3 Fossil Fuels

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

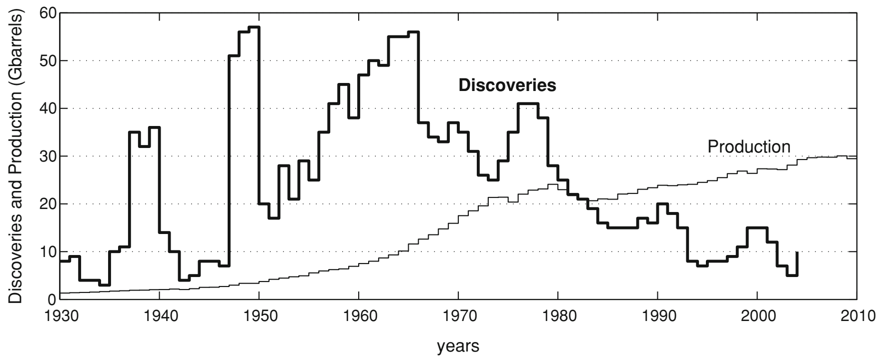

Fig. 3.1 *Bold curve* Oil discoveries worldwide by year in gigabarrels (Gbarrels) since 1930. The peak in 1948 is the discovery of the famous giant Ghawar field in Saudi Arabia. *Light curve* World oil production. Until 2004, 1,802 Gbarrels had been discovered, and 1,237 had been produced until 2011. *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

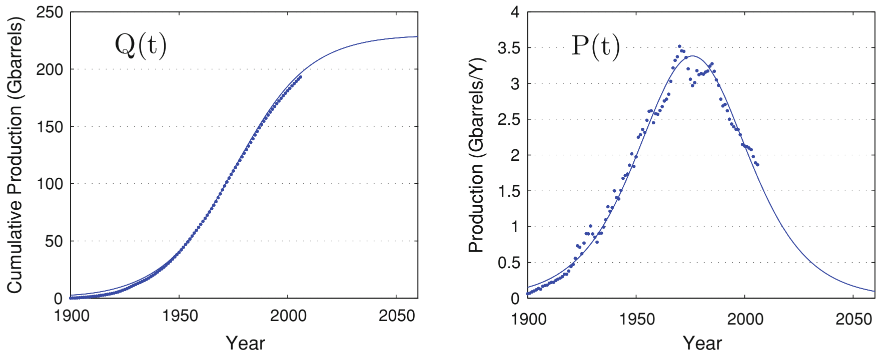

Fig. 3.2 *Plain lines* Hubbert model $P(t)$ and $Q(t)$ defined by Eqs. (3.2) and (3.1) with $a = 17$, $P_m = 13.5$ and centered around the year 1976. *Dots* US conventional oil production and cumulative production. *Source* Energy Information Administration

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,

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

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 $Q_\infty = aP_m$, 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 $\int_{-\infty}^{\infty} P(t)dt = aP_m$.

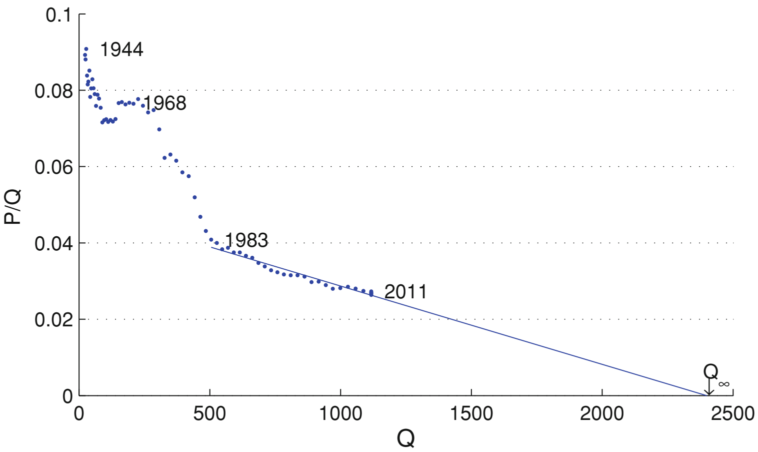

Fig. 3.3 Plot of P/Q versus Q for the real-world production numbers used in Fig. 3.1

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.

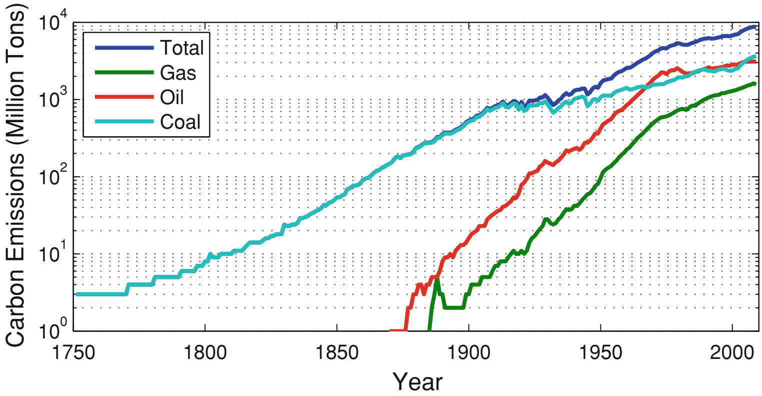

Fig. 3.4 World emissions of carbon per fossil fuel use from 1750 to 2009 (in millions of tons). The logarithmic vertical axis evidences more than 250 years of exponential growth. Because fossil fuels are almost exclusively carbon, emissions and consumption are parallel. *Source* Carbon Dioxide Information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

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[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]).

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