Boccard, Nicolas. (2018). Safety along the energy chain. Energy, vol. 150, p. 1018-1030. Available online at https://doi.org/10.1016/j.energy.2018.02.127

Safety along the Energy Chain

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March 2018

Abstract

We tackle the incidence of accidents within the energy supply chain and firstly extend the analysis from severe accidents to smaller ones. We are then able to go beyond fossil fuels technologies and estimate the hazard rate (ratio of casualties to energy) of wind power, the electricity network and the nuclear sector (for latent victims). Technologies are ranked, separately in the developed and developing worlds. In a second part, we compute the risk rate (ratio of casualties to population) for a variety of countries, accounting for the energy mix and imports; differences are found to be less glaring than for hazard rates. Lastly, we compare this risk of energy supply with the negative health impacts of energy consumption such as atmospheric pollution and road accidents. We find that for every casualty within the energy supply chain, there is a hundred more casualties among end-users in the developed countries and a thousand more in the developing ones. These stark differences call for giving priority to policies aimed at reducing the negative externalities of energy production and consumption.

Keywords: Energy, Wind Power, Accident, Hazard Rate, Comparative Risk, Health, Pollution
JEL codes : D81, L51, D61, Q2

Highlights

- We study the global incidence of accidents in the energy supply chain.
- We account for small scale accidents beyond the literature's severe ones.
- We compute novel hazard rates for Wind Power, Nuclear Energy and Power networks.
- Risk on the demand side of energy is 100 times greater than on the supply side.
- Policy design should emphasize access to electricity rather than renewable plants.

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1 Introduction

Energy is a vital ingredient of our modern society as attested by the strong correlation existing between its consumption and human development (cf. Goldemberg et al. (1985), Steinberger and Roberts (2010), Ribas et al. (2017)). Energy flows are necessary components of essential services such as heating, lighting, and transportation; electricity, a versatile form of energy, is also crucial for the digital economy and its associated services. At the same time, the energy chain is a primary emitter of the greenhouse gases driving climate change. In response to this peril, many countries have embarked on a transition toward a sustainable energy system (cf. Markovska et al. (2016), Lund et al. (2017)). The energy chain also directly impacts our social and natural environment, firstly because production and transportation are prone to accidents or disasters and secondly because consumption generates massive amounts of pollution, congestion, and accidents (on the road or at home). In the march towards sustainability, energy sources are thus assessed critically with a view to prevent undue harm. The *life cycle analysis* follows an energy technology "from the cradle to the grave" to gauge its carbon footprint. In this particular framework, renewable sources such as wind and solar power are found to be low-carbon, fossil fuels to be high-carbon while hydro and nuclear are also low-carbon but sociologically problematic due to their impact on society as a whole. Another dimension begging an independent assessment is riskiness, i.e., whether these energy technologies are hazardous to workers and users?

The first branch of research dealing with this broad question occupies engineer-economists who examine the risk of accidents in the supply chain of energy; the activities involved include extraction, transportation, processing, and distribution. The review by Felder (2009) highlights the inherent limits of the early empirical efforts by Hirschberg et al. (1998) and Sovacool (2008) (it also applies to our work). Felder further recommends to use appropriate metrics, a threshold for severe accidents and draw policy implications; we shall try to heed these instructions. The fields of health, transportation, and environmental economics contemplate the global energy system from a perspective that focuses on the negative impacts of energy consumption onto end-users and nature (e.g., Fritzsche (1989), NRC (2010)). In this article, connect these branches to inform policy choices and allow priorities to be set. Burgherr and Hirschberg (2008) already recognize that "damages caused by severe accidents in the energy sector are small in comparison to natural disasters ... and insignificant when compared to electricity external costs". We shall characterize this intuition by broadening the scope of *supply-side* risk toward several new directions which will ultimately allows comparing the risk of supplying energy with the risk of consuming energy, the so-called *demand side*.

The reason why *supply risk* has not been matched with *demand risk* is that they are built on unique concepts and, furthermore, have been developed by researchers from distinct fields, working and publishing in separate environments. For instance, supply risk focuses on *severe* accidents due to the difficulty of gathering reliable, accurate and complete information relative to the fatalities (whether workers or alien bystanders). Leaving aside the victims from other smaller accidents impedes a proper matching with the assessment of user risk performed by the World Health Organization (WHO). Another thorny issue is that casualties counts are set against different dimensions that hampers a coherent comparison between countries and across time. For instance, road casualties are usually expressed against vehicle ownership, or distance traveled while pollution casualties are set against the population. On the other side of the fence, fatalities along the energy supply chain are matched against the amount of energy consumed (itself expressed in a variety of units). At the risk of distorting the meaning of the original statistics, we shall match all fatalities against population to allow for systematic comparisons.

Major accidents, also known as *disasters*, generate much media attention and have spurred a dedicated academic literature. As we detail in Appendix A.2, *natural* disasters kill every year about 10 people per million population and destroy almost 2‰ of the wealth created by the global economy. Man-made disasters, in turn, are roughly ten times less deadly and destructive, being dominated by transportation accidents (e.g., ferries, planes, trains). Additionally, we show that while natural disaster economic losses are on the rise, the cost of man-made disaster appears to be falling over the last two decades, having passed below the threshold of one basis point (one cent per 100$). Within made-man disasters, energy-related ones are too infrequent to be studied from a statistical perspective. For that reason, Burgherr and Hirschberg (2014) (hereafter **BH**) have gathered over 30 000 records[1] of energy-related severe accidents and constructed the hazard rates for the main energy technologies (fossil fuels, nuclear, hydropower), distinguishing developed from developing countries. To achieve our previously stated goal, we must look into energy-related accidents of even smaller magnitude and also consider all technologies in all their relevant dimensions. We now describe the steps followed in our endeavor.

Section 2 looks at wind power, a technology that has achieved a sizable share of the electricity mix in the developed countries belonging to the Organisation for Economic Co-operation and Development (OECD). We compute the wind power hazard rate as the ratio of fatalities in this industry to the energy generated by wind turbines, in a manner comparable with traditional energy sources. Section 3 devises a simple method to estimate the impact of small-scale accidents made necessary by the recognition that renewable energies are developed at a much smaller industrial scale than fossil fuel. They thus suffer accidents of a much smaller scale too, i.e., scarcely ever severe.[2] Hence, energy technologies will be evaluated on a level playing field only if we manage to estimate all the casualties from accidents whether they are severe or not. Following, this search for exhaustivity, we account for the power network since transmission and distribution constitute critical components of electricity delivery that are not free

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[1] The *Energy-Related Severe Accident Database* (ENSAD) is a proprietary database from the Paul Scherrer Institute (PSI). An accident is severe if it features either five casualties, ten injured persons or significant economic losses.

[2] There is also no intrinsic reason to ignore the victims of small-scale accidents when assessing risk in the energy supply chain, only a practical one, the difficulty of efficiently tracking their many occurrences.

from hazards.[3] Section 4 deals squarely with nuclear-powered electricity which appears, at first sight, to be among the safest energy sources (at least in the OECD). Nuclear power is however subject to an intense risk aversion from the general population fearing "low-frequency-high-consequences" accidents. This peculiarity has somehow forced authors to keep this technology in a class of its own, impeding proper comparisons. To remedy this isolation, we propose to account for the latent victims of irradiation, whether workers of the nuclear sector (including uranium mining) or civilians contaminated by the particle fallout after accidents.

Section 5 gathers the casualty counts previously reported by **BH** together with our complementary estimates and match them to energy outputs in order to produce an exhaustive list of hazard rates across technologies and country groups which are then commented. Section 6 operates the transformation from hazard rate (ratio of fatalities to energy) to risk rate (ratio of fatalities to population) which constitutes the standard measuring rod on the demand side of the energy chain. Section 7 draws on data from the WHO to estimate the risk rate of two crucial energy-related negative consumption externalities, pollution and road accidents.[4] We then confront the supply and demand side of the energy chain and characterize sizable risk differences. Section 8 concludes and gives out some policy implications.

The results achieved may be synthesized as follows. The hazard rate of energy technologies in the OECD is found to be six times lower than the developing world, an outcome already stated in **BH**. The safest energy technologies used in the OECD are the power network and nuclear-powered generation, followed by natural gas and wind at about twice the hazard rate and lastly coal and oil at again twice the hazard rate. In the developing countries, geothermal, though a minor source, is the safest technology followed by natural gas and wind (all at levels commensurate with the OECD ones). Each for a different reason, hydro, nuclear and coal are an order of magnitude more perilous. Bringing the population into the picture allows assessing the toll exacted by industry to serve the energy needs of the world economy. Over the study period 1970-2008, there was about 5000 yearly casualties in the energy supply chain. Accounting for the fact that the OECD is a net energy importer, we estimate this figure across countries, finding out, for instance, that twice many people die abroad than within the EU to deliver its energy needs. At the OECD level, these home and abroad figures are on the level while in the developing countries, casualties are exclusively local.

Our second milestone is the comparison of the two sides of the energy chain, demand, and supply. Confirming a widely held intuitive guess, we find that the demand-side risk for society is two orders of magnitude higher than the supply-side one in the advanced countries and three orders greater in China and India. Additionally, we show that natural disaster risk stands between the previous two categories. We draw some obvious implications for the direction of

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[3] This addition is all the more crucial as electricity is set to become dominant in the future energy chain.

[4] This is obviously a biased selection that ignores many other externalities of energy consumption. The lack of data prevents us from expanding the selection.

future energy policy, notably to accelerate electrification rather than constructing renewable power plants. As a corollary of our study, we establish that the energy chain is safe for its consumers but risky for its workers by one order of magnitude.

2 Wind Power Accidents

Small-scale accidents are excluded because they are less likely to be reported adequately in most places. **BH** note that the ENSAD database "currently does not contain many severe accidents for new renewable technologies, which is why accident risk estimates cannot be based on empirical evidence alone" (and thus involve expert opinion). Since 2008, when their data collection ended, wind power has become a mature technology with enough records of both accidents and electricity generation to be included in a comparative assessment. We follow again **BH** in drawing from Caithness (2017) for accident information in the wind power sector.[5]

Up to October 2017, a total of 2 151 incidents are documented, 118 of which feature a single fatality and 13 a larger number of casualties. The first severe accident took place in 2011 with 5 fatalities (China) and the second one in 2012 with 17 fatalities (Brazil). Inspection reveals the predominant causes to be "fall from a turbine during maintenance" and "road accident during construction." The list, starting in 1980, overemphasizes OECD countries and above all the United States (US), Germany and the United Kingdom (UK), which was to be expected given the development path of the wind power industry. By its very construction, this list offers a lower bound to the number of fatalities the wind power industry generated. Let us then denote γ_t^w, the number of casualties occurring in the wind power supply chain during the year t. We extract the total wind powered electricity E_t^w generated during year t from British Petroleum (2017) (hereafter **BP**). The (world) hazard rate of wind power is thus the ratio $\tau_t^w = \frac{\gamma_t^w}{E_t^w}$ of yearly fatalities to the amount of electricity generated with this technology over the year. We follow **BH**'s convention to express all energy amounts in GigaWattYear with 1 GWy = 8760 GWh (more or less the consumption of a 1.5 million people European city). The five-year moving average $\tilde{\tau}_t^w$ of the hazard rate, shown on Figure 1 with a logarithmic scale, follows a clear exponential melioration path. In the 1980s, this experimental technology was relatively dangerous because one or two yearly fatalities were pitted against testimonial electricity generation. Then, in just over a decade, the risk rate falls precipitously by two orders of magnitude because generation rapidly multiplies while accidents remain limited or even absent. The 1990s signal a new era where capacity still grows at a two digits rate but where fatalities also become more frequent; the risk rate falls by another order of magnitude over the next two decades (1995-2015).

Taking into account the thousands of turbines erected and the large swaths of land occupied by wind farms, the safety improvement of the wind power technology is commendable given

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[5] A member of the "European Platform Against Windfarms," this forum collects news clips about incidents involving wind farms. Given their stated objective, we may trust their willingness to identify all possible cases.

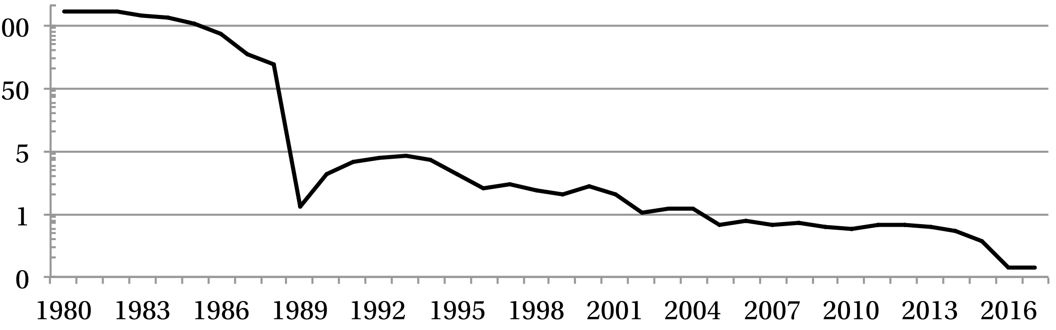

Figure 1: 5-years moving average Wind Power Hazard Rate $\tilde{\tau}_t^w$ (own elaboration)

that fossil fuels, comparable in terms of hazard rate (cf. later sections), occupy lesser land and are found at fewer locations. Our estimation is nevertheless very preliminary, and its conclusions should be viewed with a grain of salt due to the bias mentioned above in the selection of incidents. Indeed, we compute the hazard rates τ_t^{w2} and τ_t^{w2} for the US and the UK and plot them alongside the world estimate τ_t^w on Figure 2 to discover a startling result. Over the last decade, wind power took off in the UK, and it is fair to say that an exhaustive count of fatalities has been performed over the British Isles by the Caithness forum. This, in turn, leads to a hazard rate markedly worse than the world average. A similar result holds over a longer period for the US. Now, few will doubt that construction workers, drivers, and electricians are better protected from workplace accidents in these advanced countries than in the developing world. If so, then our world statistic τ_t^w is severely biased downward by a deficient information collection in the developing countries.

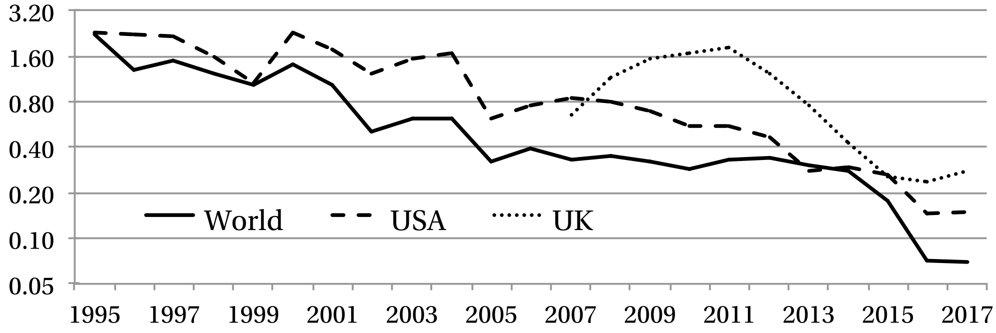

Figure 2: Comparison of the smoothed hazard rates $\tilde{\tau}_t^w, \tilde{\tau}_t^{w2}, \tilde{\tau}_t^{w3}$ for the Wind Power technology in the UK, US and the World, based on our now calculations.

The output of this section will be a long-term wind power hazard rate $\overline{\tau}^w$ comparable to the older literature on energy risk. To estimate $\overline{\tau}^w$, we consider the three distinct time spans T and three distinct geographical areas A shown in Table 1. For a given period T and area A, the total number of fatalities over the period is

$$\gamma_T^{w_A} = \sum_{t \in T} \gamma_t^{w_A}$$

with yearly mean $\overline{\gamma}_T^{w_A}$. The total energy output, extracted from **BP**, is

$$E_T^{w_A} = \sum_{t \in T} E_t^{w_A}$$

with yearly mean $\overline{E}_T^{w_A}$. The hazard rate of wind power is thus

$$\tau_T^{w_A} = \frac{\overline{\gamma}^{w_A}}{\overline{E}_T^{w_A}}$$

We first select the 1970-2008 period to maximize comparability with the ENSAD database and observe that the low number of victims is matched to a testimonial electrical output, which ultimately generates the highest risk rate in the OECD (cf. compare with Table 4). To be fair with wind power, we must acknowledge its young age which leads us to extend data collection toward the present by considering the period 1980-2016. For the last alternative, we limit ourselves to the last two decades once wind power development (and electricity generation) took off, this to level the playing field with respect to the other classical energy technologies. Compared with the previous timeframes, the hazard rates of wind power for the 1996-2016 period improve markedly, setting it within the best of class alongside natural gas.[6]

Wind Power	OECD				non-OECD				World			
	f	$\overline{\gamma}$	$\overline{E}$	τ	f	$\overline{\gamma}$	$\overline{E}$	τ	f	$\overline{\gamma}$	$\overline{E}$	τ
1980-2008	65	2.2	3.5	**0.64**	2	0.1	**0.4**	0.16	67	2.3	3.9	**0.59**
1980-2016	121	3.4	12.9	**0.26**	37	1.0	**4.8**	0.22	158	4.4	17.6	**0.25**
1996-2016	105	5.3	22.5	**0.23**	35	1.8	**8.4**	0.21	140	7.0	30.8	**0.23**

Table 1: Fatalities in accidents related to Wind Power, f = fatalities, $\overline{\gamma}$ = yearly mean of f, $\overline{E}$ = yearly electricity output in GWy, τ = hazard rate in fatalities per GWy

Our finding for the wind power hazard rate within the OECD contrasts with the current state of knowledge $\tau_0 = 0.002$ reported p746 of the Intergovernmental Panel on Climate Change report IPCC (2011). This two orders of magnitude difference is firstly due to our accounting of fatalities from both small and severe accidents (cf. next section), and secondly from the better information regarding wind power that has become available since Hirschberg et al. (2004) estimated the wind power hazard rate that later appeared in Burgherr et al. (2010), IPCC (2011) and **BH**.

3 Severe and non-severe accidents

We saw in the previous section that wind power suffered just two severe accidents but dozens of single fatality events. Leveling the playing between technologies thus requires estimating

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[6] We refrain from commenting or using the non-OECD hazard rates since they are based on minimal output level i.e., correspond to a nascent technology.

how many casualties arise from small-scale accidents in the supply chain of traditional energy technologies. We consider each in turn.

Although solar power will inevitably become a mainstream electricity technology, it has only very recently developed and does not lend itself yet to statistical analysis; it is thus excluded from our study (cf. further details in Appendix A.3). Next, we ought to look at nuclear-powered electricity, a primary low carbon technology. According to the incident records compiled by Wheatley et al. (2016), there were, over the 1970-2008 period, 13 casualties from small-scale accidents within the OECD and 10 casualties elsewhere. The Chernobyl disaster, a severe accident, contributed 38 direct casualties. We deal with the consequences of exposure radiation in the next section. The ubiquity of electricity in modern urban life calls for including a by-product of the energy chain in our study, namely the *power network* without which electricity would cease to be so versatile. By the very laws of current, the transmission and distribution of electricity cannot be linked to a particular plant or input fuel; accidents over the power network are thus excluded a priori from the ENSAD database, all the more so as they mostly involve single fatalities from electrocution or falling from a height. To compute a tentative hazard rate for the power network, we draw from the sole available source of information, the US Bureau of Labour Statistics (BLS) (cf. details in Appendix A.6). As shall be shown in Table 4 below, the power network displays a low hazard rate which ends up making all electricity technologies riskier, once their share of using the network is accounted for. As a consequence, we may claim that no electricity technology, even the greenest one, can claim to be perfectly safe unless it is used in disconnection from the central grid.

For other technologies, including those based on fossil fuels, there is no source assessing the impact of small-scale accidents exhaustively. We can only use the count σ of severe accidents published by **BH** since the ENSAD database is proprietary; we thus develop a simple method to estimate the number of casualties γ from small-scale accidents based on the frequency σ of severe accidents. For that matter, we compute the ratio $\rho = \frac{\gamma}{\sigma}$ in a variety of detailed databases.

The US administration PHMSA (2017) oversees the transmission and distribution of natural gas and liquefied natural gas over pipelines, keeping a public roster of incidents ever since 1968. From 1970 to 2008, 44 468 incidents are reported. Of these, 82 were severe, based on fatalities or injured people. At the same time, 720 people died in 535 "light" accidents (defined to be less than five casualties each). We can thus obtain a first estimate $\rho_1 = \frac{720}{82} \approx 9$ small-scale accidents casualties per severe accident. Burgherr and Hirschberg (2005) §3.3 likewise study accidents in the transmission and distribution of natural gas in Germany between 1981 and 2002. Their dataset, though smaller, includes accidents at the gas distribution company's installations as well as more frequent accidents occurring at the customer's installations. Among the 1337 reported incidents, 17 are severe while 333 people died in "light" accidents, allowing to estimate $\rho_2 = \frac{333}{17} \approx 20$. We favor this latter estimate for two reasons; firstly, it encompasses a more significant segment of the supply chain and secondly, it comes closer to the precise estimate ρ_3 we arrive at for coal mining in the US (cf. appendix A.4).

Table 2 reproduces the first table from **BH** with variables $\overline{\sigma}$ (severe accident count, yearly mean) and $\overline{\theta}$ (severe accident fatalities, yearly mean). We then use ρ_3 for coal mining in the OECD and ρ_2 for all the other cases to estimate the fatalities from "light" accidents with the formula $\widehat{\gamma} = \rho_2\overline{\sigma}$ (or $\rho_3\overline{\sigma}$). Total yearly average fatalities are thus estimated as $\overline{\Gamma} = \overline{\theta} + \widehat{\gamma} = \overline{\theta} + \rho_2\overline{\sigma}$. We observe how the impact of counting the victims from light accidents is to double the number of fatalities in the OECD (+134%) whereas the impact over the rest of the world is dampened by the greater scale of severe accidents there. At the world level, the number of fatalities rises by 68% with the inclusion of smaller events.

	OECD			non-OECD			World		
Technology	$\overline{\sigma}$	$\overline{\theta}$	$\overline{\Gamma}$	$\overline{\sigma}$	$\overline{\theta}$	$\overline{\Gamma}$	$\overline{\sigma}$	$\overline{\theta}$	$\overline{\Gamma}$
Coal	2	58	181	61	992	2,194	64	1,050	2,375
Oil+LPG	6	137	260	11	572	787	17	709	1,047
Natural gas	3	32	87	2	40	79	5	72	166
Hydro	0.03	0.4	0.9	0.5	771	782	0.6	771	782
Nuclear			0.3	0.03	1.0	1.2	0.03	1.0	1.6
Geoth+Biogas				0.08	1.0	2.5	0.08	1.0	2.5
Wind			5	0.05	0.6	1.8			7.0
Energy Sector	11	228	532	75	2,376	3,844	86	2,604	4,376
Impact			*134%*			*62%*			*68%*

Table 2: Reconstruction of total fatalities count over the period 1970-2008, based on table 1 of **BH** and own estimates, $\overline{\sigma}$ = severe accident count, $\overline{\theta}$ = severe accident casualties, $\overline{\Gamma}$ = total fatalities.

As already reported in Figure 8 of **BH** but for severe accidents only, the overall fatalities count for the OECD is almost an order of magnitude lower than in the rest of world, giving credence to the perception that energy extraction in the developing world is dangerous with respect to the safety levels enforced in advanced nations. At the same time, the OECD is a net energy importer over the entire period of study. Now, if the OECD features fewer fatalities but also a lesser (local) production, its fatality rate will not necessarily be lower than for the remaining countries. Furthermore, the safety gap may vary across technologies. We deal with these considerations in section 5 when computing hazard rates for technologies across the OECD divide.

4 Latent Victims from Nuclear Power

The literature on energy-related accidents has traditionally focused on direct casualties, i.e., people passing away within a few days of the accident. However, when a process within the energy chain is poorly designed or suffers a malfunction, it may leak fluids or radiation that will slowly harm workers; ultimately, a proportion of those pass away, often years later, as a consequence of this noxious exposure. For instance, uranium miners and millers face an increased risk of developing lung cancer (wrt. general population) due to radon exposure and uranium particle absorption. Likewise, the accidental meltdown of the core at a nuclear power plant releases radionuclides into the environment which can adversely affect human health, i.e., generate cancers in the civilian population living nearby. This section will try to compute the latent victims associated with nuclear electricity and turn this figure into a hazard rate for this energy source. We consider in turn the two channels of accidental and prolonged exposure.

4.1 Accidental Radiation

We quickly review the state of knowledge regarding the hazard rate corresponding to the accidental radiation following an accident at a nuclear power plant. Hirschberg et al. (1998) (cf. §6.5, Table 6.5.2) deal with latent victims of accidental radiation leakage at an OECD nuclear power plant operating a (western) Pressurized Water Reactor (PWR). They employ a Probabilistic Scenario Assessment (PSA)[7] to produce frequency-consequence curves. The hazard rate of latent cancer is found to be $\tau_1^e = 0.007$ casualties[8] per GWy while that for directly casualties from a severe accident is set at $\tau_1^a = 10^{-8}$ which are very low values when compared to natural gas, the safest fossil fuels based technology. A core meltdown at a Russian reactor is estimated (p 142) to be a thousand times more likely than for a western PWR. Hirschberg and Burgherr (2004) (Fig.15 & p52) sets $\tau_4^a = 0.05$ outside the OECD due to the Chernobyl accident. The upcoming European Pressurized Reactor (EPR) is a mere evolution of the PWR, as recognized by its designer Areva (2012). In Burgherr et al. (2010), the PWR accidental hazard rate is revised upward to $\tau_2^a = 0.007$ while the "better" EPR obtains a hazard rate of $\tau_3^a = 10^{-5}$ (cf. §4 Table 17), still exceptionally low. As recalled in appendix A.7, successive publications by these authors maintain these figures.

To adduce knowledge beyond the PSA black box estimates, we propose to use directly the information relative to the Chernobyl accident instead of a probabilistic method. This is undoubtedly a weak theoretical proposal but at the very least a transparent one. The Chernobyl Forum (2006), a gathering of scientists, economists and health experts from academia, states (p7) that "it is impossible to assess reliably, with any precision, the numbers of fatal cancers caused by radiation exposure due to the Chernobyl accident." Yet, the previous report, Chernobyl Forum (2005), advanced the figure of 4 000 fatal cancers which we adopt. If those victims are spread evenly across a generation lasting 75 years, we obtain $\overline{\theta}^a = \frac{4000}{75} \approx 53$ yearly fatalities that will be added to the direct victims resulting from heavy radiation exposure (and already accounted for in Table 2).[9]

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[7] This technique is reviewed by Denning and Budnitz (2018) and criticized by Sornette et al. (2013).

[8] Exponent a and e stand for nuclear **accident** and **exposure**.

[9] There is apparently a timespan problem here since our study period is 1970-2008 while the accident took place in 1986. One may, therefore, argue that the 53 yearly casualties should be allocated over the period 1987-2008 only

The 2011 Fukushima accident took place after 2008 when the data collection of **BH** ended. Since the latter constitute our primary source of information, we feel appropriate to exclude posterior events to maintain consistency. At any rate, the report on the consequence of the accident by UNSCEAR (2013) “does not expect significant changes in future cancer statistics that could be attributed to radiation exposure from the accident,” a claim further reiterated by the follow-up report UNSCEAR (2016). We shall, therefore, attribute no latent victims to this event. Future research will, however, have to account for the (indirect) victims of excessive stress in the aftermath of the evacuation triggered by the accident (on top of the original earthquake).

4.2 Continuous Exposure

Numerous workers in the nuclear power supply chain are potentially exposed to ionizing radiation and are thus monitored. The recently published multi-cohort study of Leuraud et al. (2015) covers most of the workers at risk in the US, UK, and France. It allows us to estimate a positive but low hazard rate of 3 fatalities per million workers from leukemia induced by protracted low-dose ionizing radiation exposure as follows: per the study, the average cumulative red bone marrow dose was 16 mGy while the excess risk of leukemia per Gy was estimated to be 3. According to the standard linear no-threshold model, this implies a risk of $\frac{3\times 16}{1000} \approx 5\%$. Applied to the observed 531 leukemia casualties reported in the study yields $\frac{531\times 0.05}{1+0.05} \approx 24$ excess deaths. Given the total of 8.22 million years of work covered by the study, the worker peril[10] rate is $\omega_1^e = \frac{24}{8.22} \approx 3$ deaths per million worker.

Using nuclear electricity generation data from **BP**, we observe that the countries mentioned above generated about half of the world’s nuclear power electricity over 1970-2008, hence the exposed worker population at world level was about twice the 309 000 multi-cohort, i.e., $L_1^e =$ 0.62 million workers. Applying ω_1^e, we may attribute $\overline{\gamma}_1^e = \omega_1^e L_1^e = 3 \times 0.6 \approx 2$ yearly casualties from continuous radiation exposure to the world nuclear industry over the study period. The OECD estimate is $\overline{\gamma}_2^e = \sigma_1 \overline{\gamma}_1^e$ where $\sigma_1 = 86\%$ is the OECD share of nuclear electricity generation; the estimate for the rest of the world is the complement $\overline{\gamma}_3^e = (1-\sigma_1)\overline{\gamma}_1^e$.

Regarding uranium extraction, the empirical health literature has followed cohorts of workers to estimate latent victims, but we are unaware of any intent to link these to the generation of electricity. To assess the latent victims in this industry, we use the cohort studies by Eidemüller et al. (2012) (Canada, Northwest Territories), Jones (2014) (US, New Mexico), Schubauer-Berigan et al. (2009) (US, Colorado), Rage et al. (2015) (France) and Walsh et al. (2015) (East Germany). For each, we extract the excess deaths from lung cancer and the total number of worker-years

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(22 years instead of 39). An opposite argument would merely lump the 4000 figure over the study period which would increase the yearly level to 103. In the absence of a clearcut case for one or the other, we stick with our median choice.

[10] We use an original label to avoid confusion since hazard has already been assigned.

of the cohort.[11] Proceeding as above, we compute a peril rate per million uranium worker; the values found are not too different, and their average $\omega_1^u = 666$ is the peril rate we adopt.[12] This finding indicates that uranium mining, as practiced after the second world war, was among the most dangerous professional activities, many more times than working at a nuclear power plant and on par with lumberjack or fisherman (cf. appendix A.5 for comparison with other activities).

The next step is to estimate the productivity v of uranium miners. Due to a lack of precise data, we can only use employment at mines which necessarily includes other personal. In the US, which we assume representative of the OECD, each worker produced a yearly average of $v_1 = 1311$ kg of Uranium between 1970 and 2008. Uranium for the French nuclear reactors was mined during the 1990s in Niger with similar productivity.[13] For the non-OECD block, we draw from Paul (2007) the employment and production of the Wismut mining company in East Germany, a significant producer in the Soviet area, active until 1990. We obtain a low figure of $v_2 = 160$ kgU per worker which is nevertheless in the ballpark of $v_3 = 200$ kgU exhibited over the more recent 1980-1996 period by uranium mining companies from Russia, Kazakstan or Czechoslovakia.

Using OECD/NEA (2006) and NEA (2015), we compute the uranium requirement $R \approx 46$ ktU of all nuclear power plants over the 1970-2008 period. It is distributed between the OECD and the rest of the world on the basis of σ_1, the share of nuclear electricity produced in the OECD. We thus find that the OECD uranium labour requirement is $L_1^u = \frac{\sigma_1 R}{v_1} \approx 30\,000$ workers per year. Using the peril rate ω_2^u, we obtain an estimate of $\gamma_1^u = \omega_1^u L_1^u \approx 20$ yearly latent fatalities. Outside the OECD, the lower fuel requirement, due to a low nuclear electricity generation, nevertheless requires $L_2^u = \frac{(1-\sigma_1)R}{v_2} \approx 40\,000$ workers because of the much lower mining productivity v_2. The corresponding latent yearly casualty count is $\gamma_2^u = \omega_1^u L_2^u \approx 27$. Table 3 summarizes the estimates thus far obtained for the nuclear industry which (cf. next section) drive the hazard rate of nuclear power orders of magnitude higher than previously reported.

Casualties	OECD	nonOECD	World
Uranium miners	20	27	47
Power plant workers	1.6	0.3	2
Chernobyl		53	53
Total	22	80	102

Table 3: Latents victims of radiation (own elaboration)

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[11] The ratio of recorded deaths to excess deaths is the ratio of standardized mortality rate (SMR) to SMR minus 1. The Canadian study over 1950-1999 concludes “there was no statistically significant evidence of a relationship between radon exposure and any other disease (other than lung cancer).” We thus assume that other illnesses did not generate a significant number of latent casualties.

[12] The exponent u stands for **uranium**.

[13] Current productivity in modern Canadian and Australian mines is about thrice greater.

5 Hazard rates across energies and country groups

This section gathers the various casualty counts estimated up to now across technologies to derive their hazard rates defined as the ratio of casualties to energy supplied. In a closed economy, this latter quantity is either production or consumption since stock variation is minimal. The OECD is, however, a massive energy importer. Hence, the casualties of the oil sector within the OECD should be compared to the amount of oil extracted within the OECD, that is to say, production. At the same time, many energy-related accidents take place during local distribution,[14] so that the correct comparator would be the consumption within the OECD. To account for both influences, we use the average of production and consumption, taken from **BP** over the 1970-2008 period.

Another more serious problem is how to account for the multiplicity of energy carriers and the heterogeneity of the final services they deliver. Indeed, most oil is turned into kinetic energy to move cars; most natural gas is transformed into thermal energy to heat homes, most coal is turned into electricity while the energy obtained from wind, solar and nuclear fission is directly converted into electricity. The accepted ad-hoc solution to this puzzle is to convert fossil fuels quantities into electricity amounts (GWy) using the heat rate of the corresponding power plants.[15] This procedure undoubtedly favors direct sources of electricity like geothermal, nuclear, hydro, solar or wind since fossil fuels amounts are made thrice smaller, thus raising their hazard rates mechanically by a factor 3.

Table 4 displays our results across technologies and areas. These hazard rates are higher than those found by **BH** since we account for the added fatalities from light accidents and several additional energy delivery technologies. For comparison purposes, appendix A.7 offers a retrospective table of the hazard rates previously appearing in the literature.

We now comment this first milestone. The lowest hazard rates, almost nil, correspond to geothermal, biogas and hydro in the OECD as these technologies do not feature any severe accident. Nuclear power appears here to be more hazardous than previously reported by **BH** because they did not account for the latent casualties along its supply chain, mostly in uranium mines. Wind power displays an average level of safety; it is not devoid of risks for workers because it involves (building) construction and working at elevated height but, as we saw in the dedicated section, its safety record is improving rapidly. The older fossil fuel technologies of oil and coal explicitly involve the most significant accident risks within the OECD. Lastly, the

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[14] Burgherr and Hirschberg (2008) reveal that for oil and gas, transportation is the perilous stage with pipeline or sea accidents over long distance. The distribution stage also claims lives of innocent bystanders in street accidents involving tank trucks or gas-pipe explosions. Conversely, the overwhelming majority of coal chain victims are work-related with lives lost to gas explosions in mines. Lastly, hydropower and nuclear power accidents occur at the site of power plants during construction or exploitation.

[15] The conversion factors are the mean operating heat rates computed by the Energy Information Administration (EIA) for all US power plants over the period 1970-2008 with 33% for coal, 32% for oil and 35% for natural gas.

Region	OECD			non-OECD			World		
Technology	$\overline{\Gamma}$	E	τ	$\overline{\Gamma}$	E	τ	$\overline{\Gamma}$	E	τ
Coal	181	441	0.41	2,194	491	4.5	2,375	932	2.5
Oil+LPG	260	609	0.43	787	725	1.1	1,047	1,334	0.79
Natural gas	87	413	0.21	79	371	0.21	166	784	0.21
Hydro	1	134	0.01	782	108	7.2	782	243	3.2
Nuclear	22	161	0.14	81	26	3.1	103	187	0.55
Geoth+Biogas		11	0.00	2.5	23	0.11	3	34	0.07
Wind	5	22	0.23	2	8	0.21	7	24	0.29
Power Network	120	848	0.14	107	504	0.21	227	1,352	0.17
Energy Sector	*676*	*2,310*	*0.3*	*4,034*	*2,091*	*1.9*	*4,711*	*4,401*	*1.1*

Table 4: Hazard Rate across regions and technologies, $\overline{\Gamma}$ = fatalities (from Tables 2 & 3), E = energy output in GWy (extracted from **BP**), τ = hazard rate, ratio of Γ to E

power networks, transmitting electricity towards final users, convey their dose of risk but are nevertheless quite safe given the tremendous amount of energy they carry. Imputing the power network fatalities across electricity generating technologies would slightly increase hazard rates and bring them closer but without altering our rankings. It also implies that no technology can claim to be perfectly safe insofar as all use the transmission and distribution networks. Our findings considerably differ from those reported in Sovacool et al. (2015) because their database only captures a small fraction of accidents (compared to the ENSAD one on which we build).

Comparing the OECD with the rest of the world, we observe that geothermal and natural gas fare equally well. This may be due to the use of the same modern technologies for extraction and transportation. For the other technologies, the hazard rates outside the OECD tend to be much higher, the overall energy sector hazard rate being six times over (1.9 vs. 0.3). Oil extraction, coupled with LPG processing, is three times safer in the OECD but at a third of the global output; this means that developing countries are probably extracting oil within intrinsically riskier environments. Nuclear power outside the OECD is riskier by one order of magnitude for three compounding reasons, a severe accident with latent victims, lower miner productivity and lower generation of electricity. The coal safety record, driven by China, at comparable extraction volume is worse than in the OECD by one order of magnitude (but appears to have improved markedly over the last two decades). This striking difference is probably due to the stricter security measures in the OECD, themselves a response to the catastrophes that occurred during the industrial revolution.

The most dangerous energy source is then hydropower because of a single event, the deadly 1975 Banqiao dam failure in China. The hydro hazard rate would be **1** without this event, making coal the most dangerous source, again because of a large number of severe accidents in China. At the outset, nuclear and coal are the most dangerous technologies but for different populations (civilians vs. miners) and different distributions across time (direct casualties from many severe accidents vs. thousands of latent victims in a single catastrophe).

6 Energy Delivery and Fatalities

To distinguish the US from the EU within the OECD as well as China from India within the block of developing countries, we use the adequate hazard rate τ from Table 4 together with the energy content $\overline{E}$ for each technology to compute the fatality count $\overline{\Gamma} = \tau\overline{E}$ shown in the first columns of Table 5 (cf. details in Tables 10 & 11 of appendix A.8).

We find out that close to 5000 people die every year in the process of delivering energy to world end users (over the period 1970-2008). The "home" column indicate local victims, i.e., linked to energy production within the country whereas the "abroad" column indicates non-OECD residents (mostly workers) who were victims of deadly accidents in the process of bringing energy to the OECD. The EU has a higher casualties count than the US because even though it consumes less energy overall, it imports energy from riskier non-OECD areas that incorporate a greater number of fatalities. China suffers a quarter of the total because of its large population and fast advancing economic level; together they drive a high coal consumption (and its many associated fatalities). India, although populous too, is still at an early stage of economic development and thus suffers less total casualties than, for instance, the US. Overall, local victims in the OECD stand around 500 while the developing world burdens with over 4000, of which 600 can be attributed to the energy exports towards the OECD.

	$\overline{\Gamma}$	Home	Abroad	Population	ϕ	Home	Abroad
EU	558	166	392	475	1.2	0.4	0.8
US	442	260	182	253	1.7	1.0	0.7
OECD	1,194	564	631	1,061	1.1	0.5	0.6
China	1,295	1,285	11	1,125	1.2	1.1	0.0
India	291	274	18	860	0.3	0.3	0.0
non-OECD	4,347	4,347		4,171	1.0	1.0	
World	4,910	4,910		5,232	0.9	0.9	

Table 5: Risk Rate in the Supply Chain of Energy, $\overline{\Gamma}$ = fatality count (Table 11), Population from proxied by the United Nations (millions), ϕ = supply risk rate (own elaboration)

We then incorporate the average population π over the period for each country to compute the risk rate $\phi = \frac{\Gamma}{\pi}$. The last two columns of Table 5 again split the overall risk ϕ into a home and abroad components. We note how the EU with its modest local energy production is responsible for more casualties (per capita) in the developing world than the US, even though the latter consumes more energy. To serve a 10 million people agglomeration, such as Paris or London, over a year, the energy industry suffers about 4 local casualties and another 8 from abroad while to serve New-York its energy (assuming the same population), there are 10 American casualties and 7 foreign ones. The count for a similar metropolis of India is only 3 local fatalities because energy consumption per capita is still very low. For a Chinese metropolis, the 11 local casualties are commensurate with OECD levels, even though energy consumption per capita was markedly inferior over that period.

7 Demand vs. Supply in the Energy chain

7.1 Externalities of Energy Consumption

When consuming energy, we expose ourselves directly and indirectly to various environmental hazards. Indeed, the combustion of fossil fuels is responsible for a significant share of *outdoor pollution* which, according to the WHO generates a broad spectrum of acute and chronic health effects, ultimately increasing mortality from cardiovascular and respiratory disease and lung cancer. Additionally, the indoor use of solid fuels such as dung, wood or coal to cook and heat in developing countries causes an *indoor pollution* with similar if not stronger deleterious health impacts. Lastly, the transportation of goods and people is mostly powered by oil and brings about thousands of fatal *road accidents* every year. Together these environmental hazards make up a large part of what may be deemed the *demand side* of safety within the energy chain; it is estimated and compared to the supply side.

The *Global Burden of Disease* (GBD) study undertaken by IHME (2017) builds on data ranging from 1990 to 2016. Since risk in the energy supply chain was studied over the period 1970-2008, we use the Compound annual growth rate (CAGR) over 1990-2016 for any variable to estimate the average expected level between 1970 and 2008; it turns out to be proximate to the 1990 level. We sum the risk rates from pollution generated by ambient particulate matter and ozone to produce an *outdoor pollution* risk rate ϕ_1. We must, however, account for the fact that some of the outdoor air pollution vectors do not originate with energy (e.g., desert particles, agricultural emissions). We use the detailed study of Lelieveld et al. (2015) (data from 2010) to associate energy with the outdoor pollution arising from the following sectors: road, industry, heating and power plants. We obtain a share α that allows computing the net risk rate $\phi_2 = \alpha\phi_1$ of energy-related outdoor pollution. The GBD variable "household air pollution from solid fuels" gives us an *indoor pollution* riskrate ϕ_3. The risk rate ϕ_4 of *road accidents* is the ratio of yearly casualties to population; it is precisely estimated in many places thanks to the administrative record keeping of crashes. The GBD estimates are markedly superior to the official figures published in the EU, US and India which we shall keep as our preferred source; for China and the world mean, we stick to the GBD estimates which are proximate to those found in the WHO (2013) report on road safety.

As shown in Table 6 below, we find that between 1970 and 2008, total outdoor pollution was quite elevated in the OECD and even more in India and China but after the “attribution” treatment, the impact of energy generated outdoor air pollution separates the OECD from the rest of the world. We note that the prevalence of indoor pollution was very limited in the OECD but very high in China and India. Road safety was a serious problem everywhere although the measure used here for comparison purposes is not ideal since it does not reflect car ownership and use. We finally define the *demand side risk rate* as the sums of hazard rates for air pollution and road accidents $\phi^c = \phi_2 + \phi_3 + \phi_4$.

7.2 Hazard of Energy Consumption vs. Production

We can now match the risk ϕ^s faced by producers of energy with the risk ϕ^c faced by consumers. Table 6 clarifies the toll paid by society to enjoy the benefits of cheap and abundant energy. Our first observation is that all demand-side components are much larger than the supply side figures we've seen in the previous sections. Rich countries face a similar demand side hazard rate of about 500; it is about four times lower than the risk faced by China or India and three times less than the world average. In the OECD, atmospheric pollution bears the culprit while it is indoor pollution in the developing countries.

1970-2008	EU	US	China	India	World
PM outdoor ϕ_1	543	455	866	822	657
Energy share α	54%	63%	61%	75%	56%
PM outdoor Energy ϕ_2	292	288	526	619	370
PM indoor ϕ_3	58	4	1,251	1,178	747
Road accidents ϕ_4	183	197	251	165	221
Demand side ϕ^c	532	489	2,028	1,962	1,338
Supply side ϕ^s	1.2	1.7	1.2	0.3	0.9
Ratio $\frac{\phi^c}{\phi^s}$	*453*	*280*	*1,762*	*5,794*	*1,426*

Table 6: Risk Rate ϕ, casualties per million population

The ratios of demand to supply-side risk rates shown in the table's last line, reveal that end-users of energy services are more at risk by two to three *orders of magnitude* with respect to the entire supply chain that delivers those energy services to them. This conclusion, which is robust to large and compounding estimation errors,[16] is a *folk theorem*, a claim that every reader knows intuitively to be correct but not clearly documented up to now.

The relationship between energy-related risk and natural disaster risk can be established using the open source data from Guha-Sapir et al. (2017) that allows distinguishing the OECD from the rest of the world (unlike with the proprietary data from SwissRe (2017)). We find a nat-

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[16] A staggering 100% underestimation error in supply risk and a similar overestimation for demand risk would lower the ratio by a factor 4 without changing the substance of our finding.

ural disaster risk rates $\phi_5 = 3$ for the OECD and $\phi_6 = 14$ elsewhere over the period 1981-2015. Hence, the developed world appears to be shielded by its convenient location in the northern hemisphere where the climate is milder and by its greater income that allows erecting defenses against natural disasters (cf. Boccard (2017)). At the outset, the risk of natural disasters appears to be more pressing than the supply side risk of energy delivery by one order of magnitude but less pressing by a similar order of magnitude than the diffuse health-related risks of energy consumption.

7.3 Current Situation

Upon noticing that the study period 1970-2008 is already quite distant, one is tempted to update estimate towards the present. This is feasible for the demand side of energy risk which shows a marked melioration with a CAGR of about −1.5% for India and the US and a CAGR of −2.5% China and the EU (cf. details computations in Appendix A.9). Regarding risk along the supply chain, Figure 7 in Burgherr et al. (2010) reveals that the hazard rate for fossil fuels in the OECD was cut by a factor three between 1970 and 2008, i.e., fell at a GAGR of −3%. We may also note that, except for oil, most of the supply hazards identified regard predominantly the energy workers. A proxy for the evolution of the risk across the supply chain of energy may then be found in the workers' risk rate. We draw from the US economy where such information is available back to 1990. The risk rate for coal workers has fallen at a CAGR of 3.5%, from about 600 down to 100 casualties per million workers. For Oil & Gas extraction, the progress is less impressive (−0.4%) with a current rate of about 160 casualties per million workers. The power sector has improved at a rate of −2.2% (current rate below 50). The overall fall in workplace fatality risk across all sectors of the US economy has been −2.6%; it is even better in Europe with a CAGR of −5.4% (since 1990). Together, the three industries mentioned above employ over a million people in the US and represent a substantial share of total energy jobs in the US economy; it is thus likely that in the developed world (aka OECD), the hazard rate for energy delivery is already below 100 yearly fatalities per million workers.

Summarizing, it would appear that risk in the supply chain of energy has fallen faster than the demand risk faced by consumers. At any rate, the previously observed striking ratios have been amplified; any conclusion valid under the main data used in this article will thus carry on to the present day with even greater force. Nowadays, the demand-side risk rate in the OECD is $\phi_2^c \approx 280$ yearly fatalities per million population while the supply-side risk rate is $\phi_2^s \approx 1$. In the developing world, the former is about four times larger and the latter half smaller. Lastly, note that the peril rate $\omega \approx 100$ (fatalities per million employed) faced by an OECD worker of the energy industry is smaller but commensurate with the risk faced by any user of energy services.

8 Conclusion and Policy Implications

Burgherr and Hirschberg (2014) synthesize their long-running study of *energy-related hazard*. In this article, we broaden the scope of technologies under review to firstly create a level playing field and secondly to connect this supply side with the demand side made of all the users of energy-intensive products. Our first result is to show that wind power, a low carbon technology, has already achieved the status of low-risk technology. As a result of our estimation, we refine the hazard rate currently published by the IPCC. Our second result is to account for small-scale accidents (beyond severe ones) and observe that altogether they weight as much as the severe ones. The hazard rates for all technologies previously assessed are thus more or less doubled. Our third result is to produce a multi-pronged estimation for the latent victims of the nuclear power industry chain. Unexpectedly, it makes nuclear power much riskier than previously reported in the literature. At the world level, it triples the hazard rate of natural gas but remains safer than oil (and coal). It goes without saying that our estimates, being based on the sparsely available information, should be taken with a grain of salt and constitute a call for further investigation.

Concerning income level, the hazard rate of energy supply is six times lower in the OECD countries than in the developing world. But, as the former consume much more per capita, the toll exacted upon the population is not overtly different, with a world average of one yearly fatality per million inhabitants for the entire energy supply chain. Lastly, our main contribution is to connect the supply and demand sides of the energy chain, bringing into the picture the critical issues of atmospheric pollution and road accidents. Confirming the early guess of Burgherr and Hirschberg (2008), we demonstrate that *several orders of magnitude separate the risk of obtaining energy from the risk of using energy*.

To offer policy implications for these findings, we must account for a significant difference between the two sides; whereas there are at most a few thousand firms on the supply side, there are hundreds of millions of households on the demand side. An idea will, therefore, be easier to implement in the first arena because changing the habits of the population through education takes much longer than changing practice in the industry through regulation and laws (even after accounting for lobbying resistance). As we have already seen in §7.3, risk has markedly fallen over the last decades, thus proving that policies work. Air quality melioration in the OECD is entirely due to stricter emission rules on plants and car exhaust (since economic activity has kept rising). Likewise, road safety owes probably more to safer cars and safer infrastructure than safe driving. At the outset, society appears to be able to deliver energy quite safely to end-users but leaves them exposed to harmful environmental hazards that are two orders of magnitude more pressing (three orders in the developing world). For that reason, user safety appears to be the "low hanging fruit" that should receive policy priority with initiatives focused on industries that may positively affect the quality of life. For instance, the funding of the World Bank (2015)'s

"Sustainable Energy for All" (SE4All) program should be geared at "universal access to electricity" rather than "increasing modern RES share." Indeed, the former option of connecting villages in developing countries to the power grid or build a local independent grid will allow electric appliances to replace cooking stoves and ultimately eradicate indoor pollution (cf. Gordon et al. (2017)). The latter option, on the other hand, will most likely fail to displace any polluting sources since these countries experience strong growth in electricity demand (and must add capacity anyway). Wind energy will thus end up powering refrigerators, air conditioning, and TVs in the households of the newly affluent middle class of urban centers. Clearly, the former option delivers faster and broader results bettering citizens' life.[17] Another well known "triple-win" policy worth recalling in our context is to develop public transportation as it reduces pollution, congestion, and accidents on the road.

The supply side of energy should not be forgotten because the hazard rate for workers is commensurate with the hazard rate faced by consumers. The two clear paths for action are workplace and transportation risk. For instance, the high degree of safety required from the nuclear sector offers an excellent measuring rod for all industrial activities where workers are at risk.

Acknowledgment

This work was supported by the Generalitat de Catalunya through contract AGAUR (SGR 1360) & the XREPP network as well as by the Ministerio de Economía y Competitividad through contract ECO2016-76255-P. Data sources are available at the figshare repository. We thank the organizers F. Marty and T. Reverdy as well as the audience at the workshop on "the European electricity market and national energy policies", held in Paris in September 2017 for their insightful comments.

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[17] In Figure #1 of said report, we see that the growth objective for universal access to energy is not even 1% per year as opposed to 7.5% for building RES and in table #1 that only 2.5% of the world's investments for the SE4All program goes to universal access.

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Appendix

The appendix collates a series of capsules informing in more depth points raised in the text.

A.1 Nomenclature

A.1.1 Symbols

$\overline{x}$ yearly mean of vriable x (over the study period)

E Energy output

σ severe accident count

θ casualty count for severe accidents

γ casualty count for non severe accidents

ρ $= \frac{\gamma}{\sigma}$, intermediate ratio to be estimated in several accident studies

Γ $= \theta + \gamma$, casualty count for all kinds of accidents

τ $= \frac{\Gamma}{E}$, **hazard rate**, ratio of casualties to energy generated

ω worker **peril rate**, ratio of yearly fatalities to total employement

ϕ **risk rate**, ratio of fatalities to population

A.1.2 Acronyms

A weblink is included when relevant.

UN	United Nations
HDI	Human Development Index
WHO	World Health Organization
OECD	Organisation for Economic Co-operation and Development
GHO	Global Health Observatory
GBD	Global Burden of Disease
PSI	Paul Scherrer Institute
ENSAD	Energy-Related Severe Accident Database
GWy	Giga-Watt-Year defined as 8760 GWh
PSA	Probabilistic Scenario Assessment
BLS	Bureau of Labour Statistics
EIA	Energy Information Administration
IMF	International Monetary Fund
GDP	Gross Domestic Product
PPP	Purchasing Power Parities
CAGR	Compound Annual Growth Rate
Supply risk	a potentially fatal risk to workers and bystanders generated by an activity within the energy supply chain.
Demand risk	a potentially fatal risk to end-users generated by the consumption of an energy-intensive product or service.

A.2 Disaster Cost Evolution

The socio-economic impact of disasters is briefly reviewed using a variety of sources. The figures quoted in the main text refer to the last 2008-2017 decade. Natural and man-made disaster casualties and losses are sourced from SwissRe (2017). World population is sourced from the UN while the Gross Domestic Product measured in Purchasing Power Parities (GDP-PPP) is sourced from the International Monetary Fund (IMF). To obtain meaningful indicators for an evolution, we look at the ratio of victims to world population and the ratio of total losses to world aggregate GDP-PPP. We extend the period back to 2001 in order to take into account the exceptional 9/11 event. As can be observed from Table 7, natural disasters kill about 10 people per million population every year which is neither large nor minuscule.[18] Man-made disasters, on the other hand, are ten times less deadly and constitute a less pressing matter as we argue in the conclusion. Looking at economics losses, natural disasters destroy a little less than 2‰ of the wealth created every year by human societies. Without the 9/11 event, the losses from man-made disasters would also be a tenth of the previous category. The table also disaggregate insured losses across a variety of cause to reveal the prevalence of transportation accidents in terms of casualties and of fire for insured economic losses. Energy-related accidents are not categorized but feature dominantly in the mining and fire categories. Their casualty count is extremely small because as we argued in the main text, disasters are only the tip of the iceberg when studying safety along the energy supply chain.

2001-2016	Natural	Man-made	Transport	Political	Fire	Mining	other
Victims /bn pop	10,342	1,043	489	280	145	86	43
Losses /M$GDP	1,681	257					
insured losses		72	18	20	32	2	1

Table 7: Disaster Summary Information

Beyond the average levels achieved over the recent decades, we may consider the evolution of economic losses due to disasters. As shown in Boccard (2018), natural disaster losses are growing over the period period 1970-2017 while man-made ones appear to be receding (cf. SwissRe in online spreadsheet). The econometric estimation reveals a positive slope parameter for natural disasters, statistically significative at the 1‰ level while for man-made ones, the parameter is negative but not significant at the usual 5% level.

A.3 Solar Power Hazard Rate

Solar power includes the thermal and photovoltaic technologies. Utility-scale projects make the bulk of the installed capacity. For these large endeavors, we should expect a hazard rate similar or lower than for wind power since solar plants do not involve working at elevated heights (but they likewise involve electrical work and road transportation of heavy equipments). An internet search reveals just two casualties in 2013 in California. The possibly more dangerous activities in the solar power chain corresponds to the millions of photovoltaic panels mounted on residential rooftops. An internet search reveals three casualties who fell from rooftops in California.

Using information from the California Energy Commission and the EIA, we estimate the entire historical output from Californian residential solar power to be above 10 TWh (basically

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[18] With a world crude death rate of 8‰, it may be said that one death for every 744 is caused by a natural disaster.

achieved since 2013) so that the corresponding hazard rate is a high $\omega_1^s = 2.6$ fatalities per GWy. Another computation based on the number of rooftops casualties in the US and the proportion of solar panel jobs among all rooftops jobs yield an expected 2 yearly casualties. If we set this against the energy output over the 20 years lifetime of the capacity installed, we obtain $\omega_2^s = 2.7$.

Even though these two figures are close, the underlying information is too thin to warrant calling them estimates. As a consequence, we omit them from our main reporting. Notice that Sovacool et al. (2015)'s hazard rates are considerably smaller than ours for fossil fuels but commensurate for wind power (0.3); their solar power estimate is $\omega_3^s = 0.16$ fatality per Gwy.

A.4 Coal Hazard Rate

Our method to estimate small-scale accident casualties is based on the $\rho_2 = 20$ multiplier applied to the count of severe accidents. For the extraction of coal in the OECD, between 1970 and 2008, we should therefore find 1600 casualties which turns out to be suspiciously small. The US Mine Safety and Health Administration maintains an exhaustive count of US coal miner casualties since 1900 (as well as employment figures). Between 1970 and 2008, there were 3245 casualties, 450 of which took place in 25 severe accidents; this means that the casualty count of small-scale accidents is 2765, solely for the USA. This leads us to reconsider our initial 1600 estimate.

Assuming that the US is representative of the OECD, we use the ratio of OECD to US coal production over the period to recompute an estimated total of 7046 coal miner fatalities over the period 1970-2008. The use of this more informative value makes coal markedly more dangerous than natural gas whereas in the work of **BH**, they stood on equal foot.

The detailed information regarding individual accidents in US coal mines allows us to compute precisely a multiplier $\rho_3 = \frac{\gamma}{\sigma} \approx 100$, meaning that there are many more small accidents when compared to oil & gas extraction. This finding lead us to favor the multiplier $\rho_2 = 20$ as a mid-range value in between the low $\rho_1 = 9$ found for natural gas in Germany and the high $\rho_3 = 100$ found for coal mining in the US.

A.5 Worker Risk in the Energy Chain

The energy chain is highly capitalistic and employs fewer workers per unit of output than the global economy. Hence, the low hazard rates per unit of output we obtain in the main text mask the fact that several energy jobs are among the most dangerous activities. Using data from the US BLS (2016) for the period 2011-2015, we compute the mean workplace risk rate to be $\omega_4 = 34$ yearly casualties per million worker; there are however glaring disparities since the risk is solely $\omega_5 = 6$ for an office worker or a woman. Wiatrowski and Janocha (2014) estimate a comparable EU risk rate to be slightly lower at about $\omega_6 = 31$. It is notable that these low-risk rates are the fruit of a sustained safety effort since the US and EU risk rates have been falling over the last three decades at respective CAGR of 5.4% and 2.3%. Table 8 presents a list of dangerous jobs, their risk rate, the ratio to that of an office worker and, when relevant, the energy field where the activity is featured.

Activity	ω	$\frac{\omega}{\omega_5}$	**Energy field**
Logger	1,121	187	Biomass
Fisher	735	123	
Pilot	528	88	Wind
Roofer	399	67	Solar
Refuse	351	59	
Trucker	252	42	Wind, Biomass
Farmer	241	40	
Power-line	208	35	Network, All
Construction	157	26	Wind
Miner	148	25	Coal
Oil&Gas	139	23	Oil, NatGas
Police	138	23	
Athlete	99	17	
Electrician	96	16	

Table 8: Fatalities per million worker in the US, ω = risk rate in fatalities per million worker, $\frac{\omega}{\omega_5}$ = relative risk wrt. office worker

A.6 Power Network Hazard Rate

We use the *Occupational Fatal Injuries Profiles* of the BLS to search for fatalities in the *Electric Power Generation, Transmission and Distribution* sector (NAICS 2211XX) for the period 2003-2014 and within sectors 9410 & 9430 in the 3-digit SIC industry classification for the period 1992-2002. A close look at individual accident records reveals that most fatal accidents are electrocution or road accidents. We then search the *Occupational Employment Statistics* for the same sectors in order to construct the worker risk rate in the US power sector.

Next, we compute the trend of this indicator over the 1992-2014 period and use its average rate of change to reconstruct the risk rate back to 1980, the date for which fatalities information are available in the mining and oil sectors (which serve as comparators). The average hazard over 1980-2008 is found to be 22% greater than over the 1992-2014 period; this premium is used to upscale the yearly death count $\gamma_1 = 37$ over the known period into an estimate for 1980-2008 at $\gamma_2 = 45$ yearly fatalities. We then use the mean US electricity output over the same period, $E_2 = 359$ GWy, to compute the power sector hazard rate at a low $\tau = \frac{\gamma_2}{E_2} \approx 0.14$ casualties per GWy.

To relate safety in the US power sector to the situation within the entire OECD, we use the fact recalled in Appendix A.5 that general worker safety in the EU is slightly better than in the US. Given the weight of those two blocks within the OECD, once we account for the less developed member nations, the average should be close to the US level which is therefore adopted as our central hazard rate for the OECD power sector. Lastly, since all energy technologies are riskier outside the OECD (vs. inside), the power sector is bound to be riskier with a premium that we arbitrarily set at 50%.

A.7 Historical Hazard Rate Estimations

We recall in Table 9 the estimates of hazard rates for energy-related severe accidents that appeared in Hirschberg et al. (1998), Burgherr et al. (2010) and Burgherr and Hirschberg (2014). To appreciate change over time, we add our own, based on the latest fatalities counts and output data from **BP**. Beware that the Coal entries for non-OECD exclude China while this is not the case with our estimate. We observe some small variations but not enough to change the rankings between technologies.

Fat./GWy	OECD				non OECD				World			
published	1998	2010	2014	2016	1998	2010	2014	2016	1998	1998	2014	2016
data end	1996	2008	2008	2008	1996	2008	2008	2008	1986	1996	2008	2008
Coal	0.128	0.072	0.120	0.131	0.521	1.080	0.575	0.588	0.333	0.342	n.a.	0.298
Oil	0.124	0.041	0.096	0.159	0.797	1.690	0.951	0.746	0.256	0.418		0.478
Nat. Gas	0.055	0.050	0.072	0.078	0.122	0.202	0.116	0.108	0.109	0.085		0.092
LPG	1.089			1.039	9.806			2.561	3.844	3.279		1.615
Hydro	0.004	0.003	0.003		2.190	2.130	7.030	7.115	1.154	0.883		3.177
Nuclear	0.006	0.005	0.007		0.053		0.030	0.037	0.024	0.008		0.005
Wind	0.003	0.002	0.002									

Table 9: Comparing hazard rate estimates since 1998

A.8 Energy Volumes

For each technology, we extract from **BP** over the 1970-2008 period, production as well as imports for a variety of countries or groups.

To produce the next table, we apply the OECD hazard rates only to the part of OECD consumption that is produced locally whereas for imports into the OECD (shown with grey background), we use the greater hazard rate from non-OECD countries.[19]

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[19] In order to square the total number of fatalities, we do not sum import columns because those productions are already within the non-OECD cells.

Area/Tech.	Coal	Coal	Oil	Oil	Gas	Gas	Nuke	Hydro	Geo	Wind	Power	Total
per year	Prod	Imp	Prod	Imp	Prod	Imp						
EU	143	35	86	205	82	55	70	35	3.2	1.8	280	**628**
US	198		178	164	223	21	57	32	4.4	0.6	323	**920**
OECD	430	21	367	482	382	62	161	134	10.7	2.6	848	**2,002**
China	239		54	10	9		1	19	0.1	0.1	117	**402**
India	45		11	16	5	0	1	7	0.1	0.2	40	**101**
non-OECD	501		966		402		26	108	2.6	0.3	504	**1,953**
World	932		1,334		784		187	243	13.3	2.9	1,352	**3,955**

Table 10: Yearly average volume over 1970-2008 in GWy

Area/Tech.	Coal	Coal	Oil	Oil	Gas	Gas	Nuke	Hydro	Geo	Wind	Power	Total
per year	Prod	Imp	Prod	Imp	Prod	Imp						
EU	58	157	37	223	17	12	10	0.2		4.5	40	**558**
US	81		76	178	47	4	8	0.2		1.6	46	**442**
OECD	176	94	157	523	81	13	22	0.9		6.5	120	**1,194**
China	1,066		58	11	2			133		0.2	25	**1,295**
India	199		12	17	1	0.1		53		0.4	9	**291**
non-OECD	2,241		1,049		86		81	782	0.3	0.8	107	**4,347**
World	2,417		1,206		166		103	782	0.3	7.3	227	**4,910**

Table 11: Average yearly fatalities in the energy sector over 1970-2008

A.9 Demand Side Energy Risk today

Table 12 updates Table 6 with the most recent data, assuming on the supply side an evolution of hazard rates in line with that of worker safety. There is a scarcity of information to assess progress on the supply side in the developing world; we use Qian and Lin (2016)'s study of the construction industry in China to compute a CAGR of -3.5% between 2001 and 2015 that is also used for India.

2016	EU	US	China	India	World
PM outdoor ϕ_1	375	327	837	855	554
Energy share α	54%	63%	61%	75%	56%
PM outdoor Energy ϕ_2	202	208	509	644	312
PM indoor ϕ_3	9	3	443	595	349
Road accidents ϕ_4	52	116	180	114	182
Demand side ϕ^c	263	326	1,132	1,353	842
Supply side ϕ^s	0.3	0.9	0.5	0.1	0.4
Ratio $\frac{\phi^c}{\phi^s}$	901	363	2,308	9,377	2,297
$\Delta\phi^c$ (1990 → 2016)	-2.8%	-1.6%	-2.3%	-1.5%	-1.8%
$\Delta\phi^s$ (1990 → 2016)	-5.4%	-2.6%	-3.4%	-3.4%	-3.7%

Table 12: Risk Rate ϕ, casualties per million population