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Safety along the energy chain

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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.

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. [1–3]. 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. [4,5]. 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 [6] highlights the inherent limits of the early empirical efforts by Refs. [7] and [8] (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., [9,10]. In this article, connect these branches to inform policy choices and allow

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priorities to be set. [11] 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 allow 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, [12] (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 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 greater 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 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.

[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.

[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.