Constraints and Hazards

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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

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[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

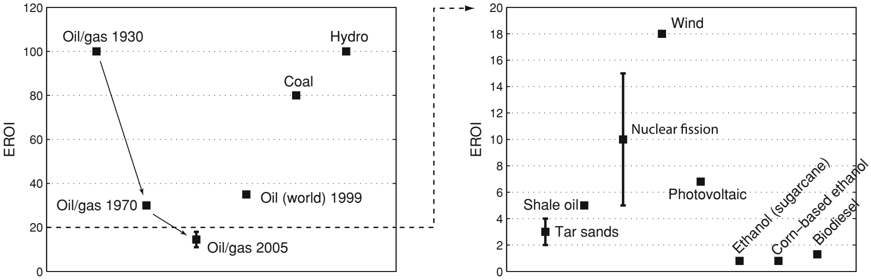

Fig. 7.1 Energy return on investment (EROI) for various energy sources. Numbers from Table 2 of Ref. [3]

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]

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[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

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[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.

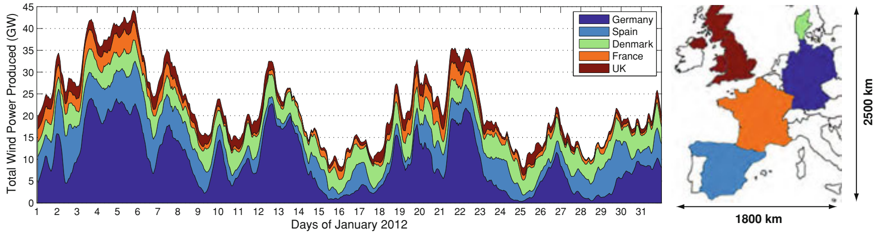

Fig. 7.2 Total wind power during January 2012, for 5 important European wind power producers. *Source* H. Flocard, Sauvons le Climat, www.sauvonsleclimat.org & www.pfbach.dk

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

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[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

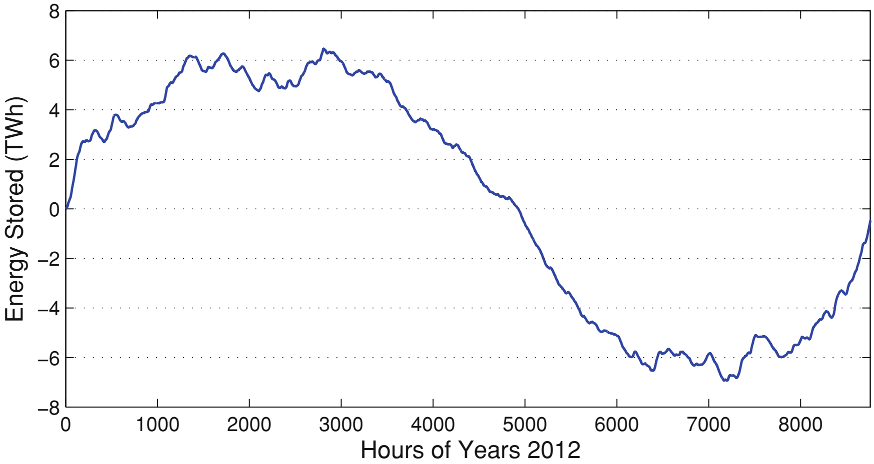

Fig. 7.3 Amount of energy stored $A(n)$, from Eq. (7.1), in terawatt hour. Wind production numbers are identical to Fig. 7.2, but considered over the whole year 2012

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

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[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

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[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*

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[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

	Coal				
Year	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

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[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

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[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

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[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

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[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.

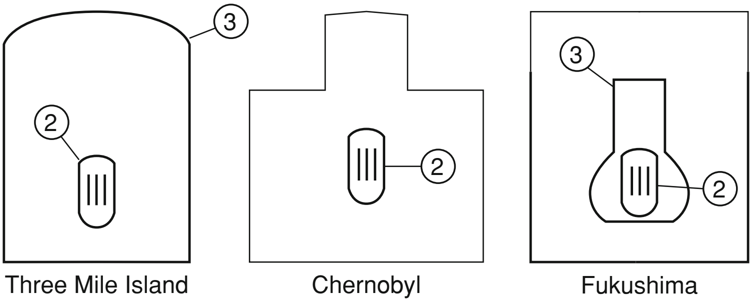

Fig. 7.4 Schematic representation of the Three Mile Island, Chernobyl, and Fukushima reactors. The *bold lines* picture containment vessels. In all cases, container number 1 are the fuel rods

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[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

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[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.

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[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.

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[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.

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