26]

Even if NIF were to achieve ignition in 2014 or 2015, there would still be a long way to electricity production. In contrast with magnetic fusion, where a continuous source of heat would be produced, inertial fusion would generate energy the way a car engine does. A continuous source of electricity would thus result from a few

---

[25] The 7 TeV protons from CERN's LHC in Geneva are far too energetic. They would just go right through the target without depositing any energy in it. Regarding ions accelerators with the right energy range, even the next largest machine worldwide, the "Facility for antiproton and ion research" (FAIR) in Germany, falls short. FAIR should start operating toward 2016. It should be able to accelerate bunches of 4×10^{13} protons at 29 GeV each, for a total of "only" 0.2 MJ per bunch [41].

[26] See [47] for a technical review of NIF progresses up to 2013.

micro "explosions" per seconds. Right now, NIF is just trying to achieve one single of these micro-explosions. The road to a 1 GW power plant is still long.

Finally, another route to inertial fusion could prove worthy. The basics remain the same, as Eqs. (6.24, 6.25) qualitatively apply even if the region enclosing the plasma is not spherical. We saw above that one way of injecting as much energy as 1 MJ in a region as small as 1 mm is to use a laser. Another option consists in sending an enormous current in a thin wire a few mm long. The wire quickly vaporizes and turns into a plasma. Then, the laws of physics have the plasma column pinching under the action of the current still circulating in it. As of 2013, the largest machine is the "Z-machine," hosted at the US Sandia National Laboratories in Albuquerque, New Mexico. It holds the world record temperature with more than 2.3 billion Kelvin (200 keV). In other experiments where DT was introduced, nearly 3.9×10^{13} fusion events have been detected [48]. Yet, energies involves so far remain far below what would be needed for ignition.

Just a word about alternative fusion schemes like "bubble fusion" or "cold fusion." Bubble fusion is supposed to happen when gas bubbles collapse in a liquid, both gas and liquid being of course appropriately chosen. The collapse would create such a high temperature that nuclei would fusion. No one ever succeeded in reproducing the supposedly successful experiments [49]. Cold fusion, in which fusion was claimed to have been achieved in a test tube, follows the same tracks [50]. See [29] for more on these two approaches.

The only convincing scheme for not-so-hot fusion is the so-called muon catalyzed [51–53]. A muon is a particle looking pretty much like an electron, but 200 times heavier. You can form a H_2-like molecular ion with 1 tritium atom, 1 deuterium, and 1 muon instead of 1 electron. Doing so, the high muon mass drives the atoms 200 times closer than they are in an ordinary, electronically bounded molecule. Simply put, the muon climbs part of the Coulomb hill for you. As a result, deuterium' and tritium' probability to fusion is dramatically enhanced, to the point it becomes significant even at room temperature. Unfortunately, it poses many practical problems. For example, muons are unstable with a lifetime of 2×10^{-6} s. As such, there are no muon reservoirs. You need to produce them, which is energetically extremely costly. As of 2013, few scientists are still working on that field as these basic hurdles (you are not going to change the muon lifetime) are prohibitive.

Our energy review is now over. Table 6.3 summarizes the order of magnitudes we found, following the energetic pattern of Chap. 5. The energy production of reference is still the 2010 world one, namely 5.3×10^{20} J. Starting with kinetic energy sources, we find wind, solar power, and geothermal energies. Then, hydropower stands for gravitational potential energy exploitation. The electromagnetic potential energy reservoir is represented by biofuels and woodfuel, and nuclear potential energy by fission and fusion.

Table 6.3 Typical numbers involved in generating the 2010 world energy production, 5.3×10^{20} J, or 12.7 Gtoe

Sources	
Kinetic energy	
Wind power	10 million km^2 wind farm
Sea currents	Gulf Stream: 2.5×10^{19} J (4.6 %)
Solar	1 million km^2 solar cells
Geothermal	All volcanic areas: 3.6×10^{18} J (0.7 %)
Gravitational force	
Hydropower	5.3×10^{19} J (10 %)
Electromagnetic force	
Biofuels	19 million km^2 field
	3.2 million km^2 field (just traffic)
Woodfuel	Twice the total amount of forests in 2005
Nuclear force	Fission of 6,310 t of Ur-235
	Fusion of 630 t of D with 880 t of T

The numbers between parenthesis indicate, when relevant, the portion of 12.7 Gtoe that could be produced

References

1. International Energy Agency, Key world energy statistics (International Energy Agency, Paris, 2012)
2. D. DeHarpporte, *South and Southeast Wind Atlas* (Van Nostrand Reinhold, New York, 1984)
3. M.R. Patel, *Wind and Solar Power Systems: Design, Analysis, and Operation*, Mechanical Engineering (Taylor & Francis, London, 2006)
4. R.C. Bansal, A.F. Zobaa, *Handbook of Renewable Energy Technology* (World Scientific, Singapore, 2011)
5. H. Kuerten, *Direct and Large-Eddy Simulation VIII*, ERCOFTAC Series (Springer, Netherlands, 2011)
6. G. Burton, *Chemical Storylines*, Salter's Advanced Chemistry Series (Butterworth Heinemann, Oxford, 2000)
7. IPCC, *Climate Change 2013–The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press, Cambridge, 2014)
8. D.J.C. McKay, *Sustainable Energy, Without the Hot Air* (UIT Cambridge Limited, Cambridge, 2009)
9. F.A. Armstrong, K.M. Blundell, *Energy... Beyond Oil* (Oxford University Press, Oxford, 2007)
10. D. Biello, *Novel Solar Photovoltaic Cells Achieve Record Efficiency Using Nanoscale Structures* (Nature News, London, 2013)
11. R.E. Blankenship, D.M. Tiede, J. Barber, G.W. Brudvig, G. Fleming, M. Ghirardi, M.R. Gunner, W. Junge, D.M. Kramer, A. Melis, T.A. Moore, C.C. Moser, D.G. Nocera, A.J. Nozik, D.R. Ort, W.W. Parson, R.C. Prince, R.T. Sayre, Comparing photosynthetic and photovoltaic efficiencies and recognizing the potential for improvement. Science **332**(6031), 805–809 (2011)

12. L.R. Brown, *Plan B 2.0: Rescuing a Planet Under Stress And a Civilization in Trouble* (W. W. Norton & Company, New York, 2006)
13. M. Johnston, J.A. Foley, T. Holloway, C. Kucharik, C. Monfreda, Resetting global expectations from agricultural biofuels. Environ. Res. Lett. **4**(1), 014004 (2009)
14. Food and Agriculture Organization of the United Nations and Organization, *Fao Statistical Yearbook 2010*, Fao Statistical Yearbook (Stylus Publishing LLC, USA, 2012)
15. R.F. Service, Battle for the barrel. Science **339**(6126), 1374–1379 (2013)
16. D.O. Hall, K.K. Rao, *Photosynthesis, Studies in Biology* (Cambridge University Press, Cambridge, 1999)
17. D.L. Turcotte, G. Schubert, *Geodynamics* (Cambridge University Press, Cambridge, 2002)
18. A. Witze, Detectors zero in on Earth's heat. Nature **496**, 17 (2013)
19. R.T. Pierrehumbert, *Principles of Planetary Climate* (Cambridge University Press, Cambridge, 2010)
20. R. Bertani, What is geothermal potential? Newslett. Int. Geoth. Assoc. **53**, 1 (2003)
21. D. Huddart, T. Stott, *Earth Environments: Past, Present and Future* (Wiley, Hoboken, 2010)
22. International Energy Agency, *Renewable Energy Essentials: Geothermal* (International Energy Agency, Paris, 2010)
23. S. Björnsson, *Geothermal Development and Research in Iceland* (Orkustofnun, Reykjavik, 2010)
24. M.Z. Jacobson, A path to sustainable energy by 2030. Sci. Am. **301**(5), 58–65 (2009)
25. B. Metz, IPCC Working Group III, *Climate Change 2007–Mitigation of Climate Change: Working Group III Contribution to the Fourth Assessment Report of the IPCC*, Climate Change 2007 (Cambridge University Press, Cambridge, 2007)
26. R.A. Kerr, The coming copper peak. Science **343**, 722 (2014)
27. Nuclear Energy Agency and International Atomic Energy Agency, *Uranium 2011: Resources, Production and Demand*, Nuclear Energy Agency (Renouf Publishing Company Limited, Gloucester, 2012)
28. R. Martin, *SuperFuel: Thorium, the Green Energy Source for the Future*, MacSci (Palgrave Macmillan, Basingstoke, 2012)
29. G. McCracken, P. Stott, *Fusion: The Energy of the Universe, Complementary Science* (Elsevier Science, Amsterdam, 2012)
30. B.T. Cleveland, T. Daily, R. Davis Jr, J.R. Distel, K. Lande, C.K. Lee, P.S. Wildenhain, J. Ullman, Measurement of the solar electron neutrino flux with the Homestake chlorine detector. Astrophys. J. **496**, 505 (1998)
31. J.N. Bahcall, Neutrinos from the Sun. Sci. Am. **221**, 28–37 (1969)
32. S.N.O. Collaboration, Measurement of the rate of $\nu_e + d \rightarrow p + p + e^-$ interactions produced by ^8B solar neutrinos at the sudbury neutrino observatory. Phys. Rev. Lett. **87**, 071301 (2001)
33. C. Lécuyer, P. Gillet, F. Robert, The hydrogen isotope composition of seawater and the global water cycle. Chem. Geol. **145**(34), 249–261 (1998)
34. E.E. Angino, G.K. Billings, Lithium content of sea water by atomic absorption spectrometry. Geochim. Cosmochim. Acta **30**(2), 153–158 (1966)
35. J.D. Lawson, Some criteria for a power producing thermonuclear reactor. Proc. Phys. Soc. B **70**, 6–10 (1957)
36. J.-M. Rax, *Physique des Plasmas: Cours et Applications*, Sciences Sup (Dunod, Paris, 2005)
37. P.-H. Rebut, The JET preliminary tritium experiment. Plasma Phys. Control. Fusion **34**(13), 1749 (1992)
38. D. van Houtte, G. Martin, A. Bécoulet, J. Bucalossi, G. Giruzzi, G.T. Hoang, Th. Loarer, B. Saoutic, The Tore Supra Team, Recent fully non-inductive operation results in Tore Supra with 6 min, 1 GJ plasma discharges. Nucl. Fusion **44**(5), L11 (2004)
39. International Atomic Energy Agency, *Summary of the ITER Final Design Report*, ITER EDA Documentation Series (International Atomic Energy Agency, Wien, 2001)

40. D. Maisonnier, J. Hayward, Technological and engineering challenges of fusion. in *Proceedings of the 2nd IAEA Technical Meeting on First Generation of Fusion Power Plants: Design & Technology*, 2007
41. B.Yu. Sharkov, FAIR: facility for antiproton and ion research in Europe new prospects for growth of nuclear science and high technologies in Russia. At. Energy **112**, 75–79 (2012)
42. J. Lindl, Development of the indirect-drive approach to inertial confinement fusion and the target physics basis for ignition and gain. Phys. Plasmas **2**, 3933–4024 (1995)
43. E. Hand, National ignition facility fires record laser shot. Nature **20122013**, 2012 (2012)
44. S.H. Glenzer, B.J. MacGowan, P. Michel, N.B. Meezan, L.J. Suter, S.N. Dixit, J.L. Kline, G.A. Kyrala, D.K. Bradley, D.A. Callahan, E.L. Dewald, L. Divol, E. Dzenitis, M.J. Edwards, A.V. Hamza, C.A. Haynam, D.E. Hinkel, D.H. Kalantar, J.D. Kilkenny, O.L. Landen, J.D. Lindl, S. LePape, J.D. Moody, A. Nikroo, T. Parham, M.B. Schneider, R.P.J. Town, P. Wegner, K. Widmann, P. Whitman, B.K.F. Young, B. Van Wonterghem, L.J. Atherton, E.I. Moses, Symmetric inertial confinement fusion implosions at ultra-high laser energies. Science **327**(5970), 1228–1231 (2010)
45. H.-S. Park, O.A. Hurricane, D.A. Callahan, D.T. Casey, E.L. Dewald, T.R. Dittrich, T. Döppner, D.E. Hinkel, L.F. Berzak Hopkins, S. Le Pape, T. Ma, P.K. Patel, B.A. Remington, H.F. Robey, J.D. Salmonson, and J.L. Kline, High-adiabat high-foot inertial confinement fusion implosion experiments on the national ignition facility. Phys. Rev. Lett. **112**, 055001 (2014)
46. O.A. Hurricane, D.A. Callahan, D.T. Casey, P.M. Celliers, C. Cerjan, E.L. Dewald, T.R. Dittrich, T. Döppner, D.E. Hinkel, L.F. Berzak Hopkins, J.L. Kline, S. Le Pape, T. Ma, A.G. MacPhee, J.L. Milovich, A. Pak, H.S. Park, P.K. Patel, B.A. Remington, J.D. Salmonson, P.T. Springer, R. Tommasini, Fuel gain exceeding unity in an inertially confined fusion implosion. Nature **506**, 343348 (2014)
47. R.K. Kirkwood, J.D. Moody, J. Kline, E. Dewald, S. Glenzer, L. Divol, P. Michel, D. Hinkel, R. Berger, E. Williams, J. Milovich, L. Yin, H. Rose, B. MacGowan, O. Landen, M. Rosen, J. Lindl, A review of laser-plasma interaction physics of indirect-drive fusion. Plasma Phys. Control. Fusion **55**(10), 103001 (2013)
48. M.G. Haines, A review of the dense Z-pinch. Plasma Phys. Control. Fusion **53**(9), 093001 (2011)
49. R.F. Service, Sonofusion back on the firing line as misconduct probe reopens. Science **316**(5827), 964 (2007)
50. J. Hecht, Clear proof: the final demonstration of the failure of cold fusion. Nature **462**(7269), 126–126 (2009)
51. L.W. Alvarez, H. Bradner, F.S. Crawford, J.A. Crawford, P. Falk-Vairant, M.L. Good, J.D. Gow, A.H. Rosenfeld, F. Solmitz, M.L. Stevenson, H.K. Ticho, R.D. Tripp, Catalysis of nuclear reactions by μ mesons. Phys. Rev. **105**, 1127–1128 (1957)
52. J.D. Jackson, Catalysis of nuclear reactions between hydrogen isotopes by μ^- mesons. Phys. Rev. **106**, 330–339 (1957)
53. J. Rafelski, S.E. Jones, Cold nuclear fusion. Sci. Am. **257**, 84–89 (1987)

Constraints and Hazards 7

Even if this part is dedicated to solutions, it would be incomplete without a mention of some constraints or drawbacks related to our energy sources. Some of them have to do with the inherent difficulties associated with any large-scale implementation of our energetic solutions and others, sadly, with casualties generated by these energy sources.

7.1 The Energy Return on Investment

Harnessing an energy source requires…energy. It takes energy to drill for oil or mine coal. It also takes energy to refine them and take them to the users. It takes energy to build, install, and maintain nuclear power plants, wind turbines, solar cells, or dams. It is thus clear that the numbers provided on Table 6.3 have to be mitigated by the very energy required to get the promised Joules.

The energy return on investment (EROI) measures just that. For any energy source, it is the amount of energy you get from an investment of 1 energy unit.[1] Nowadays, in the oil industry for example, the EROI tells you how many Joules you recover from oil when spending 1 J to do it. Clearly, if you retrieve *less* than 1 J for 1 J invested, your energy source can hardly be called a "source." An EROI less than 1 is therefore a red flag telling a given source is indeed a *sink*. It is like having a €200 commute for a €100 job.

Long ago when we were all hunter-gatherers, our ancestors would have to make sure they got at least 2,000 calories a day when foraging. Studies found the EROI for foraging could have range from 10 to 20 [1, p. 143]. For oil and gas, the EROI was about 100 in 1930, 30 in 1970 and 15 in 2005 (see Fig. 7.1). This is at the heart

---

[1] With this definition in mind, it takes $1/e$ J to get 1 J of a given source of EROI e. Therefore, any Joule recovered only counts for $(1 - 1/e)$ J. Mitigation of the numbers in Table 6.3 eventually amounts to multiply them by a factor $(1 - 1/e)$.

A. Bret, *The Energy-Climate Continuum*, DOI: 10.1007/978-3-319-07920-2_7

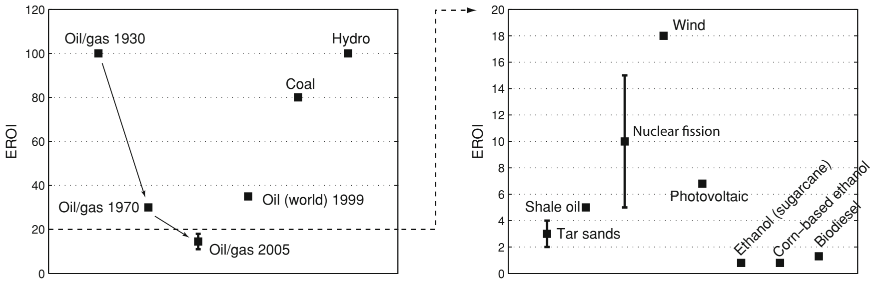

Fig. 7.1 Energy return on investment (EROI) for various energy sources. Numbers from Table 2 of Ref. [3]

of "the end of cheap oil." The more you need to dig and drill to extract one liter, the more energy you use while the liter still holds the same 42 MJ.

We thus find that having a potential energy source is not enough. Your source must in addition be easy enough to harness to return energetically more than you invested to exploit it. Some researchers think the minimum EROI a society can afford is 3 [2]. An EROI of 1 is clearly nonsense. A low EROI can be afforded as long as another energy source, so far fossil, comes to help. But our perspective is precisely life beyond fossils. There, the EROI of our solutions should rather go beyond 3.

The EROI is not an easy number to pinpoint. It is difficult to trace every energy expenses involved, decide which ones should be accounted for, and then quantify them. In a 2010 review of the literature in this respect, Murphy and Hall [3] mention for example 3 definitions of the concept, depending on the calculation boundaries. Also, EROI changes in time, like for oil, as a result of technology and resource availability evolutions. In addition, there is so far no explicit funding for EROI assessment, in spite of its importance. Before we turn to numbers, it is therefore important to recognize that here, we are no longer dealing with the kind of calculations explained so far, where basic physical principles just had to be applied.

With this in mind, where do we stand, EROI wise, with respect to the sources listed in this chapter? Figure 7.1 answers the question. In case we needed further confirmation that fossil fuels are great, this graph provides it. Not only oil is incredibly dense energetically, but it had, with hydro, the best EROI ever in human history. With an EROI around 80, coal is now the best fossil we have. Nowadays, gas and oil share a common EROI around 15. What happened in the meantime? The pattern of going first after the easiest oil field has simply been reproduced over and over. Back in 1892, Edward Doheny found oil near Los Angeles drilling with a sharpen eucalyptus branch [4, p. 191]. A century later, British Petroleum builds \$1 billion platforms like "Thunder Horse" or "Deepwater Horizon" to find oil in the Gulf of Mexico. The easy fields have been depleted, and we are now left with the tough ones.[2]

---

[2] According to Tainter and Patzek [4, p. 208], this has *definitely* something to do with the accidents related to the upper mentioned platforms.

What about non-conventional oil? For example, North Dakota shale oil, also referred to as tight oil [5–7], has been boosting the US oil production since 2005 (not shown on Fig. 3.2). Because it takes more than just drilling to extract it [8], we find its EROI at 5 instead of 15 for conventional oil.[3]

Turning now to renewables, we find hydropower at 100. The reason for this is that as was the case for fossil fuels, nature keeps making most of the job here. Build a few dams, let rain fill the reservoir and open the tap: turbines will generate electricity ready for the grid. When it comes to the rest of the renewables, much more is on your side. For wind power, the EROI lies toward 18. Photovoltaic cells are quite technological artifacts requiring a lot of energy to build. As a result, their EROI lies toward 7. Other solar technologies like flat plates or concentrating collectors are lower than this (1.9 and 1.6, respectively [3]).

The case of biofuels may be surprising. According to the graph, it lies below 2. Indeed, there is an ongoing debate in literature about whether or not their EROI is larger than unity [3,9]. From Table 6.2, we see 1 ha can yield 3,300 L of corn ethanol per year. But how much energy did your tractor used? What about fertilizers? And how much energy was spent in extracting fuel from the crops? Unlike dams or windmills which deliver electricity straight to the grid, you cannot drop crops in your car tank. As a result, EROI for sugarcane ethanol, corn ethanol, and biodiesel is estimated around 0.8, 0.8, and 1.3, respectively.

EROI for nuclear fission is around 10, give or take 5 according to the studies. There is no assessment so far for nuclear fusion because its mere feasibility is still a research topic. Besides hydro power, energies of the past are all on the left panel, with numbers going up to 100. Options for the future are all on the right panel, with a vertical scale which does not need to go beyond 20. This is a direct, measurable, consequence of the fact that there are no longer virtually "free" energy sources like fossil fuels. These were literally millions of years of *accumulated* solar energy. Nuclear set apart, all we will have in the future to power the world during 1 year, will be 1 year of the Sun. In computer science terms, we will no longer be in buffer mode. We will be in streaming mode.

7.2 Intermittency

Two of the highest EROI's among future energies are wind and solar. Yet, calculations so far do not account for the consequences of their inherent intermittency. There is by definition no Sun at night, and wind blows when it wants. The problem is that electricity (we will focus on electricity for a while) is extremely difficult to store on large scales. As a result, the electrical grid in a given country has to provide the exact

---

[3] Warning: the world of non-conventional oil is a jungle. Besides shale oil/tight oil, you have tar sands, extra heavy oil or even biofuels that some count in the category. Though not obvious for the newcomer, Shale oil and oil shale are two completely different things. And so on. The Wikipedia page on "Unconventional oil" is a good start to sort things out.

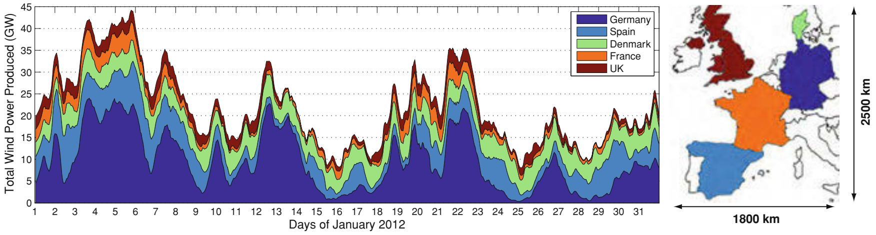

Fig. 7.2 Total wind power during January 2012, for 5 important European wind power producers. *Source* H. Flocard, Sauvons le Climat, www.sauvonsleclimat.org & www.pfbach.dk

amount of electricity needed in real time. Companies trying to work with no stock at all know how difficult it is. To do so, you need an accurate forecasting of the sells in order to plan production accordingly. This is exactly what electricity providers do. Red Eléctrica de España, for example, divides each day in 144 slots 10 min each and plans which amount of electricity it will have to produce in each one of them, and how.[4] Surplus are either exported, in case neighbour countries need it, or pump up existing dam reservoirs. At any rate, they must be small compared to the total because there is no way to get rid of large extra productions.

As long as wind or solar power remains small, their production can seamlessly be aggregated to the grid. In Spain, this is no longer the case for wind. In 2013, wind power produced nearly 20 % of the total electricity generated in Spain [10]. On February 6, 2013, at 3:20 am, wind power was providing 54 % of the Spanish electricity. Few days later, on February 15 at 2:50 am, the share was only 2.5 %.[5] How do you cope with such irregularity when you need to stick to a forecasted production no matter what? By making sure any installed GW of wind power can be backed up by the *same* amount of fossil fuel generation. In Spain, gas power plants (combined cycle) do the job. You could try with hydro, but it is no longer powerful enough to make up for a windless hour. And nuclear cannot be turned on and off quickly enough. As long as electricity is not stored on large scales, any installed wind power capacity must be sponsored by another source. And if it cannot be hydro nor nuclear, it *must* be fossil.

Now, what about the post-fossil world? What if there is no longer any fossil fuel power plant to sponsor sporadic sources? The only way to avoid storage with solar energy would be to implement a worldwide grid so that there is always some production going on somewhere. Knowing if it is politically and technically feasible is another problem way beyond the scope of this book.

For wind, one could think production over a large territory can also smooth intermittency. After all, if there is no wind in Spain, maybe there is in Germany, or France or UK, so that the total is less chaotic. Figure 7.2 shows such is not the

---

[4] See https://demanda.ree.es/demanda.html.

[5] See https://demanda.ree.es/generacion_acumulada.html.

case. We find here the total wind power production during January 2012, for 5 important European wind power producers. The total area involved is 1.7 million km^2. Yet, intermittency is obvious. Only January is shown for clarity, but data are available for the other months and show the same chaotic pattern all over the year. The maximum 2012 production was achieved on December 14 at 21:00 with 45 GW. The minimum for that same year was realized on May 28 at 10:00 am with 5 GW, nine times less.

The observed variations are not the mere fruit of the German ones (the biggest producer). A statistical analysis of the data shows significant correlations between the various productions. This is not surprising since it all depends on the weather over Western Europe. Weather scientists know the typical scale of high- and low-pressure systems, the "synoptic scale," lies around 1,000 km [11, p. 60]. It is therefore normal to find wind power correlations over a territory that large. But it means also that you would need to merge production over an area *much larger* to have a chance to efficiently compensate low productions by high ones.

7.2.1 Storage Assessment

There is therefore no way of managing the whole system to get a smooth production, at least at European scale for example. If most of the electricity was to be produced this way, storage would be mandatory. In such a case, wind turbines, at least part of them, would not feed the network directly. They would charge batteries instead, or generate hydrogen, or compressed air, or whatever storage solution you can think about (see Table 5.1). Then, the storage solution(s) would provide the current at will. Hydro power eventually works this way today: rain is intermittent, but it fills the dam reservoir, which, in turn, is partially emptied when needed to action the turbines.

How exactly storage can save the day? An interesting parallel can be drawn with the role played by a bank account. Though your salary is predictable, you are probably paid on a monthly or weekly basis. Yet, you need to spend money almost every day, in a controlled way. Your earnings are thus *stored* in your bank account, from which you spend them.

Which storage capacity should we then need? A quick analysis of the problem shows the amount of energy to store is much less than the total production. Consider the case of Fig. 7.2, but for the whole year 2012. We denote $A(n)$ the amount of energy in store at hour number n. We also denote $P(n)$ the energy produced during the nth hour, and $C(n)$ the energy consumed during the same hour. The energy stored at the nth hour is the total energy produced minus the total energy consumed, both until this time. This is,

$$A(n) = A(0) + \sum_{h=1}^{n} P(h) - \sum_{h=1}^{n} C(h), \tag{7.1}$$

where $A(0)$ is the amount of storage at the beginning of the year. You could write the same equation for your bank account: Any month's balance equals what you had on

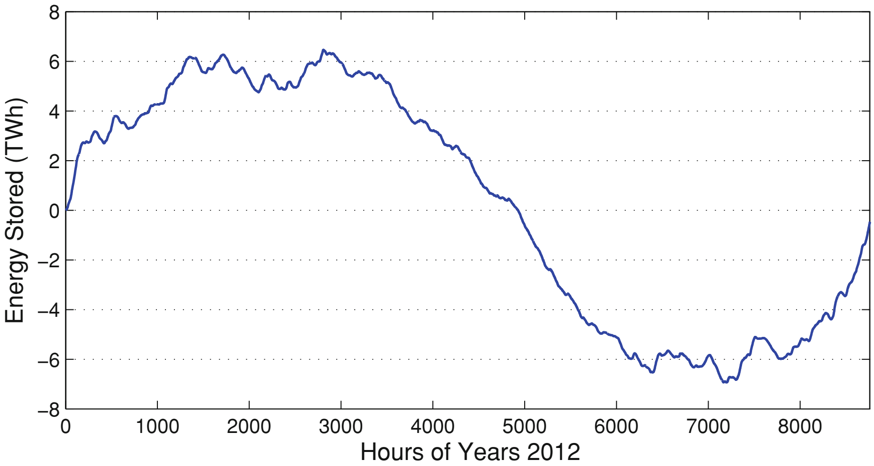

Fig. 7.3 Amount of energy stored $A(n)$, from Eq. (7.1), in terawatt hour. Wind production numbers are identical to Fig. 7.2, but considered over the whole year 2012

January 1, plus what you earned until that month, minus what you have spent. Note that we forget about the energy lost when storing and returning the energy.[6] At the end of the year, for $n \equiv n_y = 24 \times 365$, we want $A(n_y) = A(0)$ in order to repeat the whole story the next year. That simply gives,

$$\sum_{h=1}^{n_y} P(h) = \sum_{h=1}^{n_y} C(h), \tag{7.2}$$

stating we just spent what was produced.

What is then the minimum amount of storage we need, to make sure consumption can be met throughout the year? For the simple case of a flat consumption, where $C(k)$ is constant and equal to the mean consumption, we can start setting $A(0) = 0$ and compute $A(n)$ from Eq. (7.1). The result is displayed on Fig. 7.3. The energy stored starts increasing with winter winds, before it decreases and reaches 0 between $h = 4{,}626$ and 4,627 (July 24, between 6:00 and 7:00 am). It then goes negative, down to $h = 7{,}199$ (October 26, 23:00 pm) where it touches its lowest value with $A(7, 199) = -6.93$ TWh.

Of course, we cannot have negative energy in store. But we now know that if we start with $A(0) = 7$ TWh, the all curve is shifted up by the same amount, with now $A(7{,}199) > 0$. What is then the amount of storage we need? The maximum of Fig. 7.3 is $A = 6.45$ TWh for $h = 2{,}809$ (April 4, 1:00 am). If we set $A(0) = 7$ TWh, we need to add the same amount to the maximum on 7.3, giving a top storage of $A = 6.45 + 7 = 13.45$ TWh. Now, the overall 2012 production is easily computed

---

[6] It can be done by simply rescaling the production and the consumption.

and is $P = 154.3$ TWh. The relative amount of storage needed is therefore only $13.45/154.3 = 9\,\%$ of the production.

Back to the bank account image, we would agree that if you make $2,000 a month with no other incomes, your balance will not climb up to $12 \times 2,000 = \$24,000$ during the year. If you were to tell your banker how much room he needs to make for your money, $4,000 or so would probably be enough. You spend money as you make it, not in one single shot on December 31.

This simple analysis shows you do not have to buy 100 J of batteries to smooth 100 J of intermittently delivered wind energy. Just 10 J or so will suffice. A recent study simulated 4 years of electricity production over 20 % of the US [12]. The authors found wind and solar could cover almost 100 % of the needs storing only 2.67 % of the production. Note that their scenario still contemplates a small fossil backup (5 times in 4 years) and that they found that the most economical option was to produce three times the electricity needed.

Of course, you need a starter, with $A(0) \neq 0$. And even if the storage issue is less than expected, 10 % of what would be needed to power the whole world remains a considerable quantity subject to the kind of hazards we now describe.

7.3 Energy and Hazards

Hannah Arendt noted that "Progress and Doom are two sides of the same medal" [13]. When you invent the scalpel, you provide ways to kill people or to save them with surgery. When you design an Airbus A380 capable of flying up to 800 people, you also and inevitably open up the possibility to kill 800 people at once in a plane crash.[7] As the French philosopher Paul Virilio puts it [14, p. 10],

> To invent the sailing ship or the steamer is to invent the shipwreck. To invent the train is to invent the rail accident of derailment.

The section is certainly the saddest of the book. But its content had to be part of the minimum exposed. The Wikipedia article on "Hazard" reads,

> One key concept in identifying a hazard is the presence of stored energy that, when released, can cause damage. Stored energy can occur in many forms: chemical, mechanical, thermal, radioactive, electrical, etc.

People involved in risk management know very well stored energy is a source of hazard [15]. In his book *Hazard Identification and Risk Assessment*, Geoff Wells lists "stored energy" among the keywords for hazard analysis [16, p. 23]. And stored energy is precisely what we have been talking about since the beginning of this book. The image of a compressed spring ready to jump out is quite accurate. A liter of oil is

---

[7] The Airbus A380 can take up to 853 passengers. See www.airbus.com.

stored potential energy, this is why it burns. Gas is stored potential energy, and this is why it explodes. Fossil fuels can participate in these exothermic chemical reactions called “combustion.” This is the very reason why we are interested in them, and also the very reason why they can set fire to a power plant. A car or a truck is dense reservoirs of kinetic energy, and despite all efforts to prevent road accidents, more than 1.2 million people died on the roads worldwide in 2010.[8]

We will now quickly review casualties connected to energy, fossil fuels or not. But the main point of this section is that if we look for high energy density, and we do so, we need to be aware we look for risk as well.

7.3.1 Fossil Fuels

I just watched the movie *Argo*, winner of the 2013 best movie Oscar. It starts explaining how the US and the UK orchestrated the 1953 Iranian “coup” to get rid of Prime Minister Mohammad Mosaddegh who had just nationalized Iranian oil industry. They placed instead Mohammad Reza Pahlavi, “The Shah,” a dictator who would be overthrown by the 1979 revolution [17, from p. 450]. The list of dictatorships and wars related to oil is endless.[9] We will not try here to measure the amount of wounds generated this way, but the message is clear: energy, as the sustainer of our civilization has profound political, and sometimes unpleasant, consequences.

Besides its political consequences, fossil fuel industry generates accidents by the mere fact described earlier. Dealing with concentrated energy is dealing with risk. Table 7.1 gives the number of fatalities in coal mines for various countries, and in the US oil and gas industry.[10] Data are not always well maintained so that many are missing. Just the numbers reported here give a minimum of 197,461 deaths for these 3 industries since 1900. The total since 1992 is 92,305, mainly from Chinese coal mines accidents.

Oil spills have been numerous in history. Some occurred at the point of extraction like the Lakeview Gusher in 1910 or the 2010 offshore Deepwater Horizon catastrophe, where 1.2 and 0.5 million tons of oil were released, respectively. Other notorious accidents resulted from the shipwreck of some supertanker, like the Exxon Valdez in Alaska in 1989, the Prestige in Spain in 2002 or the Amoco Cadiz in France in 1978. Summing the amount of oil spilled in the events recorded on the Wikipedia page $en.wikipedia.org/wiki/List\_of\_oil\_spills$, we find that about 7 million tons of oil have been accidentally poured in the environment since 1900. This represents *only*

---

[8] World Health Organization, www.who.int.

[9] Regarding the so-called “Petro-states,” see *The Paradox of Plenty: Oil Booms and Petro-states* by Terry Lynn Karl [18].

[10] *Sources for coal:* US & Australia *New South Wales Government—International Mining Fatality Review Database (IMFRD)—US Department of Labor* China *IMFRD, China Energy Statistical Yearbook, China Energy Research Society, China Coal Industry Yearbook, cited in* [19], India *IMFRD and Government of India Ministry of Coal,* www.coal.nic.in/point18.html. *Sources for US Oil & Gas US Department of Labor, Bureau of Labor Statistics.*

Table 7.1 Deaths in coal mines and in the US Oil and Gas industry

Year	Coal				
	US	Australia	China	India	Oil and Gas US
1900–1991	101,740	821	>1,542	>1,053	
1992	55	7	4,481		82
1993	47	5	5,036		94
1994	45	14	7,121		99
1995	47	3	6,295		77
1996	39	8	5,602		83
1997	30	5	6,141		85
1998	29	4	6,304		76
1999	35	3	6,478		50
2000	38	5	5,798		83
2001	42	2	5,670		98
2002	28	2	6,995		72
2003	30	1	6,434		85
2004	28	2	6,027		98
2005	23	2	5,986		98
2006	47	2	4,746		125
2007	34	1			122
2008	30			157	120
2009	18			148	
2010	48			201	
2011	21			122	
Total	102,473	>887	>90,956	>1,598	>1,547

Sources see text

0.004 % of the 1,237 Gbarrels[11] produced during the same period (see Sect. 3.1). It is like losing 1 unit out of 25,000. But the numbers involved are so important that even an extremely small proportion of loss has dramatic consequences.

We will not try to evaluate political casualties, to add them to the numbers above. But an important point is that in a sense, industrial and political fatalities have the same origin: Fossil fuels are dangerous to deal with because they are energetically dense and ready to use. This is the very reason why we rely on them and hence protect their supply at all costs.

Fossil fuels follow another universal pattern: they generate wastes because we do not use 100 % of them. Your body needs food, yet it does not use all of it. This is

---

[11] Considering 1 ton = 7.33 barrels.

why there is something left at the end of the digestive system. Likewise, we do not use every single gram of the oil we extract. It has to be refined first before it can fill your tank. Besides greenhouse gases emissions during combustion at the latter stage, we thus find here another *inevitable* source of problems. For example, oil refining releases sulfur oxides (like SO_2), nitrogen oxides (like NO_2), and ammonia (NH_3), all classified as "extremely hazardous chemicals" by the US Code of Federal Regulations.[12] In which quantity? At least 1.6, 0.3, and 0.17 kg, respectively, per thousand liters of oil refined [20]. About 15,000 barrels are refined each day in the US[13] (225 million a year). These are therefore 3.6×10^{10} liters refined each year, resulting in the generation of 60,000 tons of sulfur oxides, 11,000 tons of nitrogen oxides, and 6,000 tons of ammonia. And since world refineries treat 100 times more oil,[14] just multiply these number by the same factor to find out about the world performances. Oil refining worldwide eventually generates at least 7.6 million tons (just sum the numbers) of "extremely hazardous chemicals." And this is just oil.

7.3.2 Hydro Power

What about our energetic solutions for the post-fossil era? Are they 100 % risk free? Clearly not, again because they are *energy*. For those which have been in use for a long time, namely hydro power and nuclear fission, significant records are available. Starting with hydro, a dam is a formidable reserve of potential energy of gravitation. What if it bursts? Sadly, it happened a number of times as reported in Table 7.2, which lists the major dam failures since 1900. Numbers varies sometimes considerably from one source to another, but we come out here with 95,391–263,684 fatalities since 1900.

Besides failure risks, dams create a lake where there was not, which frequently results in massive people displacement. The recently completed Three Gorges Dam in China forced nearly 1.2 million people to relocate [34,35]. About 20 million people were displaced in India only, between 1947 and 1992 [36, p. 161]. There are currently some 45,000 "large" (more than 15 meters high) dams in the world. Most of them were built during the second half of the last century [37]. Nearly 9,000 have been built to provide energy, the rest being mainly designed to store water for irrigation, industrial or domestic use.[15] It is estimated that the construction of these 45,000 dams has led to the displacement of some 40–80 million people worldwide [37]. This simply amounts to 890 to 1,780 persons relocated per dam.

These numbers are the consequence of Table 5.1: it takes the falling of 43 tons of water from 100 meters to render the energy of 1 liter of oil. If you want to generate

---

[12] Code of Federal Regulations, Title 40, Part 355, Appendix A. See www.ecfr.gov.

[13] US Energy Information Administration. See www.eia.gov.

[14] International Energy Agency. See www.iea.gov.

[15] International Commission on Large Dams, www.icold-cigb.org/GB/World_register/general_synthesis.asp .

Table 7.2 Major dam failures since 1900 and corresponding casualties

Dam	Year	Deaths	References
Banqiao, China	1975	85,000–230,000	[21]
Morvi, India	1979	2,500–25,000	[22,23]
Vajont, Italy	1963	1,910–2,000	[22,24,25]
Mohne, Germany	1943	1,200–1,579	[22,26]
Khadakwasla, India	1961	$>1{,}000$	[27]
Tigra, India	1917	1,000	[27,28]
Vratsa, Bulgaria	1966	600	[22,29]
St Francis, USA	1928	420–500	[22,30]
Malpasset, France	1959	421	[22,25,31]
Gleno, Italy	1923	356–600	[25,32]
Hyokiri, South Korea	1961	250	[29]
Sempor, Indonesia	1967	200	[27,29]
Canyon Lake, USA	1972	165	[30]
Ribadelago, Spain	1959	144	[22,25,33]
Buffalo Creek, USA	1972	125	[29,30]
Sella zerbino, Italy	1935	100	[25]
Total		95,391–263,684	

1 GW during 24 h,[16] you will need 88,073,394 cubic meters falling from 100 meters. If the water was stored in a basin 10 m deep, its surface had to be 8,807,339 square meters. This is the surface of a square 2.9 km wide. So your basin is indeed a lake. The laws of physics leave you no option. If you want large-scale electricity, you need to create a lake. And it you create a lake out of the blue, you will probably have to move people.

7.3.3 Nuclear Fission

Nuclear fission repeats the patterns identified with fossil fuels: it presents risks inherent with the energy density it holds, plus risks related to the unburnt fuel.

At this junction, it is worth elaborating on radioactivity beyond what was done on Sect. 6.5. As was seen, radioactivity pertains to unstable nuclei which try to make their way toward a stable position by emitting some surplus. The table of nuclides represented on Fig. 6.5 evidences various options: emission of an helium nuclei (α decay), emission of an electron and an antineutrino (β^- decay), and emission of a

---

[16] The Three Gorges Dam can deliver 22 GW.

positron and a neutrino (β^+ decay). We need to add to the list the γ decay, where a nucleus does not change its composition, but simply switches to a lower level of vibration. Doing so, it gets rid of the vibrational energy in excess emitting a very energetic photon in the γ range.

When uranium-235 (92 protons, 143 neutrons) splits in contemporary power plants, one could think it always gives the same two products. But this is not the case. For 1,000 fusion events, you will get about 60 nuclei of cesium-137 (55 protons, 82 neutrons) and zirconium-95 (40 protons, 55 neutrons), but *not* 1,000 of each [38]. What about the rest? The occurrence of production simply decreases as you recede from such nuclei. You will then recover between 10 and 60 elements close to Ce-137 and Zr-95 and then between 1 and 10 of further elements, etc. The bottom line for us is the following: if you look at Fig. 6.5, you will see fission products are *above* the stability region. All but a few are radioactive.

Once they have been produced, they start decaying. Doing so, they emit energetic particles which 1/heat the surrounding medium and 2/can be dangerous for living organisms. One of the most dangerous in this respect is iodine-131. With 53 protons and 78 neutrons, it is one of the fission products of Ur-235. As a member of the upper ellipse on Fig. 6.5, it is β^- radioactive, with a half-life of about 8 days. The problem is that our thyroid gland loves iodine because it needs it to synthesize some hormones. Since an innocuous iodine atom and an iodine-131 atom have almost the same mass and exactly the same number of electrons turning around them (53), our body chemistry treats them the same way. So if you inhale iodine-131, it will go right to your thyroid and decay there. This is why thyroid cancers have been so numerous after Chernobyl, as explained below.[17]

Physiological damages depend on the amount of radiation received and on its energy. Various units are used in this respect, to quantify the number of decay events per seconds or their effect on health. The "Becquerel" (Bq) quantifies the first. If a bunch of material undergoes 10 decay events per second, its radioactivity is 10 Bq. Health effects are measured in "Sievert" (Sv). The relation between Becquerel and Sievert is not straightforward as it involves the interaction physics of radiation with the body, together with its biological consequences.[18]

Radioactivity is *not* systematically dangerous. The poison is the dose. There is a natural level of radioactivity we cannot escape, originating, for example, from our own body[19] or ambient gases like radon. We also receive doses of radioactivity during some medical treatments. The natural dose received lies toward 2.4×10^{-3} Sv, that is 2.4 mSv, per year. Human body can therefore handle some dose of radioactivity without damage. We would not be there otherwise. Note that measuring doses in Sv/year implies they are spread out over the whole year. We can cope with 2.4 mSv a year, not with 2.4 mSv in a single day. Think about wine consumption. Drinking a

---

[17] Medicine exploits this very process to cure hyperthyroidism. Also, Fukushima residents were given iodide pills to saturate their thyroid with healthy iodine before the coming of the radioactive one.

[18] See Wikipedia article on Sievert for a starter on this and the other units related to radioactivity.

[19] About 5,000 Bq from potassium-40 [39, p. 39].

15-cl glass a week is harmless and amounts to drinking more than 10 bottles, 75 cl each, a year. Do not try to drink them in a single day.

If a few mSv/year are harmless and many are, where do problems start? Probably toward 50 mSv/year. Radiation levels up to 70 mSv/year, 12 on average [40], have been measured in the state of Kerala, India, without any significant increase of cancer rate [41], mental retardation, or cleft lip/palate [42]. Overdoses beyond 50 mSv/year, approximately, are definitely related to higher cancer rates. Active research is conducted to clarify the intermediate range 10–50 mSv/year. The simplest way to deal with it is the so-called linear non-threshold (LNT) model, where the known excess cancer rates for large doses are linearly extrapolated to small ones. Yet, the LNT model is doubtful at small doses, precisely because they fall in the range of natural radioactivity. We will see that for the Chernobyl accident, this point influences greatly the number of the computed casualties.

We thus have the fission chain reaction which presents risks in itself if badly controlled and then, the risks associated with the "ashes" of the uranium-235 burning, namely the fission products. The major accidents in the history of nuclear fission, Three Mile Island, Chernobyl, and Fukushima, are related to both kinds of processes.

7.3.3.1 Major Accidents

Figure 7.4 schematically represents the Three Mile Island, Chernobyl and Fukushima[20] reactors with their containment vessels. The fuel, together with the fission products, is locked inside fuel rods pictured by the vertical bars. This is the first containment. These bars are enclosed in container number 2, where a fluid circulates to extract the heat from the core. Then, both the Three Mile Island and Fukushima reactors counted with a heavy, thick container number 3.

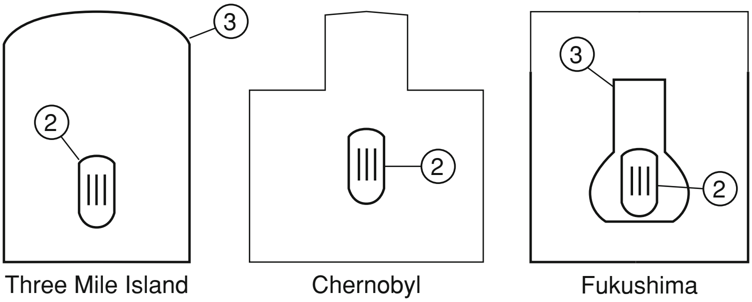

Fig. 7.4 Schematic representation of the Three Mile Island, Chernobyl, and Fukushima reactors. The *bold lines* picture containment vessels. In all cases, container number 1 are the fuel rods

---

[20] There were more than 1 reactor in trouble in Fukushima.

When the fuel in the rods has been burnt, new rods replace them. The content of the old rods is radioactive and generates heats. It is first stored in cooling pool within the reactor building, before being sent elsewhere for treatment (see below).

- The Three Mile Island accident occurred on March 28, 1979, in Pennsylvania, USA. A series of technical and human errors caused an overheating of the heart of the reactor. Fuel rods partially melted, flowing at the bottom of the vessel number 2. 195,000 persons living less than 20 miles from the plant were evacuated. Because the reactor vessel number 2 withstood the partial melting of number 1, almost no radioactive material escaped, and 98 % of the evacuated came back home 3 weeks after the accident [43]. No casualties were to deplore.
- The Chernobyl accident occurred on April 26, 1986, in Ukraine. A chain of human errors during a test provoked a rapid heating of the reactor. The fuel rods melted and the reactor container number 2 blew out. Note that it was a chemical explosion, not a nuclear one. Since there was no container number 3, the explosion easily blew out the building housing the reactor, and considerable quantity of radioactive material escaped in the air. Pictures taken after the accident show a devastated building, while the Three Mile Island remained externally intact. Finally, evacuation was badly handed as the first warning, for example, were only given two days later although the city of Pripyat (now a ghost town) and its 49,000 habitants were only 3 km away [44]. Two workers were killed on the day of the accident. Within 4 months, 28 more had died from acute radiation syndrome [45]. Beyond this, much work has been dedicated to quantifying the excess cancer mortality related to the massive emissions of radioactive material. Regarding the population that was exposed to high doses (average >50 mSv), the predicted excess cancer mortality is 4,010. When extrapolating the predictions with the LNT model to the population exposed to lower doses (average >10 mSv), an additional 5,325 are retrieved [45]. Among these 5,325, 5,160 pertain to average doses >7 mSv. Accounting then for the 30 early fatalities, we obtain a total of 4,040–9,365 deaths, past and future, depending on the way weak doses impact is treated. A total of 220,000 persons were relocated to safe areas [45]. A 30 km-radius exclusion zone has been created around the site. What about wildlife? Surprisingly, it seems terrestrial wildlife is now abundant *inside* the exclusion zone, as compared to outside [46,47]. Radioactivity does impact animals, but the impact seems outweighed by the total absence of humans. While birds could be more affected [48], plants apparently adapted [49] and pine trees growth was severely depressed [50].
- The Fukushima accident occurred on March 11, 2011. This day, Japan was shaken by a powerful earthquake, and then hit by the consecutive tsunami. The earthquake damaged the electrical infrastructures of the country, forcing the power plant to switch to diesel generators. Then, the tsunami stroke full force the plant which is bordering the sea. It flooded the generators, leaving the reactors in service without cooling pumps. Even if fission reactions had been stopped with the earthquake, the radioactive ashes in the rods were still producing heat which could no longer be removed. The heart of the reactors in service melted. In one of them, the melted material made its way through the containment wall number 2. Vapor

> from the circuit normally cooling the rods found its way out. Through some chemical reactions, it generated hydrogen which exploded, blowing in some cases the outer structure of the reactor building. Radioactive materials were released into the environment. Finally, the cooling pools where spent fuels were stored started to boil. One of them set fire to its surroundings. No casualties were to deplore, and consequences of the received doses on neighboring populations are expected to be very low [51]. More than 200,000 persons living less than 30 km from the power plant were evacuated. In 25 % of the evacuated zone, doses are now lower than 20 mSv/year, and people should be allowed to move back soon. Radiation ranges from 20 to 50 mSv/year over 13 % of the evacuated zone. There, access is allowed for short periods of time, but not residence. In the remaining 63 %, residence may be forbidden for many years [52].

Fukushima could be ranked between Three Mile Island and Chernobyl in terms of gravity. In Three Mile Island, the core melted, but containers 2 and 3 integrity were maintained. In Fukushima, container 2 integrity was violated, which was enough for some radioactive material to be released in the environment. In Chernobyl, the container 2 blew out, and there was no number 3.

7.3.3.2 Wastes

Once all the Ur-235, or part of it,[21] has split, the fuel rods are removed from the core. Fission products are radioactive and treated according to their lifetime and the amount of energy released by their decay. They are typically categorized into *very-low-level wastes* (VLLW), *low-level wastes* (LLW), *intermediate-level wastes* (ILW), and *high-level wastes* (HLW) [54].

Wastes up to intermediate level do not originate exclusively from fuel rods. We also find here substances from nuclear plants dismantlement, nuclear research or nuclear medicine. VLLWs need hermetic storage over a few years to get back to innocuous activity. LLWs and ILWs need a few hundred years, typically 300. HLWs require about 100,000 years. To start with, these latter wastes are stored after treatment in cooling pools within the reactor building[22] or elsewhere, like the AREVA site at La Hague, France. On the long term, deep geological repository has been studied for decades in several countries and should start operating in 2025 in France, Finland, and Sweden [55].

Regarding the quantities involved, France, with 75.9 % of electricity generation and 15.6 % [56] of the world total, is a good test bed. As of December 2010, the total volume of nuclear wastes ever generated in France was 1,320,000 m^3. HLW with high or medium activity represented 0.2 % and 3.1 % of the total, respectively, for a volume of 2,100 and 41,000 m^3 (in total, an Olympic swimming pool 35 meters

---

[21] Quite small indeed, around 5 %. The rest can be recycled [53].

[22] The kind of pool already mentioned in relation with the Fukushima accident.

deep). High activity HLW accounted for 96.8 % of all the wastes' radioactivity, and medium activity ones for 3.2 % [57].

7.3.4 Future Risks

Wind and solar energies are so far way below 1 % in terms of their contribution to the global energy production [56]. It is thus too early to assess the associated hazards. Yet, we can note they meet the requirements to generate dangers if they should go global.

We found that potential problems are associated with energy concentration and pollution. Let us quickly review how they could arise with large-scale implantation of wind and solar energies.

Solar and wind energies per se do not present an high energy density. This is the origin of the important numbers reported on Table 6.3. Yet, their large-scale implementation would require storage, for example, hydrogen storage. And here, we find high energy density, hence risk, as the German aircraft Hindenburg and Challenger space shuttle disasters demonstrated. The ARIA (Analysis, Research and Information on Accidents) database[23] operated by the French Ministry of Ecology, reported 213 hydrogen-related accidents between 1989 and 2007, for a total of 80 fatalities [58]. Suppose hydrogen storage is globally implemented. Storing just 1 % of the 2012 world energy production would require 6×10^{11} liters of hydrogen at 700 bar. It seems difficult to swear such amount of compressed explosive material would not generate its own danger.

Large-scale hydrogen use would also result in a significant volume of hydrogen leakage. What could be the consequences on the atmosphere dynamic, and on the climate? Some studies reported that it should be neutral [59]. Others emphasize possible negative effects on the stratosphere [60].

We found potential problems could be political when a key resource is geographically localized. In case huge amounts of solar cells of wind turbines end up concentrated in a given region, how could such a strategic place go without fostering political tensions? If occidental countries are willing to maintain the integrity of the strait of Hormuz at all costs, what about the Sahara,[24] for instance, if it were to host a good part of the world energy production?

Nuclear fusion considerably mitigates the problems associated to her sister fission. In a fusion power plant, the amount of deuterium and tritium present in the reactor at any time is extremely small. The reaction chamber is quite similar to a fireplace holding few firewood and needing constant feeding. In case of a reactor power failure, the tokamak immediately cools down. The same is true for inertial fusion: relying on repeated micro-explosions like a car engine, everything stops if you forget to inject the next deuterium–tritium little ball.

---

[23] See www.aria.developpement-durable.gouv.fr.

[24] See the "Desertec" project for example, www.desertec.org.

Regarding wastes and radioactivity, things are also much better. Fission generates a lot of them, by design. As shown in Fig. 6.5, there is no way to shortcut the laws of nuclear physics. Heavy nuclei fission has to give many radioactive products. With fusion, the origin of radioactivity is the tritium and the neutron coming out of the fusion reaction.[25] Tritium is a β^- emitter with a half-life of 12.3 years. The emitted electron has a low energy and is stopped by human skin. The glowing greenish indicators on some old watches were made mixing a little bit of tritium with phosphor. What about the neutron? It will hit the walls of the chambers and "activate" some of its atoms. It means some nuclei of the chamber wall will absorb the neutron and may get transmuted to radioactive isotopes. But here you have choice. The laws of physics are not strict to the point they tell you how exactly the chamber should be built. So you can choose your materials to minimize activation. It is worth nothing that we are here working in the lower left corner of Fig. 6.5, where radioactivity is reduced because the number of available nuclei and their size is limited. As a consequence, radiation doses convey by nuclear fusion wastes would fall below 10 times that of coal ash before 100 years [61, p. 42].

Fuel would not be a strategic matter either, as deuterium is derived from sea water and tritium bred in the power plant. Indeed, the main drawback here in view of our problem may be just time. The first demonstration power plant could start operating in 2037 [62]. Assume then a 4 GW commercial reactor, producing 1.2×10^{17} J (35 TWh) per year, is ready for 2050. From there, it would take 38 years of a sustained 30 % annual growth, to reach half of the world 2010 energy production.[26] While fusion energy may become a key ingredient of the twenty-second-century energy mix, it will probably not help much in the transition that needs to take place within the next 50 years.

References

1. V. Smil. *Energy in Nature and Society: General Energetics of Complex Systems*. MIT Press, 2008
2. Charles A. S. Hall, Stephen Balogh, and David J.R. Murphy. What is the minimum EROI that a sustainable society must have? Energies, **2**(1):**2**5–47, **2**009.
3. D.J. Murphy, C.A.S. Hall. Year in review—EROI or energy return on (energy) invested. Ann. N. Y. Acad. Sci. **1185**(1), 102–118 (2010)
4. J.A. Tainter, T.W. Patzek, *Drilling Down: The Gulf Oil Debacle and Our Energy Dilemma* (Bücher. Springer New York, SpringerLink, 2012)
5. M. Levi, *The Power Surge: Energy, Opportunity, and the Battle for America's Future* (Oxford University Press, USA, 2013)

---

[25] There are neutronless and tritiumless fusion reactions, like $\mathrm{D}+\mathrm{He3} \rightarrow \mathrm{He4}+\mathrm{p}$. But they require even more energy than $\mathrm{D}+\mathrm{T}$.

[26] Just solve $1.2 \times 10^{17}(1.3)^n = 5.3 \times 10^{21}/2$, where is n the number of years.

6. K. Aleklett, O. Qvennerstedt, M. Lardelli, *Peeking at Peak Oil* (Bücher. Springer New York, SpringerLink, 2012)
7. C.E. McGlade, A review of the uncertainties in estimates of global oil resources. Energy **47**(1), 262–270 (2012)
8. Richard A. Kerr, Technology is turning U.S. oil around but not the World's. Science **335**(6068), 522–523 (2012)
9. Tommy Dalgaard, Uffe Jørgensen, Jørgen E. Olesen, Erik Steen Jensen, and Erik Steen Kristensen. Looking at biofuels and bioenergy. Science **312**(5781), 1743–1744 (2006)
10. Red Eléctrica de España, *The Spanish electricity system preliminary report 2013* (S.A.U,Technical report, Red Eléctrica de España, December 2013)
11. J.E. Martin. *Mid-Latitude Atmospheric Dynamics: A First Course*. Wiley, 2006.
12. Cory Budischak, DeAnna Sewell, Heather Thomson, Leon Mach, Dana E. Veron, Willett Kempton, Cost-minimized combinations of wind power, solar power and electrochemical storage, powering the grid up to 99.9% of the time. Journal of Power Sources **225**, 60–74 (2013)
13. H. Arendt. *The Origins of Totalitarianism*. (Houghton Mifflin Harcourt, India, 1973)
14. P. Virilio. *The Original Accident*. (Wiley, New York, 2007)
15. C. Hohenemser, R.W. Kates, P. Slovic, The nature of technological hazard. Science **220**, 378–384 (1983)
16. G.L. Wells. *Hazard Identification & Risk Assessment*. (Inst of Chemical Engineers, Mumbai, 1996)
17. D. Yergin. *The prize: the epic quest for oil, money, and power*. Simon & Schuster, 1991.
18. T.L. Karl, *The Paradox of Plenty: Oil Booms and Petro-states*, Studies in international political economy (University of California Press, California, 1997)
19. D. Fridley, Ed. China Energy Databook-User Guide and Documentation, Version 7.0. (Lawrence Berkeley National Laboratory: Lawrence Berkeley National Laboratory, 2008)
20. US Environmental Protection Agency and Office of Air Quality Planning and Standards. AP42 Compilation of Air Pollutant Emission Factors. Number chapter 5 in Compilation of Air Pollutant Emission Factors. U.S. Environmental Protection Agency, Office of Air and Radiation, (Office of Air Quality Planning and Standards, 1985)
21. D. Qing, J.G. Thibodeau, P.B. Williams, Probe International, and International Rivers Network. The River Dragon Has Come!: The Three Gorges Dam and the Fate of China's Yangtze River. (East Gate Bks. Sharpe, 1998)
22. D. Proske, *Catalogue of Risks: Natural, Technical Social and Health Risks* (Springer London Limited, London, 2008)
23. U. Sandesara, T. Wooten. *No One Had a Tongue to Speak: The Untold Story of One of History's Deadliest Floods*. (Prometheus Books, New York, 2011)
24. C. Zaetta, P. Santonastaso, A. Favaro. Long-term physical and psychological effects of the vajont disaster. Eur J Psychotraumatology, **2**, 2011.
25. L. Berga. Dam Safety: *Proceedings of the International Symposium on New Trends And Guidelines on Dam Safety*, Barcelona, Spain, 17–19 June 1998
26. R. Blank, J. Echternkamp, K. Fings, J. Förster, W. Heinemann, T. Jersak, A. Nolzen, *Germany and the Second World War:Volume IX/I: German Wartime Society 1939–1945: Politicization, Disintegration, and the Struggle for Survival* (Clarendon Press Germany and the Second World War, Germany, 2008)
27. V.P. Jauhari. *Sustaining River Linking*. (Mittal Publications, New Delhi, 2005)
28. S.S.K. Jain, P.K. Agarwal, V.V.P. Singh, *Hydrology and Water Resources of India Water science and technology library* (Springer London Limited, London, 2007)
29. V.P. Singh, *Dam Breach Modeling Technology* (Springer Water Science and Technology Library, London, 1996)
30. US Departement of Homeland Security, *Estimating loss of life for dam failure scenarios* (Technical report, US Departement of Homeland Security, 2011)
31. C. Jaeger. *Rock Mechanics and Engineering*. Cambridge University Press, 1979.

32. Marco Pilotti, Andrea Maranzoni, Massimo Tomirotti, and Giulia Valerio. 1923 Gleno Dam Break: Case Study and Numerical Modeling. J. Hydraul Eng. **137**(4), 480–492 (2011)
33. José Lera. 40 años de la tragedia de Ribadelago, en la que murieron 144 personas. El País, 10 Jan 1999.
34. International Rivers Network, *Human rights dammed off at Three Gorges* (Technical report, International Rivers Network, 2003)
35. Y. Tan. *Resettlement in the Three Gorges Project in China*. (Hong Kong University Press, 2008)
36. J.R. McNeill, *Something New Under the Sun: An Environmental History of the Twentieth-Century World* (Norton, The Global Century Series. W. W, 2001)
37. World Commission on Dams. Dams and Development: A New Framework for Decision-making: the Report of the World Commission on Dams, Nov 2000. Earthscan, 2000.
38. A.L. Nichols, D.L. Aldama, M. Verpelli, Handbook of nuclear data for safeguards: Database extensions, august, *Report INDC(NDS)-0534* (International Atomic Energy Agency, Vienna, Austria, August, 2008)
39. A. Ansari. *Radiation Threats and Your Safety: A Guide to Preparation and Response for Professionals and Community*. (Taylor & Francis, UK, 2009)
40. M.T. Derin, P. Vijayagopal, B. Venkatraman, R.C. Chaubey, A. Gopinathan. Radionuclides and radiation indices of high background radiation area in Chavara-Neendakara placer deposits (Kerala, India). PLoS ONE, **7**(11), e50468, (2012)
41. K.R.R. Nair, B. Rajan, S. Akiba, P. Jayalekshmi, M.K. Nair, P. Gangadharan, T. Koga, H. Morishima, S. Nakamura, T. Sugahara. Background radiation and cancer incidence in Kerala, india-karunagappally cohort study. Health Phys, **96**, 55–66 (2009)
42. P.K.M. Koya, M.P. Chougaonkar, P. Predeep, P.J. Jojo, V.D. Cheriyan, Y.S. Mayya, M. Seshadri, Effect of low and chronic radiation exposure: a case-control study of mental retardation and cleft lip/palate in the monazite-bearing coastal areas of southern Kerala. Radiation Res. **177**(1), 16–109 (2012)
43. Susan Cutter, Kent Barnes, Evacuation behavior and Three Mile Island. Disasters **6**(2), 116–124 (1982)
44. I. Gusev, A. Guskova, and F.A. Mettler. *Medical Management of Radiation Accidents*, Second Edition. (Taylor & Francis, UK, 2010)
45. United Nations. Sources and Effects of Ionizing Radiation: Unscear 2008 Report: Effects: Scientific Annexes C, D and E. Sources and Effects of Ionizing Radiation: United Nations Scientific Committee on the Effects of Atomic Radiation : UNSCEAR 2008 Report to the General Assembly, with Scientific Annexes. Bernan Assoc, 2011
46. Robert J. Baker, Ronald K. Chesser, The Chornobyl nuclear disaster and subsequent creation of a wildlife preserve. Environ. Toxicol. Chem. **19**(5), 1231–1232 (2000)
47. Sacha Vignieri, Wildlife, wildlands, water, and more. Science **336**(6080), 414–417 (2012)
48. H. Ellegren, G. Lindgren, C.R. Primmer, A.P. Moller, Fitness loss and germline mutations in barn swallows breeding in Chernobyl. Nature **389**(6651), 593–596 (1997)
49. M. Danchenko, L. Skultety, N.M. Rashydov, V.V. Berezhna, L Mátel, T Salaj, Anna Pret'ová, and Martin Hajduch. Proteomic analysis of mature soybean seeds from the chernobyl area suggests plant adaptation to the contaminated environment. J. Proteome Res. **8**(6), 2915–2922 (2009)
50. A.Timothy, Mousseau, M. Shane. Welch, Igor Chizhevsky, Oleg Bondarenko, Gennadi Milinevsky, David J. Tedeschi, Andrea Bonisoli-Alquati, and Anders Pape Møller. Tree rings reveal extent of exposure to ionizing radiation in scots pine pinus sylvestris. Trees, **27**, 1443–1453 (2013)
51. World Health Organization. Global report on fukushima nuclear accident details health risks. Public Health & Environment e-News, **52**, Feb 2013.
52. Nat. News Fukushima (2013). Fallout of fear. **493**(7432), 290
53. AREVA. Rapport dinformation sur la sûreté nucléaire et la radioprotection du site AREVA la hague. Technical report, AREVA, 2011.

54. International Atomic Energy Agency, *Classification of Radioactive Waste: General Safety Guide* (IAEA safety standards series, International Atomic Energy Agency, 2009)
55. Declan Butler, France digs deep for nuclear waste. Nat. News **466**(7308), 804–805 (2010)
56. International Energy Agency. *Key world energy statistics*. International Energy Agency, 2012.
57. ANDRA. Inventaire national des matières et déchets radioactifs édition, *Les essentiels* (Technical report, Agence nationale pour la gestion des déchets radioactifs, January, 2012)
58. Bureau for analysis of industrial risks and pollution, *Accidentology involving hydrogen* (Technical report, Bureau for analysis of industrial risks and pollution, 2007)
59. Martin G. Schultz, Thomas Diehl, Guy P. Brasseur, Werner Zittel, Air pollution and climate-forcing impacts of a global hydrogen economy. Science **302**(5645), 624–627 (2003)
60. K. Tracey, Tromp, Run-Lie Shia, Mark Allen, John M. Eiler, and Y. L. Yung. Potential environmental impact of a hydrogen economy on the stratosphere. Science **300**(5626), 1740–1742 (2003)
61. M. Kikuchi, K. Lackner, M.Q. Tran. *Fusion Physics*. (International Atomic Energy Agency, Vienna, 2012)
62. D. Maisonnier, J. Hayward. Technological and engineering challenges of fusion. *Proceedings of the 2nd IAEA Technical Meeting on First Generation of Fusion Power Plants*: Design & Technology, 2007

A Toy Model

8

Imagine a large swimming pool in the desert. It was almost full when you saw it first, as a tap had been filling it for a long time. You came in with your folks and found this huge amount of water. You settled down, and as the Dire Strait's song *Telegraph Road* goes,

> …the other travelers came riding down the track,
> And they never went further, no, they never went back,
> Then came the churches then came the schools,
> Then came the lawyers then came the rules,
> Then came the trains and the trucks with their loads…

Houses and industries were built, all thanks to this huge reserve of water. One day though, the pool starts to run out of water. You can clearly see the bottom and realize one thing: when the pool is empty, your sole source of water will be the tap. Soon, all you have built and done from the pool will have to run from what comes out of the tap only.

We are quite in the same situation. Fossil fuels are nothing but accumulated solar energy. Industrial revolution came in 200 years ago and found this huge energy pool ready to use. We have built a whole way of life, a civilization, on it. Now, the pool is (nearly) half empty, and we realize that soon, even before it is empty, we should better run on the tap only. What has been designed spending millions of years of accumulated solar energy, will soon have to run in just-in-time mode, plus nuclear.

Let us now try to be as optimistic as possible, and see what numbers tell us for the future. The scenario presented now is *by no means* a prediction. As the Danish Physicist Niels Bohr may have said, "Prediction is very difficult, especially about the future." Many already experienced how risky forecasting is in the present matter. In his book *Energy at the Crossroads*, Vaclav Smil has a chapter entitled "Against Forecasting" where he writes, "for more than 100 years long-term forecasts of energy affairs…have, save for a few proverbial exceptions confirming the rule, a manifest record of failure" [1, p. 121]. It is rather what scientists call a "toy model", allowing to quickly play with numbers and check, order of magnitude wise, what happens

A. Bret, *The Energy-Climate Continuum*, DOI: 10.1007/978-3-319-07920-2_8

under such and such assumptions. So no "here's what is going to happen" here. Rather, "what if?"

According to the United Nation "medium scenario," the world population could stabilize[1] around 10 billion between 2050 and 2100 [2]. We saw with Fig. 1.2 that the 2010 world energy consumption was 1.8 toe per capita. For OECD countries, this was 4.6. China had 1.8 and counting. Suppose we assign ourselves a long-term world target of 2–4 toe per capita. That leaves 20–40 Gtoe to find each year. Such targets already imply significant savings from OECD countries. In addition, they are quite relevant to human development because the Human Development Index,[2] a composite indicator mixing life expectancy, educational attainment, and income, increases dramatically with energy consumption per capita until 2 toe and stagnates beyond 4 ([1, p. 102], [3]). In (very) short, life gets much better with energy until 2 toe per capita. And beyond 4, more energy does not make you any happier.

We will now make some assumptions on fossil decrease, carbon sequestration, and future energies growth:

- Figure 4.10 shows that the two IPCC emission scenarios yielding a reasonable warming are number I and II. For both, global GHG emissions peak before 2020 and are cut by 50 % minimum by 2050 [4, p. 198]. How should we translate this to an *energy* scenario? Let us focus on Fig. 5.3 and imagine fossil fuels consumption has been divided by 2. Then, the related CO_2 emissions are also cut by half. But the 17.3 % of emissions related to deforestation are *not* necessarily so. The same is true for the 7.9 % related to NO_2, mostly linked to fertilizers use. In a first approximation, we will say an $x\,\%$ reduction in fossil fuels results in the same $x\,\%$ reduction of GHG emissions. But reality could be far less generous than that.

  The next step is to include carbon sequestration. Emissions can be cut burning less oil, *or* storing part of the carbon emitted by the oil we do burn. Based on the analysis of Sect. 5.5, we will say half can be sequestered. But we cannot expect to do so right now. For practical reasons, the sequestered fraction η can only reach 50 % progressively in time. We will assume it grows 20 % a year initially, reaching 50 % soon after 2050, thus following a logistic law similar to Eq. (3.1),

  $$\eta(y) = \frac{50\,\%}{1 + \mathrm{e}^{-(y-2045)/5}}. \tag{8.1}$$

  Sequestration allows to burn more fossils. If I keep 50 % of the carbon for me, I can burn 2 tons of fuels and emit only 1 ton of carbon. With 10 % sequestration, I can burn 1.11 tons, keep $1.11 \times 10\,\%$, and emit only $1.11 - 1.11 \times 10\,\% = 1$ ton.

---

[1] This stabilization is due to the fact that fertility has been steadily dropping all over the world during the last decades. For example, the USA and Bangladesh are now surprisingly close fertility wise, with 1.9 and 2.2 children per woman, respectively, in 2011. See lively statistics on these topics and many others, at www.gapminder.org.

[2] See www.hdr.undp.org/en/statistics/hdi

More generally, storing $\eta\%$ allows to burn $1/(1-\eta)$ tons of fuel and still emit only 1 ton of carbon.
We thus started computing the amount of fossil fuel energy available, decreasing it from its 2012 value by a fix percentage each year (∼0.8 %) in order to cut it by half in 2050. For each year, the corresponding amount of fuel has then been divided by $(1-\eta)$, yielding the "authorized" quantity of fuel for that year.

- Other energy sources have been assumed to follow the production curve,

$$P(y) = \frac{P_\infty}{1 + e^{-(y-y_0)/a}}, \tag{8.2}$$

  where y is the year considered, P_∞ is the long-term production potential and y_0 a year parameter allowing to shift the curve in time. In practice, y_0 is adjusted to fit the data for year 2010 at $y = 2010$. Finally, $1/a$ is the annual growth in the early, exponential, phase.[3]
  Since we are dealing with *renewable* sources, or virtually so, production now tends to a constant instead of rising before dropping to zero.
- A very optimistic value for a is 10, giving an annual growth $1/a = 10\,\%$. Why? Because the mean annual growth of fossil fuels from 1800 to 2000 was only 4.2 % ($a = 24$, computed from Fig. 8.1 data). And we are talking about an easily extractable resource everyone wanted. Clearly, this is a *mean* value, implying they were periods of faster growth. But when it comes to setting an average over a century, history seems to teach 10 % could be difficult to achieve.
- The final potentials have been set following Table 6.3 for sources likely to play a global role. Biomass has been set to 2 Gtoe, assuming we will not harness all of the world's forests.
- Wind and solar have been set to 5 Gtoe noting the numbers required in Table 6.3 to generate 12 Gtoe are already challenging. In addition, their large-scale implementation would demand energy storage, which necessarily results in energy losses during the process electricity → storage → electricity. The overall yield today is around 50 %, implying the numbers in Table 6.3 would have to be doubled.[4]
- The parameter y_0 is finally set to bridge actual 2010 numbers in each case but fusion. For the latter, $y_0 = 2144$ gives a 2050 production equivalent to a single 4 GW power plant.
- Table 8.1 summarizes all parameter values for the sources considered.

---

[3] For $y \ll y_0 - a$, $P(y) \sim P_\infty e^{(y-y_0)/a}$. It follows that $P(y+1)/P(y) = e^{1/a} \sim 1 + 1/a$ for $a \gg 1$.

[4] The challenge here is that you cannot avoid two energy conversions: electricity → storage *and then* storage → electricity. For the first step, efficiency can raise up to 80 % [6]. For the second, the best fuel cells currently reach 65% [7], giving an overall yield of $80 \times 65\,\% = 52\,\%$ at best. And storage itself may equally have an energetic cost, as is the case for compressed hydrogen, for example, where compression takes its toll.

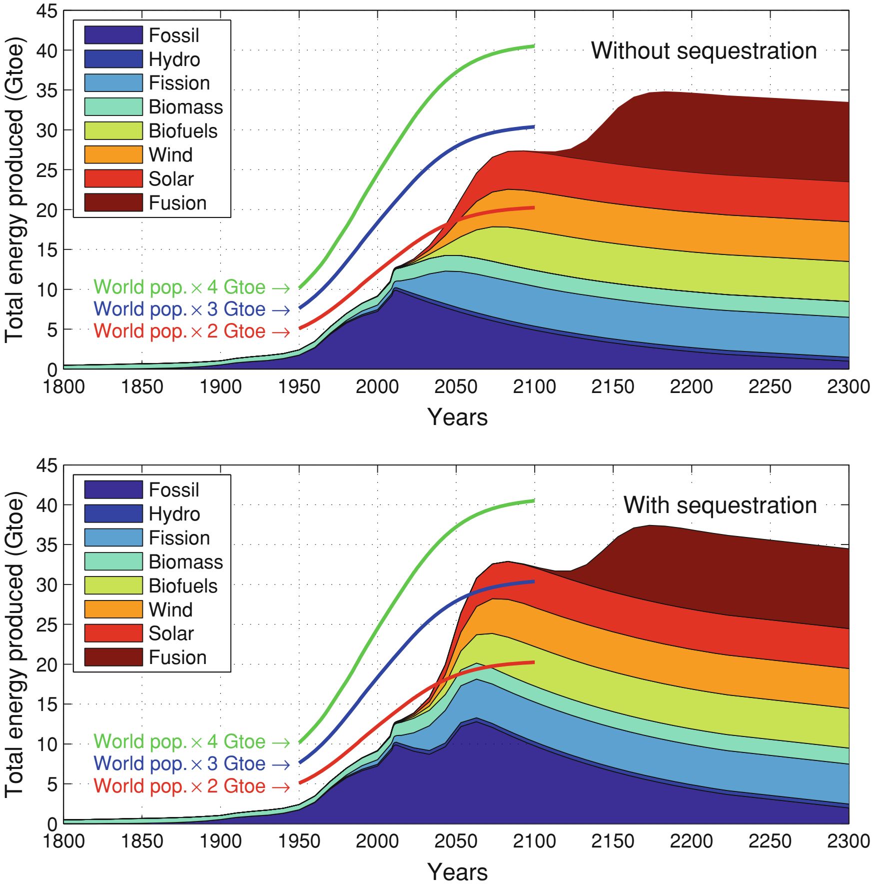

Fig. 8.1 Cumulative energy production accounting for the parameters given in Table 8.1 *Sources* Population data, [2], CD-ROM Edition. Fossil fuels before 2011, [5]

Table 8.1 Parameters considered in Fig. (8.1) for Eq. (8.2), for each energy source

	Hydro	Fission	Biomass	Biofuels	Wind	Solar	Fusion
P_∞ (Gtoe)	0.5	5	2	5	5	5	10
a	10	10	10	10	10	10	10
y_0	2005	2028	2000	2054	2054	2054	2144

Figure 8.1 displays the results of the calculations. Everything before 2010 is history [5], the rest being the fruit of the hypothesis just described. Among the non-fossil energies, biomass and hydro are limited, and wind/solar and nuclear fission account only for 0.9 and 5.7 % of today's global energy production [8]. For this reasons, two perspectives, short term and long term, can be distinguished.

Table 8.2 Year when a 5 % share of the global mix was achieved for 3 different rising energy sources, and additional years needed to reach definite milestones since then

New source	Year 5 %	10 %	15 %	20 %	25 %	33 %	40 %
Coal	1840	15	25	30	35	45	55
Oil	1915	15	20	35	40	50	60
Gas	1930	20	30	40	55		

Gas has yet to achieve 33 %. From [5]

The short term perspective extends until about 2100. It is thus “short” with respect to the 5 centuries span of the graphs, not to the human life. Only my grandsons are likely to live past it. During this first period of time, fossil fuels cannot help but remaining the dominant energy source, simply because it takes time for other sources to grow significantly. And remember the assumed growth rate is twice the fossils’ one in their boom years. The reduction of carbon emissions set by the climate constraint generates an energy gap when requiring 3 toe/capita or more.[5] Without carbon sequestration, the gap persists beyond 2100 (upper graph) whereas it is filled around 2050 with sequestration (lower graph).

This first perspective eventually pertains to the transition between the “fossil world” and the next, long term, one. On the long term, typically beyond 2100, the determinant parameters turn out to be the end potential of each energy source. Here of course, all kind of combinations are possible from the possibilities offered by Table 6.3 and the number of toe’s you wish to “offer.” Yet, considering the numbers or the technical challenges ahead, it seems a long-term solution is not easier to find than the formula for the transition.

In his book *Energy Transitions: History, Requirements, Prospects*, Vaclav Smil analyzes *past* energy transitions [5]. The nineteenth century witnessed a transition from biomass fuels to coal. Then, oil stepped in before the twentieth century to become the first primary energy source around 1950. Finally, gas also rose by the end of the nineteenth century, achieving a significant share as a primary energy source toward 1950 as well. Each transition is eventually defined by the rise of a new energy source. Smil starts defining a series of milestones corresponding to 5, 10, 15, 20, 25, 33, and 40 % share. Then, for each transition, he measures the number of years required to reach each milestones since the first one (5 %).

Table 8.2 summarizes the results. The time scales are strikingly similar for transitions separated by nearly one century. Whether we turn to the rise of coal, or that of oil or gas, the typical time it took for each to reach a 30 % share is 5 decades.

---

[5] The world is now at 1.8 toe/capita. But Brazil, India, and China, with more than 2.5 billion people and 1.36, 0.59, and 1.8 toe/capita, respectively, seem to be willing to join the 4.6 toe of OECD countries.

So history seems to agree with our little simulation. Bringing fossil fuels from 80 % of the mix down to 40 % in 2050, growth of energy demand notwithstanding, is far from easy.

References

1. V. Smil, *Energy at the Crossroads: Global Perspectives and Uncertainties* (MIT Press, cambridge, 2005)
2. United Nations. *World Population Prospects: The 2010 Revision*, Population Studies (United Nations Publications, New York, 2012)
3. D.M. Martínez, B.W. Ebenhack, Understanding the role of energy consumption in human development through the use of saturation phenomena. Energ. Policy **36**(4), 1430–1435 (2008)
4. B. Metz and IPCC Working Group III, Climate Change 2007—Mitigation of Climate Change: Working Group III Contribution to the Fourth Assessment Report of the IPCC. Climate Change 2007 (Cambridge University Press, (Cambridge, 2007)
5. V. Smil, *Energy Transitions: History, Requirements, Prospects* (Praeger, Westport, 2010)
6. G.W. Crabtree, M.S. Dresselhaus, M.V. Buchanan, The hydrogen economy. Phys. Today **57**(12), 39–44 (2004)
7. E.D. Wachsman, K.T. Lee, Lowering the Temperature of Solid Oxide Fuel Cells. Science **334**, 935 (2011)
8. International Energy Agency. *Key world energy statistics*. International Energy Agency, 2012

Part III
History

9

Why Societies are Fragile

History is the great instructor of public life
Cicero, 55 BC

There is no easy solution. No "silver bullet." Alternative energies are not as convenient as fossil fuels, precisely because we travelled the easy road first. Though obvious, it is worth thinking about it: The industrial revolution soared on fossil fuels *because* they were easier to harness than all the rest. If there was an even easier path, someone would have spotted it during the last 200 years. By virtue of their mere availability, their low technical requirements, plus some basic physical reasons reviewed in Chap. 5, oil, coal, and gas are an energetic must. Children facing a plate with some food they like and some they do not usually eat what they like first. By definition, what remains after this is something they do not like. Humanity did exactly the same with its energetic meal. How could have it been otherwise?

When facing an unknown perspective, most people start wondering what others did in the same situation. It is for sure a good reflex. As the Book of Proverbs puts it, "victory is won through many advisers" (Proverbs 11.14). Potential advisers in this respect can be past societies who ran through severe problems and overcame them, or not. This is the reason why this last part is devoted to history. Until now, we tried to introduce principles and orders of magnitude that have to be accounted for when thinking about the problem and devising energetic solutions. Our main guides were physics and arithmetic. But history can be a guide too.

We will now review a few examples of civilizations which run into different forms of challenges. Some, like the Easter Island society or the Roman Empire, could not find a solution and collapsed. But instances of successful response to challenges also exist. In this respect, we will see how the rise of fossil fuels, namely coal, in the nineteenth century may have contributed to the end of slavery. Also, the positive reactions of the industrialized world to the problem of the "ozone hole" in the second half of the twentieth century are worth emphasizing.

A. Bret, *The Energy-Climate Continuum*, DOI: 10.1007/978-3-319-07920-2_9

Though very different in many ways, our 4 examples share common aspects which make them very interesting for us. On the one hand, we can successfully draw parallels between the parts of the world involved, and our twenty-first-century one. On the other hand, all four cases relate to a shortage of resources and how people dealt with it.

Historians frequently call "collapse" instances of societies, civilizations, and empires, which vanished. In *The Collapse of Complex Societies*, Joseph Tainter mentions 18 of such events[1]: The Western Chou Empire (China), the Harappan Civilization (India), Mesopotamia, the Egyptian Old Kingdom, the Hittite Empire (Turkey), the Minoan Civilization (Crete), the Mycenaean Civilization (Greece), the Western Roman Empire, the Olmec (Mexico), the Lowland Classic Maya (Yucatán peninsula), the Mesoamerican Highlands (Mexico), Casas Grandes (Mexico), the Chacoans (New Mexico, USA), the Hohokam (Arizona, USA), the Eastern Woodlands (Mississippi Valley, USA), the Huari and Tiahuanaco Empires (Peru), the Kachin (Burma), and the Ik (Uganda) [1].

In *Collapse: How Societies Choose to Fail or Succeed*, Jared Diamond discusses collapse in Easter and Pitcairn Islands (Polynesia), the Anasazi (Colorado), the Maya, the Greenland Norse, and Rwanda [2].

The British historian Arnold Toynbee analyzed the rise and fall of all relevant civilizations in his monumental work *A Study of History* [3,4].

It is then clear that collapse is nothing exceptional throughout history. The Maya and Egyptians pyramids, or the Roman coliseum, are vivid proofs that many ancient civilizations disappeared. Even if the collapse may not have been as sudden as the very word suggests, it must have happened.

Why then is collapse so widespread in history? Why are societies fragile?

9.1 External Versus Structural Factors

The *reasons* for collapse have been one of the most debated topic among historians. While it seems difficult to single out *one* reason, let us here comment on structural factors emphasized by Joseph Tainter in *The Collapse of Complex Societies* [1]. According to Tainter, the reasons for the collapse of a given society are not so much external than *structural*. For example, barbarian invasions terminated the Roman Empire when the Visigoths sacked Rome in 410 AD. But the Empire knew about disaster before. In 390 BC, for example, the Gallic chief Brennus had sacked Rome already. In 53 BC, Rome was severely defeated when trying to invade the Parthian Empire [5, p. 292]. But it survived these disasters, and many more. Why then did it succumb in the fifth century, and not before?

Before we explain Tainter's thesis, an illustration could be helpful to discriminate between external and structural factors. It starts with a simple question: Why is the pencil standing on its tip on Fig. 9.1 bound to fall? One could think it is because

---

[1] Between parentheses, broad location in terms of modern geography.

Fig. 9.1 Unstable and stable configurations for a pencil

sooner or later, a little wind will blow or the desk will slightly shake. But the pencil would not fall if it were hanging by its upper part, like the right one on the figure.

In reality, a pencil on its tip will end up falling because it is *unstable*. A stable system, like the pencil hanging by its upper part, or a ball inside a bowl, comes back to its initial position when you give it a little push. By contrast, an unstable system can survive only in the total absence of external perturbations. But there are *always* external perturbations, and an unstable system will not stand against the slightest one. A stable system wants to return to its initial state when moved apart. An unstable one does not come back. It moves even further instead.[2] The pencil on its tip does not fall because of wind or vibrations. It falls because it is unstable. External factors (wind, desk vibrations…) are not the problem. The problem is internal. Structural.

9.2 Declining Marginal Return

Let us now turn to Tainter's idea. A developing society grows in size, population, and complexity.[3] Increasing complexity arises in response to the increasing amount of problems posed by an increasing size. While the society is in its growing phase, any increase in complexity brings about benefits justifying the investment. Schooling system, public health care, and so on are all welcome. Indeed, this is nearly the definition of the "growing phase."

---

[2] Interestingly, a dictatorial regime is unstable. When the repression needed to maintain it is released, people get away from it as fast as they can. People in Barcelona quickly resumed speaking Catalan after Franco died in 1975, and the main Barcelona avenue was renamed from "Avenida del Generalísimo Francisco Franco" to "Avinguda Diagonal" in 1979. When the Berlin wall was torn down, East Berliners did not run to rebuild it. The list is endless.

[3] In information theory, the complexity of a string is the length of the shortest binary program that outputs that string (see "Kolmogorov complexity" in Wikipedia). In other words, the complexity of a system is related to the amount of information it takes to describe it. That matches an intuitive idea of complexity. It would take much longer to describe the organization of a modern country than that of a group of hunter-gatherers.

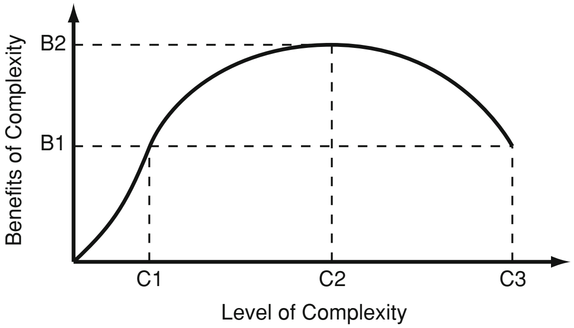

Fig. 9.2 The marginal product of increasing complexity. From [1, p. 119]

Yet, sooner or later comes a time when the benefits of successive layers of complexity are each time thinner. This is what Tainter calls the "point of declining marginal return" [1, p. 93]).

Figure 9.2 displays Tainter's schematic representation of the process. While complexity has not reached C_1, any investment in it is worth making because it brings an increasing benefit. Past C_1, any increase in complexity still brings about benefits, but in diminishing proportions.[4] At C_2, society has become so involved that more complexity only serves to maintain the status quo. Beyond that point, more complexity brings *less* benefits, not more. Past C_2, it takes simplification, the opposite of complication, to get better.

In a sense (we will see now in which sense), society is stable before C_2, and unstable after. Suppose you are in C_1. Moving to the left results in less benefits, so everyone will be willing to come back right. And moving to the right delivers benefits everyone wants to enjoy. But if you are in C_3, you need to *simplify* if you want more benefits. And simplifying a complex society is extremely difficult. Spain, for example, "enjoys" at least 5 layers of administration: state, autonomous community, province, comarca, and city.[5] How do you suppress even an single layer, once it has been active for decades? A daunting task indeed. So the most probable evolution is toward more complexity, which brings now *less* benefits. In C_1, society is stable in the sense that it spontaneously evolves toward a desired state. Not beyond C_2.

A society standing between C_2 and C_3 is extremely vulnerable. Its natural tendency to increase complexity faces the inevitable loss of benefits it brings. It has become so involved that any attempt to solve the problems which keep arising are nothing but "kludges" making things even worse.

---

[4] The second derivative turns negative at C_1.

[5] For example, Camprodon, a village of the Western Spanish Pyrenees, is in the comarca of "Ripollés," province of "Girona," autonomous community of "Cataluña".

9.3 Energy Shortage

A society undergoing marginal decline is in danger of collapse. How does it happen? Collapse can occur because the support of the population does so. “Where marginal returns decline, the advantages to complexity become ultimately no greater (for the society as a whole) than for less costly social forms…Under such conditions, the option to decompose (this is, to sever the ties that link localized groups to a regional entity) becomes attractive to certain components of a complex society” [1, p. 121]. Justice, for instance, may become so inefficient that some take it into their hands. Public services may deteriorate to the point people refuse to pay taxes, etc. In *The Social Contract*, the French philosopher Jean-Jacques Rousseau explained how people form a society by giving up, or delegating, some rights against some advantages. In the absence of such advantages, they become prone to get their rights back.[6]

But collapse may come from another direction. The concept of collapse from declining marginal return is apparently disconnected from energy issues. But only apparently because we need to answer the following question: How do you fuel an ever-increasing complexity? It takes resources to organize, administer, protect, and rule.[7] It takes energy to make something specific happen, instead of anything. It even takes energy just to maintain a given order, as everyone trying to avoid complete disorder in a 3-kids family household will notice. Things, from my hard drive directory to the whole country, do not get organized alone. They need help, which means energy.

When we discussed how societies go for example from C_1 to C_2, the *implicit* assumption was that there is enough energy supply to do so. Energy consumption in C_2 will be higher than in C_1, and we assumed it was no problem. In fact, we did not even mention it. Yet, even if you are happily sitting before C_1 and running out of energy, you will not be able to maintain your current complexity, and you will collapse.

A society reaching point C_2 on Fig. 9.2 turns unstable and can collapse because of the lack of support of its members, or from the lack of the energy needed to maintain its complex structure. In reality, things are quite intertwined. For example, an excessive complexity is likely to result in an energy shortage simply because maintaining it is energy consuming. We thus need to keep in mind that reality is not

---

[6] One of these rights is justice. As Jared Diamond puts it in *The World Until Yesterday*, “the overriding goal of state justice is to maintain society’s stability by providing a mandatory alternative to do-it-yourself justice” [6, p. 99].

[7] There is a deep connection between complexity, information, and energy. “Entropy,” for example, is a quantitative measure of the lack of *information* one has on a given system. It is directly related to the *energy* of that system through $\partial S/\partial E = 1/T$, where S, E, and T are the system’s entropy, energy, and temperature, respectively [7]. These concepts also apply to living organisms. As an illustration, Chap. 6 of Erwin Schrödinger’s famous essay *What is Life?* is entitled “Order, Disorder and Entropy” [8].

clear-cut. In addition, good *external* reasons for collapse have been identified, like, for example, relying too heavily on a collapsing partner.[8]

Yet, the factors explained here applied well to the two unfortunate examples we will now review: the Roman Empire and Easter Island.

References

1. J. Tainter, *The Collapse of Complex Societies. New Studies in Archaeology* (Cambridge University Press, Cambridge, 1990)
2. J.M. Diamond, *Collapse: How Societies Choose to Fail or Succeed* (Penguin, Harmondsworth, 2006)
3. A.J. Toynbee, D.C. Somervell, *A Study of History: Abridgement of Volumes I-VI* (Oxford University Press, USA, 1947)
4. A.J. Toynbee, D.C. Somervell, *A Study of History: Abridgement of Volumes VII–X* (Oxford University Press, Oxford, 1987)
5. I. Morris, *Why the West Rules-for Now: The Patterns of History, and What They Reveal About the Future* (Profile Books, London, 2010)
6. J.M. Diamond, *The World Until Yesterday: What Can We Learn from Traditional Societies?* (Viking, New York City, 2012)
7. S. Blundell, K.M. Blundell., *Concepts in Thermal Physics* (Oxford University Press, Oxford, 2006)
8. E. Schrodinger, R. Penrose, *What is Life?: With Mind and Matter and Autobiographical Sketches*, Canto Classics (Cambridge University Press, Cambridge, 2012)
9. J.A. Brothen, Population Decline and Plague in Late Medieval Norway. Annales de démographie historique, pp. 137–149 (1996)

---

[8] Such was the case of the Vikings who settled in Greenland from 986 to 1400 AD. Depending heavily on Norway's support, they could not overcome (among other challenges) the black death which killed half of Norway in 1350 ([2, p. 277], [9]).

When Things Went Wrong

10

The lessons to learn from Rome and Eastern Island are quite obvious, and we will see there is no need to detail them when going through each case. But some characteristics of our present times are equally featured by our two cases and are worth emphasizing.

First: Our world is highly connected. Thanks to transportation and the Internet, financial crisis, viruses, vaccines, or news quickly spread throughout the world. We no longer count distances in kilometers but in hours. For good or bad, nearly every part of the world is connected to every other part. This is the very reason why we can have a global problem which requires global solutions.

Second: There is nowhere to run for help. The challenge is planetary, not national. And on the planet, there is nothing bigger than the planet. No one in the Solar System can help. We are therefore condemned to find a fix within us.

10.1 Rome: Out of Conquests

10.1.1 Connected and Alone

Like our world, the Roman Empire formed a quite closed and unified entity. The historian Ian Morris writes [1, p. 286],

> By the first century CE a fusion Greco-Roman culture was developing. Rich men could travel from the Jordan to the Rhine, stopping in similar-looking cities, eating off much the same gold plates, watching familiar Greek tragedies, and making clever allusions to Homer and Virgil, everywhere finding like-minded men who would appreciate their sophistication.

Transportations were well established, allowing for people and goods to travel easily and participate in the unification of the Empire. The Stanford Geospatial Network Model of the Roman World[1] indicates it would only take 24 days to travel

---

[1] The ORBIS system. See orbis.stanford.edu.

A. Bret, *The Energy-Climate Continuum*, DOI: 10.1007/978-3-319-07920-2_10

from Petra (now Jordania) to Luguvalium (now Carlisle, northern England). The Roman Empire enjoyed therefore the kind of connectedness we now know, on a surprising large scale for its time.

In addition, it ran into problems it had to solve alone. The reason for this is not necessarily that it ignored all other empires of the world. Of course, Romans did not know about America or Australia. But they knew too well Alexander the Great had reached India and that India was *not* part of the Roman Empire. They perfectly knew silk was from China, or "Serica," as they would name this quite loosely localized home of the "Seres."[2] They would even long to conquer the rest of their known universe, as wrote to emperor Domitian the poet Statius toward 90 AD, "You shall bear a thousand trophies, only permit the triumphs. Bactra and Babylon have still to be curbed with new tributes, not yet are Indian laurels in Jove's bosom, not yet do Arabs and Seres make petition".[3]

The reason why Rome had to solve its energy crisis alone is simple: As we will see soon, *conquests* had been Rome's energy source. The parallel is not merely rhetoric: Conquering new territories meant gaining extra solar energy under the form of conquered arable lands [4, p. 109] and extra mechanical energy under the form of captured slaves. As Max Weber pointed out, "The ancient plantation consumed slaves the way a modern blast furnace consumes coal" [5, p. 398]. Rome ran out of fuel when running out of conquests. It is therefore obvious no one else could help relieving the energy gap. Getting outside help would have been like begging, "please, be conquered."

10.1.2 The Collapse

With about 46 million souls [6, p. 21] gathered around its *Mare Nostrum*, it seems Rome was pretty much like our world, in miniature. At its pinnacle, some would hope it would last forever. In this respect, Aelius Aristides, a Greek writer from the second century, wrote in 155 AD,

> For the eternal duration of this Empire the whole civilized world prays all together. Let all the gods grant that this Empire and this city flourish forever and never cease until stones float on water and trees cease to put forth shoots in spring.
> Aelius Aristides, *The Roman Oration*.

Yet, as strange as it seemed, the Empire would collapse some three centuries later. What happened then?

---

[2] "Serica" means "silk" in Latin. Regarding the way Romans perceived China, see *De Rome à la Chine: Sur les Routes de la Soie au Temps des Césars*, by Jean-Noël Robert [2].

[3] Publius Papinius Statius, *Silvae*, book IV.1.14–15, [3, p. 249]. "Bactra" was the capital of "Bactria," an empire located toward the actual Afghanistan and founded by a remnant of Alexander's army. Its disintegration around 130 BC is the first historical event recorded in both Roman and Chinese documents [1, p. 272].

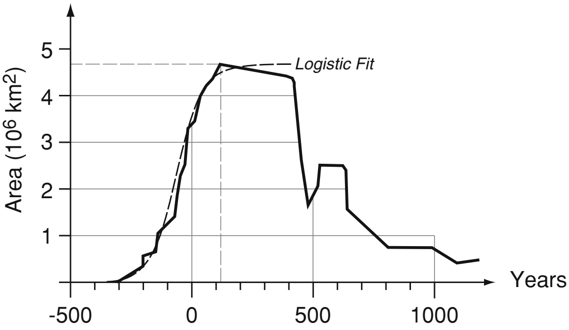

Fig. 10.1 Extension of the Roman Empire in terms of time. The Visigoths sacked Rome in 410. It is generally considered that the Western Roman Empire died in 476, when the German Odoacer became king of Italy. The remaining Eastern Empire (or Byzantine Empire) conducted some successful but temporary reconquests during the sixth century. From [7]

Figure 10.1 gives an element of answer. It shows the surface extension of the Empire as a function of time. The political scientists Rein Taagepera plotted it in 1968 by measuring the Roman Empire area on a series of historical maps. He could even fit the growing phase with the kind of logistic law given by Eq. 3.1, already mentioned in this book when dealing with oil production. The parallel is striking between the recent exponential growth of our energy consumption and the early exponential growth of the Empire extension. At this stage, let us simply quote Tainter [8, p. 129],

> The policy of expansion was at first highly successful. Not only were the conquered provinces looted of their accumulated surpluses, even their working capital, but permanent tributes, taxes, and land rentals were imposed. The consequences for Rome were bountiful. In 167 BC the Romans seized the treasury of the King of Macedonia, a feat that allowed them to eliminate taxation of themselves. After the Kingdom of Pergamon was annexed in 130 BC the state budget doubled, from 100 million to 200 million sesterces. Pompey raised it further to 340 million sesterces after the conquest of Syria in 63 BC. Julius Caesar's conquest of Gaul acquired so much gold that this metal dropped 36 percent in value. With this kind of payoff, Rome's conquests under the Republic were economically self-perpetuating. The initial series of victories, undertaken as a matter of self-preservation, began increasingly to provide the economic base for further conquests. By the last two centuries BC Rome's victories may have become nearly costless, in an economic sense, as conquered nations footed the hill for further expansion. This process culminated with Octavian's (later Augustus) conquest of Egypt. The booty of Egypt allowed Augustus to distribute money to the plebeians of Rome - and even, when necessary, to relieve shortages in the state budget out of his personal fortune…Augustus (27 BC–14 AD) terminated the policy of expansion, particularly after losses to the Germans, and concentrated instead on maintaining a stable army and restoring the prosperity that had been ruptured by the civil wars.

For four centuries, conquests had constantly provided extra money, extra slaves, and extra solar energy. But they could not last forever. A larger territory implies an ever increasing number of remote provinces difficult to administer. It also implies an ever increasing number of enemies along the growing frontier, multiplying the odds of running into a fierce competitor [8, p. 149]. Rome eventually ran into all issues and had to stop conquering to focus on *maintaining*. The problem is that the Empire had been designed to operate with more than it could produce, simply because for centuries, conquests were constantly bringing extra resources.

The challenge was therefore to maintain without anymore conquests an Empire that needed them to operate.[4] By 200 AD or so, Rome had reached something like point C_2 in Fig. 9.2 and turned unstable.

Rome needed fuel, namely conquests, but could no longer expand. It then had to find the resources where it could afford. Though unpopular, finding the money conquests could no longer provide was doable. Imperial lands and treasures were sold, currency debased.[5] Marcus Aurelius, who reigned from 161 to 180 AD, had to raise taxes again after 300 years without them. But the slaves supply dramatically fell, which proved disastrous[6] [11]. Finally, replacing the extra solar energy generated by annexing territories was simply impossible.

Little by little, Rome lost the support of the population. This very support from the people, even the defeated ones, had been the strength of the Empire. Though nothing historical, the following dialogue from a secret meeting of the "People's Front of Judea"[7] in the Monty Python's movie *The Life of Brian*, nicely summarizes the benefits conquered people eventually enjoyed with being Roman,

> Apart from the sanitation, the medicine, education, wine, public order, irrigation, roads, the fresh water system, and public health…what have the Romans ever done for us?
>
> Brought peace?
>
> Oh peace! Shut up!

Romans themselves were frequently found emigrating to newly conquered territories [8, p. 128]. Yet, as the pressure on population got worse until the fifth century, it severely undermined its support. In this context, invasions were not always feared and "at least a portion of the overtaxed peasantry openly welcomed the relief they thought the barbarians would bring from the burdens of Roman rule…To many, there

---

[4] The situation is quite similar to the present day difficulties rich countries have in reducing their public debt. France's debt, for example, has grown nearly steadily since 1970 (see http://www.insee.fr). The whole country has been used to spend more than it earns for at least 40 years. It is therefore *designed* to work this way. And France is obviously not the only one in this situation. In October 2013, the USA faced default due to an impossibility to raise the debt ceiling. It has to spend more than it gets. It is also designed this way.

[5] The denarius went from 98 % down to 58 % silver, between 69 and 200 AD [8, p. 135].

[6] Slaves were an important part of the Empire machinery. During the third century AD, they would amount to some 10 % of the total population. But the wealthiest 1.36 % of Roman society would own 49 % of them [9, p. 59]. The rich Seneca (4 BC–AD 65), tutor then advisor to emperor Nero, wrote in his *Epistulae morales ad Lucilium* (87.2) that he was travelling light taking only "very few slaves - one carriage-load" (probably 4 or 5, [10]).

[7] Those who know the movie also know it *must not* be confused with the "Judean People's Front."

were simply no remaining benefits to the Empire, as both barbarians and tax collectors crossed and ravaged their lands" [8, p. 150–151]. The good old days of the Pax Romana were gone.

Rome eventually succumbed to the two factors mentioned in Chap. 9. On the one hand, it lost the support of a population each time less inclined to work or fight for an Empire which was not bringing so much good. On the other hand, conquests had been fueling the Roman Empire. When they came to an end, it became difficult to maintain a structure that needed them to operate, let alone fixing the inevitable sources of unexpected stress.

As it became unstable, Rome could no longer endure and recover from perturbations it once could withstand. Collapse was only a matter of time.

10.2 Easter Island: Out of Forests

EXTRACT FROM THE OFFICIAL LOG
OF
MR JACOB ROGGEVEEN;
RELATING TO HIS
DISCOVERY OF EASTER ISLAND

> About the 10th glass in the afternoon watch The African Galley, which was sailing ahead of us, lay to to wait for us, making the signal of land in sight…to the land [was given] the name of *Paásch Eyland*, because it was discovered by us on Easter Day…we saw smoke rising in several places from which we concluded that there were people dwelling on the same.
> What the form of worship of these people comprises we were not able to gather any full knowledge of, owing to the shortness of our stay among them; we noticed only that they kindle fire in front of certain remarkably tall stone figures they set up…At first, these stone figures caused us to be filled with wonder, for we could not understand how it was possible that people who are destitute of heavy or thick timber, and also of stout cordage, out of which to construct gear, had been able to erect them; nevertheless some of these statues were a good 30 feet in height and broad in proportion.
> As to their seagoing craft, they are of poor and flimsy construction; for their canoes are fitted together of a number of small boards and light frames, which they skilfully lace together with very fine laid twine…We found [the island]…destitute of large trees.
> Reference [12, pp. 6, 7, 15, 16, 19, 21].

So goes the log of Jacob Roggeveen, Dutch explorer and commander in chief of the expedition which discovered Easter Island on Easter Day, April 5, 1722. The "stone figures" mentioned in the text are called "Moai" and are still visible today on the island. How could the islanders have erected hundreds of such 10 m high and tens of tons monsters,[8] on an island destitute of "large threes," "heavy or thick

---

[8] The largest ever found was 20 m high and weighted about 270 tons. It was found lying and unfinished [13, p. 113].

Fig. 10.2 Easter islanders and French explorers next to one Moai, by Gaspard Duché de Vancy, 1786 [14]

timber, and also of stout cordage"? In 1786, the French artist Gaspard Duché de Vancy represented the islanders next to one Moai (Fig. 10.2), rendering the size of the statues and the bare aspect of the island. This absence of trees is all the more difficult to understand that other islands of the Pacific Ocean located at the same latitude, such as Pitcairn or Cook, display an abundant vegetation. It must have been equally puzzling to note "poor and flimsy construction" seagoing crafts for people living on an island.

10.2.1 Connected and Alone

Connectedness and loneliness are even more obvious than for the Roman Empire. The closest continental land is Chile, 3,700 km to the east. The closest inhabited island is Pitcairn, 2,000 km to the west. This means Easter islanders could not call anyone for help in case of trouble.

Regarding connectedness, suffice it to say that the island has the shape of an isosceles triangle, which base and height are 23 and 12 km long respectively. Clans territories notwithstanding, you could walk from one end to another in a single day.

10.2.2 Too Few trees and People

Many tried to decipher the Easter Island enigma. A notable example is the expedition of Katherine Routledge, who stayed on the island from March 1914 to August 1915 and subsequently wrote *The Mystery of Easter Island* [15]. Though she definitely emitted hypotheses, in the absence of absolute dating technique and written history, she had to admit that "it is impossible as yet to give with any certainty a connected account of the early history of Easter Island" [15, p. 298].

The puzzle really started to fall in place in the 1950s, when the carbon-14 dating technique was discovered [16]. Archeologists could dig into the ground through successive layers of sediments, analyze the pollens deposited in each one, and use the carbon-14 technique to date them. It turns out that there were large palm trees (among others) on Easter island from 3000 BC at least, until their number started to decline sharply around 1300 AD [17].

Regarding the population of the island, explorers who visited it between 1722 and 1860 estimated it between 1,000 and 2,000. The number reported just before slave traders arrived in 1862 was 3,000 [13, p. 178], [18]. Explorers also noticed the island could host far more people than that. Several points indicate population must have risen higher before. For example, the island was colonized around 1000 AD.[9] Assuming there were 38 settlers [20] and a population doubling every 40 years, we get to 3,000 people by 1315 AD, not 1722. Various modelizations of the evolution of the population come out with a maximum of 10,000 [20–22]. James Cook, who spent time there in 1774, noted many parts of the island had been cultivated in the past and were abandoned. Twelve years later in 1786, the French explorer La Pérouse, who visited the island with the author of the painting of Fig. 10.2, noted only one-tenth of the island was being used. Another clue comes from the mere number of people needed for a society to build the 887 Moai found so far [23]. Eventually, it is thought population could have reached some 10,000.

Turning now to the statues, the golden age of their building lasted from 1150 to 1500 AD [13, p. 128]. They were apparently erected in honor of famous ancestors. Bordering the shore and facing inland, they seemed like protectors of the people. Due to their highly symbolic role, they became an object of rivalry between the clans living on the island [24, p. 111].

Eighteenth century explorer did not find anyone building a statue. So, what happened? Where had the trees, the people and the Moai's builders, gone?

10.2.3 About Trees and People

As already noticed, deforestation started around 1300 AD. Indeed, depending on the site, woodland clearance started between 1100 and 1450 AD [25], with an overall deforestation completed by 1500 AD. The simultaneous rise of charcoal in the very sediments containing the declining pollens shows many trees were burnt. Palms were chopped for a number of reasons: building canoes, making firewood, producing agricultural lands, or providing the material for the Moai industry. Some authors

---

[9] The estimated date of colonization varies from 600 to 1200 AD [18,19]. But the reasoning holds even with the latest date.

have suggested rats imported by the settlers may have played a prominent role by gnawing the trees seeds [13, p. 172], [18]. But recent works found no evidences for such claim [17,25,26], though rats may definitely have "helped" in the process. Also, a reconstruction of the regional climate for the period 800–1750 AD concluded that large-scale climate changes over the island might be too small to explain the observed deforestation [27]. It definitely seems deforestation was mostly driven by the islanders.

The clearing of the forest had dire consequences. One palm tree provided more than 400 L of sap per year, plus nuts and palm hearts [23]. It also provided the needed material to built solid canoes instead of the fragile "seagoing craft" Jacob Roggeveen saw in 1722. Deforestation prompted soil erosion, giving way to less fertile lands. It also deprived the islanders from the fauna hosted by the forests and from the accessories (timber, cordage) needed for building Moai.

10.2.4 The End

With no forests left, food got scarce and the Eastern island diet changed. The initial one was rich in dolphins, fishes, seabirds, land birds, and (imported) rats [28, p. 105]. With no quality ship to fish, dolphins and large fishes nearly disappeared from the menu. Birds, and food from the trees, also disappeared with the trees hosting them. The post 1500 AD diet incorporates the same amount of rats, with a tremendous increase of chicken.

Stress on resources brought conflicts. The various clans who had erected to Moai during the boom years started to fight and to topple each other's Moai. Katherine Routledge collected the legends told by the islanders during her 1914–1915 stay. According to these, fights between clans were part of the island history from the early settlement [15, p. 277]. But they got more intense.[10] While examining more than 600 early islanders skeletons, the forensic anthropologist Douglas Owsley concluded "When I compare the frequency of injuries that I have observed in the Easter Island population with other collections that I have worked with, it certainly shows the high end, it's the extreme. It was a period of social disintegration. You have got endemic warfare, it is chronic—they are slugging it out, there is no doubt about it" [30,31]. Cannibalism was probably involved too. In this respect, we read in the report William Thomson wrote on the island in 1889 to the Smithsonian Institution [32, p. 472],

> The traditions abound with instances of anthropophagism, and in all Polynesia there were no more confirmed cannibals than these [Easter] islanders. The practice is said to have originated with a band of natives who were defeated in war and besieged in their stronghold until reduced to the borders of starvation.

---

[10] See Ref. [29] for more on wars in traditional societies.

In the same vein, when referring to some episode of Moai toppling during a conflict, Katherine Routledge wrote “The events occurred just before living memory, and, like most stories in Easter Island, it is connected with cannibalism” [15, p. 173].

So people arrived, grew in number thanks to the forest, overexploited it, and then fought when resources had been depleted. From which of the perils invoked in Chap. 9 did this society succumb? Energy shortage comes to mind first. Indeed, the forest, through the calories it provided, was the Eastern Island source of energy. Society grew complex to the point it could dedicate part of its resources to Moai building. But when the fuel behind it all ran out, it collapsed.

References

1. I. Morris, *Why the West Rules—for Now: The Patterns of History, and What They Reveal About the Future* (Profile Books, London, 2010)
2. J.N. Robert, *De Rome à la Chine: Sur les Routes de la Soie au Temps des Césars* (iUniverse, Bloomington, 1999)
3. P.P. Statius, D.R.S. Bailey, *Silvae* (Harvard University Press, Caecilius Statius, 2003)
4. J.A. Tainter, T.W. Patzek, *Drilling Down: The Gulf Oil Debacle and Our Energy Dilemma* (Springer, New York, 2012). SpringerLink: Bücher
5. M. Weber, *The Agrarian Sociology of Ancient Civilizations* (Verso Books, World History Series, 2013)
6. Colin McEvedy, Richard Jones, *Atlas of world Population History* (Penguin, Harmondsworth, 1978)
7. R. Taagepera, Growth curves of empires. Gen. Syst. **13**, 171 (1968)
8. J. Tainter, *The Collapse of Complex Societies. New Studies in Archaeology* (Cambridge University Press, Cambridge, 1990)
9. K. Harper, *Slavery in the Late Roman World, AD 275–425* (Cambridge University Press, Cambridge, 2011)
10. J.A. Madden, Slaves in the Roman Empire: numbers and origins. Classics Ireland **109**, 3 (1996)
11. W.R. Stephens, The fall of Rome reconsidered: a synthesis of manpower and taxation arguments. Mid-Am. Rev. Sociol. **7**, 49 (1982)
12. The voyage of Captain Don Felipe González: in the ship of the line San Lorenzo, with the frigate Santa Rosalia in company, to Easter Island in 1770–1. Preceded by an extract from Mynheer Jacob Roggeveen’s official log of his discovery of and visit to Easter Island in 1722. Number v. 13 in New light on Drake: a collection of documents relating to his voyage of circumnavigation, 1577–1580. Hakluyt Society, 1908
13. P.G. Bahn, J.R. Flenley, *Easter Island, Earth Island* (Thames and Hudson, London, 1992)
14. J.F. de Galaup, *Atlas Du Voyage de La Pérouse (1797)*
15. K. Routledge, *The Mystery of Easter Island* (Cosimo, New York, 2007)
16. J.R. Arnold, W.F. Libby, Age determinations by radiocarbon content: checks with samples of known age. Science **110**, 678 (1949)
17. Daniel Mann, James Edwards, Julie Chase, Warren Beck, Richard Reanier, Michele Mass, Bruce Finney, John Loret, Drought, vegetation change, and human history on Rapa Nui (Isla de Pascua, Easter Island). Quat. Res. **69**, 16–28 (2008)
18. Terry L. Hunt, Carl P. Lipo, Late colonization of Easter Island. Science **311**(5767), 1603–1606 (2006)

19. Helene Martinsson-Wallin, Susan J. Crockford, Early settlement of Rapa Nui (Easter Island). Asian Perspect. **40**(2), 244–278 (2001)
20. Anthony Cole, John Flenley, Modelling human population change on Easter Island far-from-equilibrium. Quat. Int. **184**, 150–165 (2008)
21. J.A. Brander, M.S. Taylor, The simple economics of Easter Island: A Ricardo-Malthus model of renewable resource use. Am. Econ. Rev. **88**(1), 119–138 (1998)
22. M. Bologna, J.C. Flores, A simple mathematical model of society collapse applied to Easter Island. EPL **81**, 48006 (2008)
23. Jared Diamond, Easter Island revisited. Science **317**(5845), 1692–1694 (2007)
24. J. Flenley, P. Bahn, *The Enigmas of Easter Island* (Oxford University Press, UK, 2003)
25. A. Mieth, H.R. Bork, Humans, climate or introduced rats which is to blame for the woodland destruction on prehistoric Rapa Nui (Easter Island)? J. Archaeol. Sci. **37**(2), 417–426 (2010)
26. M. Prebble, J.M. Wilmshurst, Wilmshurst. Detecting the initial impact of humans and introduced species on island environments in Remote Oceania using palaeoecology. Biol. Invasions **11**(7), 1529–1556 (2009)
27. C. Junk, M. Claussen, Simulated climate variability in the region of Rapa Nui during the last millennium. Clim. Past **7**(2), 579–586 (2011)
28. J.M. Diamond, *Collapse: How Societies Choose to Fail Or Succeed* (Penguin, Harmondsworth, 2006)
29. J.M. Diamond, *The World Until Yesterday: What Can We Learn from Traditional Societies?* (Viking, New York City, 2012)
30. P. Bahn, Anthropology: head to head. Nature **476**(7359), 150151 (2011)
31. P. Bahn, J. Flenley, Rats, men—or dead ducks? Current World Archaeology **49**, 8 (2011)
32. W.J. Thomson, *Te Pito Te Henua, or Easter Island* (Government Printer, South Africa, 1891)

When Things Went Right

11

> *We can never give anything up; we only exchange one thing for another*
>
> Sigmund Freud, 1907

Surely, at this point of the book, positive experiences may come as a relief. After two instances of resource shortage which could not find remedy, we will now see two instances where it could.

Our first example has to do with the abolition of slavery. We already mentioned in Chap. 1 that slavery exists at least since the third millennium BC. Later on came the oriental and the occidental trades [1]. The end of the latter during the nineteenth century gives us our first fortunate history. Why telling it in a book about energy and energy transition? Simply because from the energetic point of view, giving up slavery meant giving up an energy source. And because giving up something for nothing is extremely difficult, offering an alternative helped tremendously. Here, it seems the alternative was the tandem coal/steam engine.

Our next story will be the one of the ozone hole. By the late twentieth century, people started to realize that a kind of gas widely used in the industry was damaging the atmospheric ozone layer. This layer is made of O_3 molecules (three oxygen atoms together) and protects us from some harmful solar radiations. Action was taken worldwide, and the problem was solved. Today, the ozone concentration in the atmosphere is slowly recovering. This case features in miniature all the ingredients of our present challenge: An important resource has to be replaced because it pollutes. We will see how that was achieved.

A. Bret, *The Energy-Climate Continuum*, DOI: 10.1007/978-3-319-07920-2_11

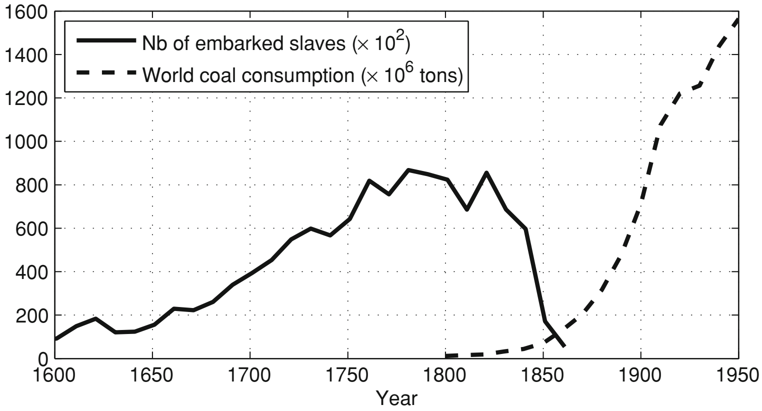

Fig. 11.1 World coal consumption versus number of slaves embarked per year (10 year averaged). *Source* Coal consumption, [4, p. 155]—Slaves, www.slavevoyages.org

11.1 Coal and Slavery

Already in the fourth century BC, Aristotle noted that slaves would not be needed if there were machines like the "Tripods of Hephaestus"[1] to perform their work [2]. Later on in 1891, Oscar Wilde wrote [3, p. 141],

> The fact is, that civilization requires slaves. The Greeks were quite right there. Unless there are slaves to do the ugly, horrible, uninteresting work, culture and contemplation become almost impossible. Human slavery is wrong, insecure, and demoralizing. On mechanical slavery, on the slavery of the machine, the future of the world depends.

On the one hand, the advent of slavery can be viewed as a part of an ever increasing search for extra energy. On the other hand, we just checked that long before the industrial revolution, some thought "machines" could replace slaves. By 1800, the Atlantic slave trade was at its peak. By the same time, the coal-fueled steam engine was about to launch the industrial revolution. One would expect it may have had a positive, abolishing effect on slavery. Is there a way to check our expectation?

Figure 11.1 displays the evolution of the number of slaves embarked through the Atlantic trade, versus the world coal consumption at the same time. The trade reached its maximum around 1800, with some 80,000 slaves traded each year. From 1500 to 1866, more than 12 million slaves were embarked. The figure is quite self-explanatory. Of course, a plot is not a proof. The rise of coal consumption and the simultaneous fall of slaves traded could just be mere coincidence. Yet, historians

---

[1] The Greek god Hephaestus built the "Tripods," automata that would go in and out of Mont Olympus.

think they were connected. It appears that harnessing fossil fuels definitely helped abolishing slavery.

11.1.1 Direct Factor

The historian Ian Morris suggests greed, together with fear and sloth, is one of the motors of history [5, p. 26]. And energy, by the power it bestows, is definitely an object of greed. Slavery was one solution to the long-standing problem of energy shortage. Although new energy sources usually do not replace the old ones but come on top instead (see Fig. 3.4), coal certainly drove many to rethink slavery in terms of a poor energy provider.

The synchrony in time and place between the introduction of coal-fueled machines and the rise of abolitionism is hard to ignore. While Fig. 11.1 features the world coal consumption, slave trade only refers to the part of the world involved in it, that is, Western Europe. Yet, the advent of steam power in *Russia* also matches the abolition of serfdom in this country. Moreover, even before the abolition, the rise of anti-slavery movements, first in Britain and then in the USA, also matches the massive introduction of the coal/steam engine tandem in each country [6].

The mere energy factor, according to which 1 kg of coal provides the same energy than some 15 slave workdays,[2] was obviously directly involved. But a number of indirect factors helped coal pave the way to the abolition of slavery. Let us now discuss them.

11.1.2 Indirect Factors

The industrial revolution ushered in an age of belief in progress where people thought machines would relief them from painful tasks. This new mentality made society, or at least part of it, more sensitive to the suffering of slaves. Labor had to be dignified for the indignity of slavery to be fully exposed. Yet, labor had been considered a curse for ages, as evidenced by these lines from the book of Genesis where Adam is expelled from the Garden of Eden,

> Cursed is the ground because of you; through painful toil you will eat food from it all the days of your life.
> It will produce thorns and thistles for you, and you will eat the plants of the field.
> By the sweat of your brow you will eat your food until you return to the ground, since from it you were taken. *Genesis 3.17–19 (New International Version)*

In the words of David Brion Davis "It was not until writers in the Enlightenment and early nineteenth century began to ennoble free labour…that it became possible

---

[2] Assuming like in Chap. 1 that a slave would provide 2 MJ/day, and remembering 1 kg of coal contains about 30 MJ (see Appendix A).

to launch a popular attack on slavery as a backward and inhuman institution that stigmatized and dishonored the very essence of labour" [7, p. 56].

The industrial revolution also paved the way to the dismission of slavery in less noble manners. Even at the time when forced labor was still accepted in Britain, entrepreneurs who had invested in machines quickly realized the advantages of paying the workers so that they could buy what they would produce. Later on in the USA (in 1914), Henry Ford had the same idea when he set the wage of his workers, $5/day, in terms of the price of his "Model T".[3] He wanted to make sure they could buy the cars they were making [8, p. 125]. This explains, at least in part, the success of the anti-slavery movement in Britain, as a cause that could merge industrialists' and workers' interests [6].

11.1.3 Nineteenth-Century Thoughts

The coal/slavery connection is not just something we realize now, looking back at the nineteenth century. Many already did it then. In 1832, John Quincy Adams, US president from 1825 to 1829, explained to the US Congress that in Great Britain, "such was the multiplication of physical power by the agency of machinery, that the mechanical inventions in use were estimated as equivalent to the manual labor of two hundred millions of people" (cited in [6]).

Some supplied machines to West Indies plantations in the very purpose of easing human labor. In a 1824 letter to William Huskisson, president of the British Board of Trade, John Ashton Yates, wrote "We are informed on good authorities, that in some of our colonies, the practice [of night work] has been almost wholly abandoned (in consequence partly of the introduction of steam-engines) and the grinding of the cane ceases at sunset".[4]

A 1830 account on slavery in Mauritius goes along the same line [9, p. xi],

> Within that period [the last twenty years] the yearly exportable produce of Mauritius, from being null, has gradually approached to 30,000 tons of sugar…This prosperity is to be attributed solely to our having called into action the intelligence of man, in preference to his merely physical powers. Thus the Slave has been raised, in many respects, to the rank of a European labourer; and he often possesses greater comforts, while his irksome toil has been changed into an easy task; indeed, nine-tenths of human labour has been replaced by eighty steam engines and sugar mills.

These lines were penned to answer the critics of *The Anti-Slavery Monthly Reporter*, an abolitionist British periodical. Their author, Charles Telfair, was a notable British slave owner in the colony of Mauritius. It is thus very interesting to note how he too definitely agrees machines were there to relieve slaves. And the list could go on.

---

[3] About $500. It was then 4 months of a worker's wage.

[4] See www.recoveredhistories.org. John Ashton Yates was a Presbyterian author who wrote on trade and slavery.

A search on the string "steam engine" in the www.recoveredhistories.org database returns many nineteenth-century documents.

It would be erroneous to credit the abolition of slavery to the sole coal/steam engine tandem. There were even instances, like in the Cuban sugar mills, where the efficiency brought by the machines made it more difficult to free the slaves [6]. Nor it could be pretended that the potential replacement of men by machine was the main drive of the abolitionist movement. Yet, the historian Jean-François Mouhot writes "it was widely accepted by people across all social classes at least from the beginning of the nineteenth century that machines were already, and would increasingly, supersede human labour. This idea was constantly at the back of people's minds and so did play a role in the anti-slavery movement" [6].

Against the backdrop of the insatiable human thirst for energy, machines offered an apparently limitless alternative to slavery. Forced labor could not fight against the progressive mind-set fostered by the industrial revolution. "The assumption that slavery had become both obsolete, as a result of mechanical inventions and the superiority of free labor, and immoral, as a result of historical changes in moral perception…clearly contributed greatly to the abolition of 'Negro slavery' in the Western Hemisphere" (David Brion Davis, cited in [6]).

Coal and steam engine opened the possibility of abolition. They gave munitions to abolitionists, inclined society toward it, and provided a way out to slave owners.

11.2 The Ozone Hole

By the end of the 1920s, air-conditioning and refrigeration systems were on the rise. Since they are basically concerned with carrying heat, all these systems need a fluid to do so. By that time, the substances used in this respect were quite dangerous. At the Frigidaire division of General Motors, people were trying to solve this problem and circa 1930, one of them, Thomas Midgley, synthesized "Freon"[5] [10, p. 111]. Besides having all the required physical properties to carry heat, Freon had a very interesting *chemical* property: It was chemically inert. Because explosions or intoxications are nothing but the fruit of chemical reactions, an inert gas cannot detonate nor intoxicate since by definition, it cannot participate in any chemical reaction. This is what being inert is all about.

Freon was therefore useful, inoffensive, and, on the top of it, cheap. Manufactured by the American chemical company DuPont (freon is a DuPont trademark), it was soon renamed "Freon-12" or "CFC-12," to differentiate it from all the other gases that could be synthesized in a similar way. The acronym "CFC," standing for "chlorofluorocarbons" ended up referring to a whole family of gases, all related to

---

[5] Its full chemical name is "dichlorodifluoromethane," formula CCl_2F_2. The name comes from f(luorine) + re(frigerant) + on.

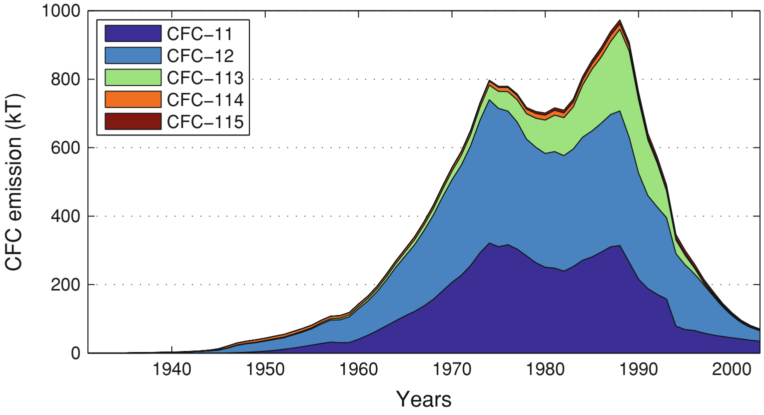

Fig. 11.2 Cumulative emissions for the main chlorofluorocarbons (CFC). The period 1930–1974 sees a nearly exponential growth. The potential dangers of CFC were discovered in 1974 and the Antarctic ozone hole in 1985. *Source*: Alternative Fluorocarbons Environmental Acceptability Study (www.afeas.org)

Freon-12. With so many good points, CFC production grew nearly exponentially until 1974, as evidenced by Fig. 11.2.

The CFC chronicles up to that point are quite similar to the fossil fuels' ones. Both have tremendous advantages, and both quickly turned "viral," as it is said today of successful *YouTube* videos. The second acts of their story are equally similar as CFC turned out to generate a pollution of its own kind: In 1974, Mario Molina and Franck Rowland warned that CFC emissions could harm the ozone layer [11].

The ozone molecule, symbol O_3, is made up of three oxygen atoms. Its presence in the upper atmosphere toward 25–35 km is highly desirable as it blocks damaging solar radiations. Molina and Rowland noticed that although inert, CFC molecules could be dissociated by sunlight and release chlorine atoms capable of altering the natural ozone cycle and reduce its concentration. Soon after, in 1985, the predicted effect was definitely observed over the Antarctic [12]. The so-called ozone hole was not really a "hole," with no ozone at all. It was only a substantial ($\sim$20 %) depletion of the ozone concentration over the Antarctic at that time. Incidentally, our two scientists were awarded the 1995 Nobel Prize in Chemistry for their finding.

When compared to the present difficulties in cutting fossil fuels, the political reaction was surprisingly quick. Granted, there were people to deny CFC dangers [13], but the end result was spectacular. Figure 11.2 clearly shows how emissions were dramatically cut after Molina and Rowland's 1974 article. CFC was banned in the USA in 1978. Then came the Montreal Protocol, signed in 1987. Ratified[6] by

---

[6] When a State signs a treaty, the signature is subject to ratification, acceptance, or approval. The State has not expressed its consent to be bound by the treaty until it ratifies it. See www.europatientrights.eu/countries/signing_and_ratifying_a_treaty.html.

all UN countries,[7] it provoked the spectacular emission drop observed from 1988 on Fig. 11.2.

Today, the ozone concentration is slowly coming back to its pre-CFC level and should recover around 2070 [14]. How then was it so “easy”? To start with, the global annual market for refrigerants is but a few $ billion,[8] while the global oil market typically moves about 30 Gbarrel times $100+ each, that is, more than $3,000 billion. Moreover, *alternatives* to CFC were quickly provided through the hydrofluorocarbons (HFC).[9] These are families of gases mimicking most of the CFC properties, but with a severely reduced ozone depletion potential. Finally, the fact that alternative gases were first provided by DuPont [15], the first producer of the phased out CFC, may not be irrelevant.

References

1. O. Pétré-Grenouilleau, *Les traites négrières: Essai d’histoire globale* (Gallimard Collection: Folio Histoire, Paris, 2006)
2. Aristotle, *The Politics* (University of Chicago Press, Chicago, 2010)
3. O. Wilde, L. Dowling, *The Soul of Man Under Socialism and Selected Critical Prose* (Penguin Books Limited, London, 2007)
4. V. Smil, *Energy Transitions: History, Requirements* (Praeger, Prospects, New York, 2010)
5. I. *Morris, Why the West Rules—for Now: The Patterns of History, and What They Reveal About the Future* (Profile Books, London, 2010)
6. Jean-François Mouhot, Past connections and present similarities in slave ownership and fossil fuel usage. Clim. Change **105**, 329–355 (2011)
7. D.B. Davis, *Inhuman Bondage: The Rise and Fall of Slavery in the New World* (Oxford University Press, Oxford, USA, 2006)
8. H. Ford, S. Crowther, *My Life and Work* (Library of American Civilization, Doubleday, New York, 1922)
9. C. Telfair, Some account of the state of slavery at Mauritius: since the British occupation, in 1810: in refutation of anonymous charges promulgated against government and that colony. J. Ridgway, 1830.
10. J.R. McNeill, *Something New Under the Sun: an Environmental History of the Twentieth-Century World* (The Global Century Series. W. W Norton, New York, 2001)
11. M.J. Molina, F.S. Rowland, Stratospheric sink for chlorofluoromethanes: chlorine atomic-catalysed destruction of ozone. Nature **249**, 810–812 (1974)
12. J.C. Farman, B.G. Gardiner, J.D. Shanklin, Large losses of total ozone in Antarctica reveal seasonal clox/nox interaction. Nature **315**, 207–210 (1985)
13. S. Roan, *Ozone Crisis: The 15-Year Evolution of a Sudden Global Emergency* (Wiley Science Editions, Wiley, 1990)

---

[7] In contrast, the Kyoto protocol on GHG emissions was signed but not ratified by the USA.

[8] See for example *Grappling With the Cost Of Saving Earth’s Ozone*, Malcolm W. Browne, The New York Times, July 17, 1990.

[9] See the Web page of the “Alternative Fluorocarbons Environmental Acceptability Study,” www.afeas.org.

14. P.A. Newman, E.R. Nash, S.R. Kawa, S.A. Montzka, S.M. Schauffler, When will the Antarctic ozone hole recover? Geophys. Res. Lett. **33**, L12814 (2006)
15. B. Smith, Ethics of Du Pont's CFC strategy 1975–1995. J. Bus. Ethics **17**, 557–568 (1998)

Conclusion

12

So what do we do now? Clearly, this is the first question that comes to mind at the end of this book. This is also the first question my students ask at the end of the course. Now that we have understood the problem and "studied medicine" (remember the preface), which plans could we lay out for the near, mid-, and long terms to 1/make sure we keep global warming within reasonable limits and 2/shift to non-fossil energy sources without disrupting our society?

The number of answers is virtually infinite and involves economy, sociology, politics, ethics…well, every single field of human knowledge. Among the famous proposals is the 2004 "Stabilization Wedge Game" set forth by Stephen Pacala and Robert Socolow, from Princeton University.[1] The goal of the game is to show that CO_2 concentration can be stabilized toward 500 ppm using only today's technology, by implementing vigorous worldwide programs in nine areas (energy efficiency, decarbonization of power, of fuels…).

More recently, the UN run Sustainable Development Solutions Network[2] initiated its Deep Decarbonization Pathways Project, to "prepare national, long-term deep decarbonization pathways that are consistent with the 2 °C target in the countries and regions accounting for over 75 % of global greenhouse gas emissions."

You can also turn to the IPCC. The reports from Workgroups II and III are about one thousand pages long, freely downloadable documents, entitled respectively, "Climate Change 2014: Impacts, Adaptation, and Vulnerability" and "Climate Change 2014: Mitigation of Climate Change." I will therefore not address the question "what do we do now?," for it is clearly impossible to summarize these works in a conclusion. Instead, I prefer to refer the reader to these treaties.

Still, I think it may be useful to conclude addressing a diffuse feeling I have repeatedly spotted among my students by the end of the course, and that you may be sharing. It goes more or less like this: "granted, the numbers on Table 6.3 are impressive. But for sure, 10 or 20 years from now, an unexpected technological

---

[1] S. Pacala and R. Socolow, *Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies*, Science, 305, 968, 2004.

[2] See www.unsdsn.org.

A. Bret, *The Energy-Climate Continuum*, DOI: 10.1007/978-3-319-07920-2_12

breakthrough will save us all." In other words, the laws of physics told us that there is no easy substitute to fossil fuels. But could we still have big surprises? Many students of mine are convinced that "we will come up with something." Are they right? Can technology fix everything?

At the risk of being completely proved wrong by the future, I would like to make the case that my students' hopes are utopian. To start with, such a faith in technology is unfounded because the problem is far from being 100 % technological. In a famous 1968 article,[3] for example, Garrett Hardin noted that "the population problem has no technical solution; it requires a fundamental extension in morality." Indeed, the amount of people we will have to power is an important part of the equation, as we saw in Chap. 8 with our toy model. But this is not an issue technology alone can solve. Implanting large-scale energy policies, even if you do have them, is not just a technological issue. It is also at least a political, economical, social, and ethical issue. The bottom line here is that technology is only a tiny part of the road toward the post-fossil world.

But there is another reason why we are unlikely to have big, unexpected technological surprises, making things easier than Table 6.3 seems to tell. Let me start with an illustration. I recently watched the classical science fiction movie *Blade Runner*. It was released in 1982, and the action takes place in 2019. From my 2013 vantage point, it was very interesting to check which foreseen progresses had been achieved, and which had not. The movie features thick cathode ray tube TV screens, which are no longer there today. Also, phones allowing you to see who you talk to, which are definitely there. Finally (the list is much longer), flying cars far from being a reality in 2013.

In a sense, it was no too difficult to understand why some futuristic items of this 30 years old movie were now reality, while others were not. The basic scientific knowledge required to make a video phone was already known in 1982. Maxwell's equations were understood by then, and the advent of video conferences was just a matter of time. But the kind of wingless flying cars we see in *Blade Runner* requires something like "anti-gravity." And here, 1982 physics, and 2013 too, tell you "sorry, it will not work." On the one hand, the fundamental laws of nature, ruling the four forces we saw in Sect. 2.5, do not have anything against broadcasting sound, and image too. But on the other hand, the very same laws tell you cannot have something "not falling." It is therefore no surprise if floating cars are still lacking our 2013 world.

The reason why we should not expect technological miracles is because we know the four forces, we know how they act and what can be expected, or not, from them. It does not mean we understand everything. We know for sure, for example, that there must be a mother theory unifying gravity and quantum mechanics. But such a theory will have predictions departing from her daughters only at incredibly high energies, nowhere to be found in the industry. Even the largest state-of-the-art particles accelerator, the LHC in Geneva, falls incredibly short.

---

[3] G. Hardin, *The Tragedy of the Commons*, Science, 162, 1243, 1968.

The amount of energy needed to take the electron out of the hydrogen atom is 13.6 eV, and there is nothing you can do about it. The amount of energy needed to take the proton out of a deuterium nucleus is 1.1 MeV, and again, there is nothing you can do about it. Technology is not going to change these numbers. Potential energy, whether gravitational, electromagnetic, or nuclear, is going to read the same for the next million years. Kinetic energy as well. And we could check in Chap. 6 how the capabilities of such and such energy source eventually boils down to such numbers.

The reason why we should not expect to find something brand new in store is precisely because we now know what is in store. We made the inventory, leaving no drawer overturned, and Fig. 2.2 is what we found. Hoping a fifth fundamental force will come to the rescue is extreme wishful thinking. Of course, efficiencies will get better here and there, but the orders of magnitude exposed in Table 6.3 are not going to change. Remember they do not even account for the EROI discussed in Sect. 7.1, nor for the losses in storage.

At some point of the movie *Apollo 13*, some astronauts find themselves nearly poisoned by the high CO_2 level in their spaceship. Assisted by a team of ground-based engineers, they proceed to a clever bricolage to have square filters work with round receptacles. Clearly, they must do with at-hand materials. While cruising somewhere between the earth and the moon, they know they can only count on the content of their module. Like we ought to, they must face the facts: they are alone in space, and the solution must come from something they already know. We are quite like the astronauts in the movie. We will have to solve our energy problems with the physics we know. There will not be unexpected fundamental surprises. There will not be a fifth force, and the known ones are going to keep acting the way they act today. There is simply nowhere else to go.

Yet, if the magnitude of the challenge before us must not be underestimated, and I think this book contributes to this point of view, some elements are definitely in place to give hope. I just would like to mention some of them, while Jared Diamond lists a few more at the end of *Collapse: How Societies Choose to Fail or Succeed*. Our situation demands considerable changes of technology, and also of attitude, in a surprisingly short amount of time. It that hopeless? Not necessarily.

To start with, the problem is in our hands. It is not something we cannot control, like the giant solar flare which destroys the earth in the 2009 movie *Knowing*. And the reason why it is in our hand is precisely because we are the ones causing it.

Second, the needed technology is ready. In their 2004 paper where they presented a portfolio of measures “to solve the carbon and climate problem for the next half-century,” Pacala and Socolow insisted that “every element in this portfolio has passed beyond the laboratory bench and demonstration project; many are already implemented somewhere at full industrial scale.” What about the timescale issue. Is it too short for the changes involved? Well, the number of cell phone subscriptions per 100 people worldwide has jumped from virtually nothing in 1985, to 90 in 2013.[4]

---

[4] See www.worldbank.org.

Who could have said 30 years would be enough to equip nearly every single human being on the planet and build the required network? Yet, it has been done.

Third, large-scale, considerable changes of attitude have already been achieved within the last decades in some parts of the World. In 1870, war between France and Germany already cost 200,000 lives. 45 years later, World War I killed 19 million people. Only 20 years later, World War II killed another 60 million. Then, shortly after 1945, the very leaders who had been involved in World War II decided things could not go on like this and ushered in the European Union. European countries accepted giving up part of their national sovereignty, to render war between them nearly impossible. It clearly does not go without frictions. But as I write these lines in 2014, I belong to the first Western European generation in several centuries, who has not been involved in any war against another major European power.

So we need a formidable shift in energetic technology and mindset, in a short amount of time. The required technology may be advanced, but it is not out of reach. The timescale is challenging, but not necessarily never-been-done-before. The change of mindset is considerable, but apparently attainable when a lot is at stake. The road map may be unclear, but it should not be a reason to stall. After all, the road may never be clear until we get to the end, and the poet may remain our best guide,

> *Caminante, son tus huellas el camino, y nada más; caminante, no hay camino se hace camino al andar. Al andar se hace camino, y al volver la vista atrás se ve la senda que nunca se ha de volver a pisar. Caminante, no hay camino, sino estelas en la mar.*
>
> *Wanderer, your footsteps are the road, and nothing more; wanderer, there is no road, the road is made by walking. By walking one makes the road, and upon glancing behind one sees the path that never will be trod again. Wanderer, there is no road-Only wakes upon the sea.*
>
> Antonio Machado (1912). [5]

---

[5] Translation, Betty Jean Craige in *Selected Poems of Antonio Machado* (Louisiana State University Press, 1979).

Notations and Units

A

A.1 Powers of Ten

When measuring the earth surface S_E, for example, you have to write down a huge number. If you want to express the result in square meters, you get

$$S_E = 514{,}718{,}540{,}364{,}152 \text{ m}^2.$$

Even in square kilometers, you still have,

$$S_E = 514{,}718{,}540 \text{ km}^2.$$

In order to save time, room, ink, and calculation mistakes, scientists abbreviate the writing in the following way: First, you set to zero the digits you do not care about. There is not much relative difference (less than 1 %) between 514,718,540 and 514,000,000. Then, you write the latter 5.14×10^8, where 8 is the number of digits you had after the first one, "5". So the second number above is 5.14×10^8 and the first one 5.14×10^{14}.

What can be done for big numbers can be done for small ones. What is the mass m_p, in kilograms, of a proton? The answer is,

$$m_p = 0.000{,}000{,}000{,}000{,}000{,}000{,}000{,}000{,}001{,}6 \text{ kg}.$$

It is far shorter to write $m_p = 1.6 \times 10^{-27}$, where 27 is the number of zeros between the point and the "1", plus 1. Using this technique, you can write $0.25 = 2.5 \times 10^{-1}$, $0.067 = 6.7 \times 10^{-2}$ and so on. This is not a mere convention. 10^{-1} is equal to $1/10$, and $1/10$ is 0.1, *really*.

What *is* a convention is the way these powers of ten have been labeled. One "kg" are 1,000 g, and one "km" are 1,000 m. Therefore, "kilo" stands for one thousand units of whatever you want. In the same way, the prefix "mega" stands for one million units, "giga" for one billion, and "tera" for one thousand billion. Their symbols are "k", "M", "G", and "T", respectively. These data are summarized below.

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

Prefix	Symbol	$10^?$	Quantity
Kilo	k	10^3	One thousand
Mega	M	10^6	One million
Giga	G	10^9	One billion
Tera	T	10^{12}	One thousand billion

A.2 Units

There are many ways of expressing the same length, namely meters, yards, miles, feet, cubits, and so on. There are also many ways of expressing energy and temperature. Temperatures can be expressed in degrees Celsius (°C) or degrees Kelvin (K). The two scales are just shifted by 273°. That is,

$$\text{T(degrees K)} = \text{T (degrees C)} + 273.$$

Why introducing degrees "Kelvin"? Simply because this is the fundamental unit of temperature in physics. So when a temperature appears in a physical formula, you need to make sure it is in Kelvin before you calculate.

Regarding *energy*, there are even more ways of measuring it. Energy is a universal concept, and many scientific communities use it, each one with some units adapted to its problems. Here are the ones used in this book:

- Physicists usually use *Joules* as a unit, symbol "J". This is the fundamental unit for energy. A mass of $m = 2$ kg at velocity $v = 1$ m/s (3.6 km/h) has a kinetic energy $\frac{1}{2}mv^2 = 1$ J.
  Note that this formula gives a number of Joules if and only if you plug mass and velocity in kg and m/s, respectively. These units pertain to the so-called International Units System, where units have been designed to work together properly in such formulas.
- Chemists, for example, are interested in energy at the molecular level. They deal with far smaller amounts of energy and use a unit called the *electron volts*, symbol "eV". One eV equals 1.6×10^{-19} J.
- People dealing with electricity frequently use *watt-hours*, symbol "Wh". One "Wh" is the energy released by a source of power 1 Watt during 1 h. It delivers therefore 1 J each second, during 1 h. Thus, 1 Wh = 3,600 J.
- When dealing with fossil fuels, it is common to express their energy content in *ton oil equivalent*, symbol "toe." One "toe" is the energy released by the combustion of 1 ton of oil. In Joules, we have 1 toe $= 42 \times 10^9$ J or 42 GJ.
  Less frequent, the *ton coal equivalent* amounts to 30 GJ.

Finally, gases concentration in the atmosphere are usually expressed in “ppm”, or “part-per-million”. It is like talking about percent, but replacing “cent,” i.e., hundred, by million. A CO_2 concentration of “1 ppm” means that out of 1 million L of atmosphere, 1 L is pure CO_2.

Wind Power Calculations

B

The first step toward establishing Eq. (6.2) is to explain the Betz limit. While the windmill takes its energy toll, the wind slows down. Let us denote V_1 the post-windmill velocity, with of course $V_1 < V$. The energy subtracted in a time t by the machine reads $\frac{1}{2}M(V^2 - V_1^2)$ because the same wind mass M had velocity V before it went through the rotor, and V_1 after. Still, we cheat a little bit here because the wind velocity before is not V all the way to the rotor. Why? Because if the velocity has to jump from V before the rotor, down to V_1 after, it cannot do so abruptly. There is necessarily a transition region around the rotor, where the velocity smoothly goes from V down to V_1. We will thus do the following: keep the formula for the subtracted energy, but write M as $M = \rho S \frac{1}{2}(V + V_1)t$. In other words, we consider the wind velocity at the rotor is simply half way.

This kind of reasoning is extremely frequent in physics. You take a complicated problem and simplify it as much as you can. You solve it, understand it, and then turn to the real case. Doing so, you follow the advice Nobel Prize winner Eugene Wigner gave to his PhD student and *double* Noble Prize winner John Bardeen ([1], p. 54),

> [Reduce the problem] to the simplest possible case, so you can understand that before you go on to something more complicated. Reduce a problem to its bare essentials, so that it contains just as much of the physics as necessary.

Coming back to our windmill, the subtracted energy now reads

$$E = \frac{1}{2}\rho S \frac{1}{2}(V + V_1)t(V^2 - V_1^2),$$

allowing to define the *power coefficient* C_p,

$$\frac{E}{\frac{1}{2}\rho S V^3 t} = C_p(x), \quad \text{with} \quad x = \frac{V_1}{V} \quad \text{and} \quad C_p(x) = \frac{1}{2}(1 + x)(1 - x^2). \tag{B.1}$$

Because $\frac{1}{2}\rho S V^3 t$ is the available wind energy before the windmill, the left-hand side is nothing but the relative amount of energy gained by the rotor. And the right-hand side is now a universal function of the ratio $x = V_1/V$, where x is expected

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

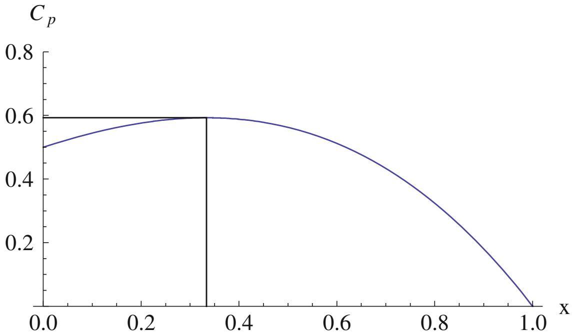

Fig. B.1 Power coefficient $C_p(x)$ defined by Eq. (B.1) for $0 < x < 1$. A maximum is reached for $x = 1/3$, with $C_p(1/3) = 16/27 \sim 59\ \%$

to vary from 0 to 1. This function if plotted on Fig. B.1 and a little derivation with respect to x shows it reaches a maximum for

$$x = \frac{1}{3}, \text{ with } C_p\left(\frac{1}{3}\right) = \frac{16}{27} \sim 59\ \%. \tag{B.2}$$

This is the so-called Betz limit, found by Albert Betz in 1920.[1] Surprisingly, the reasoning above is not too simple to survive a more detailed analysis. In the real world, the maximum efficiency is rather lower, namely toward 30 % ([3], p. 184). We shall thus consider $C_p = 0.3$ in the sequel. Neglecting the energy losses during the conversion of mechanical energy to electricity, we finally come to the power delivered by a windmill within a *constant* wind at velocity V,

$$P(V) = \frac{1}{2} C_p \rho \pi R^2 V^3. \tag{B.3}$$

Up to now, we are in a world where the wind speed and direction are constant. We will now deal with both. Given the accuracy requirements on our analysis, the order is irrelevant and we start accounting for wind speed variations.

Wind speed is not constant, but it is not unpredictable either. Suppose you monitor the wind speed at a given location during one year. Out of the 525,600 min a year counts, you check the number of minutes during which the wind blows at 1 m/s. Then, you do the same for 2, 3 m/s, and so on. If you divide each minute number by 525,600, you get the probability $f(V)$ of having such and such wind speed. Because there were surely few minutes with no wind at all, $f(V)$ must come to 0 for small velocities. Also, there were few, if any, minutes with beyond hurricane-like wind. This means $f(V)$ must equally come to 0 for large velocities. While wind speed seems to vary without any pattern, the probability $f(V)$ definitely follows one. Experts in this matter found it generally adjusts quite well to the so-called Weibull distribution [4],

$$f(V) = \frac{\pi}{2} \frac{V}{V_m^2} \exp\left(-\frac{\pi V^2}{4V_m^2}\right), \tag{B.4}$$

---

[1] See [2] for an historical account of the finding.

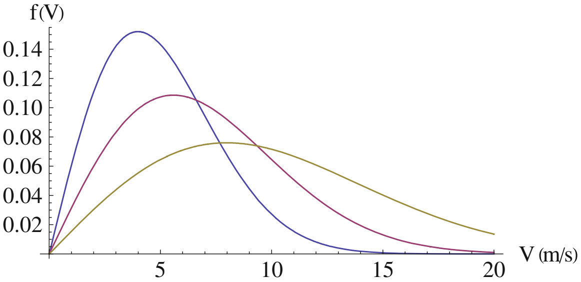

Fig. B.2 Wind speed distribution (B.4) for $V_m = 5, 7$, and 10 m/s. All curves peak at $\sqrt{2/\pi}\ V_m \sim 0.8\ V_m$

where V_m is by definition the mean wind speed at this location.[2] The wind distribution (B.4) is plotted on Fig. B.2 for various mean speeds V_m. The most probable speed, $\sqrt{2/\pi} V_m \sim 0.8 V_m$, slightly differs for the mean speed V_m.

Accounting for wind velocity variations can be done the following way. During all the minutes where the wind blew 1 m/s, you use Eq. (B.3) with $V = 1$ m/s. Now, you add all the minutes with a 2 m/s wind, plugging $V = 2$ m/s in Eq. (B.3) and so on. Mathematically, you perform the following calculation,

$$\int_0^\infty P(V) f(V) \mathrm{d}V = \frac{6}{\pi} P(V_m), \tag{B.5}$$

which gives therefore the power delivered, *accounting* for wind speed variation,[3] where $P(x)$ is the function defined by Eq. (B.3).

Is that all? Not yet. Even if we just accounted for wind speed variations, we still ignore wind *direction* variations. Though wind turbines have a system to fix wind misalignment, the so-called yawing, associated losses cannot be completely avoided for two reasons: 1/rotating a 100 m wide rotor takes a toll on the energy produced and 2/wind can change direction too quickly anyway. As a result, the yaw is not 0. It is only *statistically* distributed around 0. Suppose a gaussian-like distribution $g(\theta)$,

$$g(\theta) = \frac{\exp(-\theta^2/\theta_0^2)}{\theta_0 \sqrt{\pi} \mathrm{Erf}(\pi/\theta_0)}, \quad \text{so that} \int_{-\pi}^{\pi} g(\theta) \mathrm{d}\theta = 1, \tag{B.6}$$

---

[2] You can check that $\int_0^\infty f(V) V \mathrm{d}V = V_m$. In reality, the Weibull distribution has more free parameters than Eq. (B.4), which is just a particular case of the general Weibull function. Equation (B.4) is sometimes called the "Rayleigh distribution."

[3] For safety reasons, real windmills have their power varying like V^3 only up to the so-called rated wind speed, V_r. Power curve is then flat until a cutoff wind speed V_c, after which the turbine is stopped. The error committed assuming the V^3 scaling extends up to infinity is less than 15 % if $V_r > 1.8\ V_m$ (thanks to the rapidly decreasing exponential after $V = V_m$). This is usually the case, simply to get the most out of the turbine.

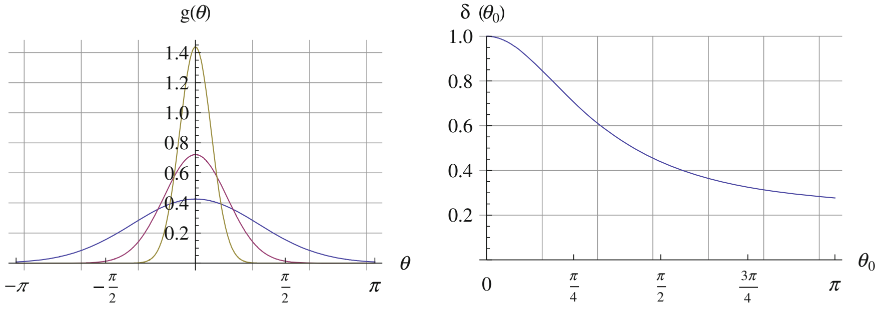

Fig. B.3 *Left* Yaw statistical distribution $g(\theta)$, Eq. (B.6), for $\theta_0 = \pi/8, \pi/4, \pi/2$ (from high to low). *Right* Loss factor $\delta(\theta_0)$, Eq. (B.7)

where Erf(x) is the error function, θ the angle with the main wind direction and θ_0 a free parameter determining the amplitude of the variation.[4] For a wind at angle θ, the amount of fluid passing through the rotor is reduced by a factor $\cos\theta$. Blades efficiency also drops, by $\cos^2\theta$, because they are optimized for upfront wind, not side wind. Average efficiency drops therefore by a factor[5] ([3], p. 98),

$$\delta(\theta_0) = \int_{-\pi/2}^{\pi/2} g(\theta)\cos^3\theta \mathrm{d}\theta. \tag{B.7}$$

Figure B.3 plots $g(\theta)$ in terms of θ_0, and the factor $\delta(\theta_0)$ above for $\theta_0 \in [0, \pi]$ ($\pi/4 = 45°$). For a wind direction statistical offset of 45°, the loss factor is $\delta(\pi/4) = 0.77$.

The power coefficient C_p in Eq. (B.3) is eventually significantly lower than the Betz limit. For face-on winds, a realistic value is 0.3 rather than 0.59. Then, yawing brings an additional, say, 0.7 factor, taking down C_p to $0.3 \times 0.7 = 0.21$. On the top of that, energy is lost when rotating the turbine, converting the mechanical energy to electricity and driving the electricity to the grid. We will eventually consider $C_p = 0.3 \times 0.7 = 0.2$ in the averaged power Eq. (B.3).

Finally (at last), we need to go from the averaged power to the annual energy produced. Wind turbines are now extremely reliable, with annual downtime shorter than a week ([5], p. 552). So we simply multiply Eq. (B.5) by the number N_s of seconds in a year and eventually find,

$$E_y = \frac{6}{\pi}P(V_m)N_s = \frac{6}{\pi}\frac{1}{2}C_p\rho\pi R^2 V_m^3 N_s. \tag{B.8}$$

Taking for the density of air $\rho = 1.2$ kg/m^3, setting $C_p = 0.2$ and $N_s = 3.15 \times 10^7$ yields Eq. (6.2).

---

[4] From Eq. (B.6), the turbine spends at least 85 % of its times with a yaw $< \theta_0$ because $\int_{-\theta_0}^{\theta_0} g(\theta)\mathrm{d}\theta > 0.85$.

[5] Integration if performed over $[-\pi/2, \pi/2]$, as alignment cannot be so bad the turbine is *against* the wind.

References

1 L. Hoddeson, V. Daitch, True Genius: *The Life and Science of John Bardeen: The only Winner of Two Nobel Prizes in Physics*. (Joseph Henry Press, 2002)

2 V.L. Okulov, G.A.M. van Kuik, The Betz-Joukowsky limit: on the contribution to rotor aerodynamics by the British, German and Russian scientific schools. Wind Energy **15**, 335 (2012)

3 T. Burton, *Wind Energy Handbook*. (Wiley, Hoboken, 2001)

4 K. Conradsen, L.B. Nielsen, L.P. Prahm, Review of Weibull Statistics for Estimation of Wind Speed Distributions. J. Appl. Meteorol. **23**, 1173–1183 (1984)

5 E.L. Petersen, Wind Energy for the Next Millennium: Proceedings of the European Wind Energy Conference, Nice, France, 1–5 March 1999. (James & James, 1999)

C

ABC of Nuclear Physics

At the heart of an atom lies its nucleus. The nucleus is uniquely determined by the number of protons and neutrons that form it. The biggest one we know so far holds 118 protons and 176 neutrons. The hydrogen atom has just one proton in its nucleus. The helium atom, two protons and two neutrons. Carbon has six of each, iron 26 protons and 30 neutrons, etc. A common way of representing the existing nuclei is the "table of nuclides" pictured on Fig. 6.5 where the number of protons appears in the horizontal axis and the number of neutrons on the vertical one.[6]

Because the number Z of protons imposes an equal number of electrons orbiting around the nucleus, Z also determines the chemistry of the element. For a given Z, several nuclei can exist with a different number of neutrons N. While both protons and neutrons stick together through the nuclear force, protons still repel each other through the Coulomb interaction, even inside the nucleus. This explains why existing nuclei tend to have more neutrons than protons: The neutrons help the mixture hold together. On each side of the squared region are boundaries beyond which nuclei cannot exist at all. Take a nucleus right on the upper boundary and give it one more neutron (one more proton if you are on the lower boundary), it will just refuse to take it. In fact, the neutron in excess will spontaneously drip out of the nuclei, which is why the frontier is called the "drip line." The upper drip line is the "neutron drip line," and the lower one the "proton drip line" [2].

Some nuclei are stable, others are unstable. While nuclei beyond the drip lines cannot exist at all, unstable nuclei can, but only for a limited amount of time. Carbon-14 is one of them. If you take 1,000 C-14 atoms and wait some 5,730 years, about half of them will have changed to nitrogen. On Fig. 6.5, only the black squares represent stable nuclei. The other cells stand for unstable nuclei which can decay in a number of ways,[7]

---

[6] Nuclear physicists think there could be a so-called Island of Stability further up in the table, around 118 protons and 184 neutrons [1].

[7] The γ decay is not listed. See the nuclear fission part of Sect. 7.3.

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

- β^- decay: A neutron in the nucleus changes into a proton. An electron and an antineutrino are ejected.
- β^+ decay: A proton in the nucleus changes into a neutron. A positron and a neutrino are ejected.
- α decay: Two protons and two neutrons, that is, an helium nucleus, are ejected from the nucleus.
- Fission: The nucleus splits into two parts. Such nuclei are called “fissile,” like uranium-235 pictured on Fig. 6.5.

Noteworthily, Fig. 6.5 shows how nuclei tend to decay in such a way that they move toward stable cells. Though stable nuclei as heavy as bismuth-209 with 126 neutrons and 83 protons exist,[8] large nuclei tend to look for a quick diet. In nuclear physics, this is the α decay, when you move down the chessboard two cells in each direction.

C.1 Getting Energy Out of Nuclear Reactions

Now that the stage has been set, we can wonder about getting energy out of nuclear reactions. The pattern is exactly the same than for the *chemical* reactions described in Sect. 2.5. A nuclear reaction can be pictured as a process during which a bunch of nuclei are dismantled, before they get reassembled into a bunch of different nuclei. A very useful concept to further discuss our problem is the one of “binding energy per nucleon,” E_B. For a given nucleus, this is the average energy needed to take out either one proton or neutron.[9] As it appears, the word “nucleon” stands for either a proton or a neutron.

It is pretty much like an investment. A good one gives dividends, providing you invested something. So you need first to invest in the right bonds, before you reap what you sowed. Here, you invest energy and hope to get more in return.

Suppose you start with a 100 nucleons nucleus. Its binding energy per nucleon is, say, $E_B = 1$ MeV (millions of eV. Numbers are not accurate). So it costs $100 \times E_B = 100$ MeV to dismantle it. You split it into two smaller nuclei N_1 and N_2. N_1 inherits 40 nucleons, and N_2 the rest, namely 60. Suppose N_1 and N_2 have the binding energies per nucleon $E_{B1} = 1.5$ and $E_{B2} = 2$ MeV, respectively. Forming N_1 and N_2, you are thus given back

$$40 \times E_{B1} + 60 \times E_{B2} = 40 \times 1.5 + 60 \times 2 = 180 \text{ MeV}.$$

---

[8] This is the record. With a half-life larger than 10^{19} years (the universe is less than 10^{11} years old), it can be considered stable [3].

[9] It is a little easier to take out one proton because the other protons help you by repelling it. But the difference is small, and we are talking average. Also, it is obvious that taking a nucleon out of the nucleus *must* cost something. The nucleus would not hold together otherwise.

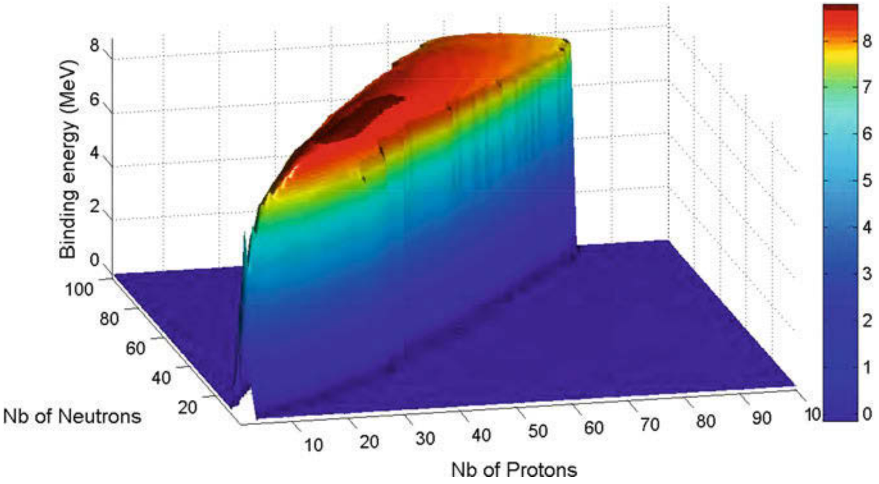

Fig. C.1 Binding energy per nucleon of know nuclei, in millions of eV (MeV)

You have won 180 − 100 = 80 MeV. The moral of this fission story is that for a fission reaction to release energy, the binding energies per nucleon of the products must be higher than that of the initial nucleus. You must fission toward higher E_B's.

Suppose now you start with two nuclei N_1 and N_2, with $E_{B1} = 1$ MeV and $E_{B2} = 2$ MeV for example. N_1 has 5 nucleons and N_2 has 10. You merge them into one single nucleus N, which holds therefore $5 + 10 = 15$ nucleons with say $E_B = 4$ MeV. To dismantle N_1 and N_2, you had to "pay," energy wise, $5 \times E_{B1} + 10 \times E_{B2} = 25$ MeV. And when the final product N forms, you receive $15 \times E_B = 60$ MeV. Here again, you won. The end gain is 60 − 25 = 35 MeV. The moral of this fusion story is that for a fusion reaction to release energy, the binding energy per nucleon of the end product must be higher than that of the initial nuclei. You must fusion toward higher E_B's.

Without a doubt, you will have noticed the two morals are the same. Whether you are doing fission or fusion, the fruit(s) of the reaction must have higher E_B than the initial element(s). If you think about it, everything comes down to the fact that the number of nucleons is conserved during the reaction.

So, can we envision exothermic nuclear reactions? Fig. C.1 shows the binding energy per nucleon E_B in terms of the number of protons and neutrons for most of the nuclei displayed on Fig. 6.5. When discussing chemical reactions in Sect. 5.3, numbers were in electron volts (eV). Here, they are in *millions* of eV. Nuclei are incredibly more difficult to unbind than molecules. The main point of this plot is that E_B clearly reaches a peak for nuclides having about $Z = 30$ protons and $N = 35$ neutrons. Nickel-62 ($Z = 28$, $N = 34$) and Iron-56 ($Z = 26$, $N = 30$) are there, the two most stable nuclei. For heavier nuclides, E_B goes down, all the way to the end of the table. And for lighter ones, it goes down as well. Therefore, there are *only* two ways of obtaining exothermic nuclear reactions: either by splitting a nucleus heavier than Nickel-62 or Iron-56 or by merging two lighter than these. This is all. Fission or Fusion.

References

1 Daniel Clery, Which way to the island? Science **333**(6048), 1377–1379 (2011)

2 J. Erler, N. Birge, M. Kortelainen, W. Nazarewicz, E. Olsen, A.M. Perhac, M. Stoitsov, The limits of the nuclear landscape. Nature **486**, 509 (2012)

3 P. de Marcillac, N. Coron, G. Dambier, J. Leblanc, J.-P. Moalic, Experimental detection of α-particles from the radioactive decay of natural bismuth. Nature **422**, 876–878 (2003)

Index

A
Albedo, 39, 42, 44, 45, 66, 75
Anthropogenic emissions, 32, 48–50
Atmosphere, 15, 26, 31, 32, 35, 37, 41, 42, 44–46, 48–51, 64, 66, 141
Average temperature, 35, 41, 44, 52, 53

B
Batteries, 61, 101
Becquerel, 108
Binding energy, 82, 84
Biofuels, 66, 74, 76–79, 92, 99
Biomass, 4, 61, 74, 78, 79, 119, 121
Brazil, 66, 121
British Petroleum, 13, 98

C
Carbon, 15, 16, 19, 30–32, 48–50, 64–66, 78, 118, 119, 121
Carbon dioxide, 13, 32, 50
Carbon emissions, 31, 49, 63, 64, 121
Carbon sequestration, 63, 118
CFC, 145–147
Chernobyl, 108–111
Climate change, 3, 9, 12, 13, 16, 35, 51
Climate modeling, 41, 46
Climate science, 9, 13, 18, 35
Coal, 5, 15, 18, 25, 30–32, 40, 53, 61, 78, 83, 98, 104, 121, 125, 142, 143, 145
Cold fusion, 92
Collapse, 92, 126, 129, 130, 135
Combustion reactions, 22, 49, 61
Complex societies, 126
Confinement time, 86, 87, 90
Conventional oil, 25, 27, 40, 99
Coulomb force, 85
Coulomb hill, 85, 92
Cryosphere, 39, 51

D
Dam, 59, 81, 101, 106
Declining marginal return, 127, 129
Deforestation, 50, 64, 118, 137, 138
Denmark, 71
Deuterium, 63, 64, 85, 89, 91, 92, 112
Drip line, 83

E
Earth, 14, 17, 18, 35, 36, 39–41, 44, 46, 48, 50, 53, 59, 67, 74, 75, 79, 80, 84, 86, 91
Easter Island, 125, 135, 137–139
Electric car, 19
Electricity, 14, 18–21, 64, 71, 80, 81, 91, 99, 100, 103, 119
Electromagnetic force, 20, 59, 60
Electron volts, 113
Emissions, 13, 31, 35, 51, 52, 64, 65, 106, 118, 146
Energy balance, 35, 41, 42, 45, 48, 62, 74, 82
Energy conservation, 16–18, 39, 66, 78
Energy consumption, 5, 75, 118, 129

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

Energy production, 14, 72–74, 76, 78, 81, 85, 92, 112, 113
Energy reservoirs, 20, 21, 59, 63
Energy return on investments, 97
Energy slaves, 5
Energy sources, 3, 7, 10, 19, 67, 69, 79, 92, 97, 99, 121
Energy storage, 22, 57, 61, 119
Experts, 9–11
Exponential growth, 27, 133, 146

F
Fatalities, 104, 105, 110
Fermi calculations, 15
Fossil fuels, 3, 5, 7, 18, 25, 30, 31, 49, 50, 53, 57, 64, 69, 79, 99, 104, 105, 117, 118, 121, 125, 146
France, 6, 35, 73, 76, 81, 100, 111
Fukushima, 109, 111
Fundamental forces, 20, 59

G
Geoengineering, 66, 67
Geothermal energy, 79, 80
Ghawar field, 26
Glaciers, 35, 37, 39
Global mean temperature, 35, 36, 46, 53
Gravity, 18, 20, 59, 74, 111
Greenhouse effect, 42–44
Greenhouse gases, 25, 32, 35, 48, 50, 63, 82
Greenland, 37, 38, 126
Gulf stream, 73

H
Half-life, 113
Heat capacity, 17, 40, 58
Hubbert model, 27–29
Hydrogen, 14, 18–20, 30, 59–63, 111, 112
Hydropower, 74, 80, 81, 99

I
Ice cores, 9, 47
Iceland, 80
Industrial revolution, 3, 31, 117, 142, 144
Inertial fusion, 91, 92, 112
Intermittency, 99, 101
International Energy Agency, 12, 25
IPCC, 12, 46, 51, 118
ITER, 89

J
James Lovelock, 37, 66
Jared Diamond, 126
Joseph tainter, 25, 126
Joules, 3, 4, 20, 39, 69, 71, 77, 80, 92, 97, 103
Jupiter, 79

K
Kinetic energy, 17, 20, 21, 57, 58, 69, 70, 73, 74, 79, 85, 104

L
Lawson criterion, 86–88, 90, 91
Liquid hydrogen, 62
Logistic curve, 133

M
Magnetic fusion, 88, 91
Mars, 44, 46, 50
Mauna Loa, 50
Methane concentration, 19, 50
Methane emissions, 65

N
Neptune, 43
Neutrino, 17, 108
Neutron, 63, 82, 84, 85, 113
NIF, 91, 92
Nitrogen, 49, 106
Nuclear energy, 79, 82
Nuclear fission, 82–84, 99, 107, 120
Nuclear force, 21, 82, 85
Nuclear fusion, 84, 112
Nuclear potential, 57, 92
Nuclear reactions, 22, 63, 82
Nucleus, 21, 22, 63, 82, 83

O
Oceans heat, 37
Oil discoveries, 26
Oil peak, 27–29, 83
Oil production, 7, 26, 28–30, 32, 99, 133
Orders of magnitude, 9, 14, 41, 43, 80
Ozone layer, 141, 146

P
Peer-reviewed journals, 10–13
Photosynthesis, 39, 49, 77, 78
Pluto, 44
Plutonium, 83
Potassium, 79
Potential energy, 17, 20, 21, 59, 60, 74, 82, 92, 98, 104
Primary energy, 7, 19, 25, 79, 121
Proton, 20, 63, 85

R
Radiation, 41, 42, 46, 48, 66, 86, 108, 111, 113
Radioactivity, 79, 107, 108, 112, 113
Roman empire, 125, 126, 131–133, 135, 136

S
Sea level, 35, 37, 39
Sievert, 108
Slavery, 125, 141–145
Solar constant, 47, 74, 75
Solar energy, 74–77, 99, 117, 132, 134
Stability, 108
Steam engine, 4, 5, 141, 143, 145
Sweden, 78, 79, 111

T
Tar sands, 25, 41, 98
Thorium, 79, 84
Three Mile Island, 109–111
Tore Supra, 89
Toy model, 117
Tritium, 63, 85, 89, 92, 112, 113

U
Unconventional oil, 3, 25, 40, 99
United Nations, 12, 16, 78
Uranium, 63, 82, 83, 85
Uranus, 43

V
Venus, 44, 46, 50
Volcanoes, 51, 80

W
Water turbines, 69, 73
Wikipedia, 12
Wind power, 15, 99–101
Woodfuel, 79, 92
World energy, 20, 69, 73, 75, 77, 79, 81, 85, 112

Z
Z-pinch, 92