

Sound reasoning in infrastructure safety

According to the Merriam-Webster dictionary, “Infrastructure is the foundational physical and organizational structure—such as roads, bridges, water supply, power grids, and telecommunication networks—necessary for a society or enterprise to function.” One might bring it up-to-date by including the digital infrastructure based on information technologies (IT), encompassing not only the Internet, which can be considered part of the telecommunications network, but also data centres; similarly solar photovoltaic arrays and wind turbines nowadays also constitute significant infrastructure for electricity generation. All of these constitute “hard” (physical) infrastructure. The provision of clean, potable water could be considered as a component of sanitation (maintenance of public health), which also includes the collection and treatment of refuse (including street sweeping), the treatment of waste water, and laboratories to measure water purity and develop new measurement techniques for that purpose. The supply of water, electricity and gas (i.e., methane—natural gas—as a chemical feedstock or simply for burning to generate heat), and telecommunications (both using cables—copper wires and optical fibres—and electromagnetic radiation) are often collectively known as “utilities”. Physical infrastructure also includes railway lines and stations, and air terminals and air control systems.

One can also identify “soft” or social infrastructure, comprising institutions serving to maintain cultural, health and economic standards appropriate to the country. Although partly intangible, it has physical manifestations such as schools, universities, public libraries, primary healthcare centres, hospitals, emergency services and offices of national statistics, and of course high-quality tangible infrastructure is very necessary for economic growth, maximizing productivity of the workforce, and contributing to a high standard of living.

Interestingly, there is a great variation of ownership across intervals of time and different countries. High-quality roads were a key part of Roman infrastructure. As well as serving commerce, they also had an important military function.¹ After the departure of the Romans, these roads were no longer kept up and such roads as there were were maintained (usually very badly) by the parishes. In 1663 the English Parliament passed the

Turnpike Act, which allowed private groups to build and maintain roads, the expenses of which were financed by tolls levied on users. This system became superfluous after railways became ubiquitous, and the modern road system is financed out of general taxation. There are examples of fine railway systems both under state (Swiss Federal Railways) and private (railways in Britain prior to nationalization in 1948) ownership. Universities in Europe are nearly all state institutions, but in the USA the leading private universities surpass the state ones in excellence. Water companies in England were usually started as private enterprises serving their communities, but continuously increasing population density motivated gradual integration of the hundreds of separate companies and in 1973 they were nationalized by grouping them into ten regional authorities under the Water Act. Only 16 years later this policy was reversed and the industry was privatized, now with only a handful of large companies. In Switzerland and other continental European countries, utilities are often run by companies wholly owned by the municipalities they serve—such as the Industrielle Werke Basel (IWB). One sometimes encounters the expression “public–private partnership” (PPP), which typically means a long-term contract between the government and a private company to provide public services, but this is only a minor matter of terminology rather than anything fundamentally different. For example, a city council may contract a private company to collect the city’s refuse, rather than organizing the business itself. Even in the latter case, however, it would not have designed and built the refuse collection lorries and refined their fuel extracted from its own wells. Hence, in reality the PPP label covers almost every activity.² Perhaps the only significant practical difference is for the labour force, the terms of employment usually being somewhat different for municipal and private company employees. Very often public and private infrastructure runs happily in symbiosis. Switzerland has a large number of large and small private railway companies as well as the federal railway system. In Great Britain, the track and its associated infrastructure are owned and maintained by the state, but the actual trains are run by private companies.

In view of its underlying importance for ensuring health and economic prosperity, considerable attention is

¹ Ensuring a safe, peaceful environment—with the help of armed and police forces—should possibly also be considered a part of infrastructure; as well as its cultural benefits, it is also essential for the efficient running of commerce, which further suggests that the minting of coins, and the creation of banks, should also be considered as infrastructure.

² In the USSR and its Council for Mutual Economic Assistance (CMEA or Comecon) satellites, all enterprises were anyway “owned by the state”, hence PPP would have had no meaning.

given to the resilience of infrastructure. Traditionally this focuses on natural hazards [1,2], lately cyber-attacks have gained prominence as an anthropogenic hazard. “Infrastructure safety” often refers to the protection of infrastructure from such hazards. Nevertheless, it also has another meaning, which emerges from the following example, taken from a recent UK Government publication about the transition to “net zero” [3]:

Safety

Grid-scale batteries pose no greater danger than other infrastructure, but it is of course vital that any risks are appropriately managed to maintain public safety and trust. While fires have occurred at battery sites in Great Britain, they are rare and are mitigated by a robust regulatory framework overseen by the Health and Safety Executive (HSE). This framework requires responsible parties to take measures to ensure health and safety throughout all stages of a battery system’s deployment. Battery developers and operators work closely with fire services in drawing up Emergency Response Plans. Fires at grid-scale battery sites appear to be less likely than those at non-domestic buildings in general from all sources. The latest available five-year annual average fire incidence rate for GB batteries is 0.7% (2020/21 to 2024/25),⁵⁹ lower than that for wider non-domestic building fires in England at 0.8% (2019/20 to 2023/24).⁶⁰

⁵⁹ <https://modoenergy.com/>

⁶⁰ <https://www.gov.uk/government/collections/fire-statistics-monitor>

Clearly this document refers to the propensity of infrastructure to cause accidents and even death. At first sight, infrastructure does have such a propensity. Here, transport is especially prominent, and within transport especially roads: in 2024 in Great Britain there were about 1,600 fatalities (of which about a quarter were pedestrians),³ almost 28,000 serious injuries, and about 100,000 other injuries.⁴ In contrast, in the same year there were 24 accidental deaths on the railways, 22 deaths of trespassers, 2 workforce fatalities, and 274 (suspected) suicides,⁵ and in the preceding year there were 11 air injuries, all in general aviation.

Apart from pedestrians and some hospital admissions, most of these fatalities and injuries are

incurred directly and voluntarily in the sense that the motorist has chosen to make a journey by car; hospital admissions present more complex picture, and there is seemingly endless debate about the degree to which citizens are responsible for their own health [4]. A pedestrian innocently knocked down and injured by a motorist, and who then subsequently died in hospital due to a nosocomial infection, would have been singularly unlucky. Most traffic fatalities are caused by human error [5], hence the infrastructure itself facilitates, rather than directly causes, the deaths—the vehicles are not themselves part of the infrastructure.

The energy distribution networks present a tangible, albeit much smaller, risk. There are about 30 occupational deaths from electrocution each year (although most of these would presumably have occurred even if the electricity were generated locally, on the premises, hence cannot be properly said to have been caused by the infrastructure) and about 50 non-occupational ones.⁶ This number compares with an annual average of two lightning strike fatalities, and the annual total of occupational fatalities of about 130 (and about 90 members of the public on occupational premises). As far as piped gas—methane—is concerned, most fatalities due to poisoning are due to the inhalation of carbon monoxide (about a dozen each year); this is about half the number of fatalities from CO generated by other fuels, but double that due to explosion. Methane is relatively safe with respect to explosion, having a much narrower flammability range, and a much higher minimum ignition energy, compared with hydrogen, which has a very fast flame propagation speed. Acetylene—which is the candidate feedstock for the personal nanofactory [6]—has a minimum ignition energy comparable with that of hydrogen, but a wider flammability range (it can self-decompose even in the absence of oxygen) and a lower autoignition temperature. For context regarding poisoning, note that there are about 5,000 domestic deaths annually from various kinds of poisoning. Hence, despite the potential dangers of electricity transmitted at up to 400 kV and of piping a flammable and explosive gas, very few fatalities can be directly attributed to this infrastructure. Piped water is even safer—most dangers arise due to poor maintenance (the consequences of leaks).

More pertinent perhaps are possible health risks associated with proximity to high-voltage transmission

³ Compared with a total of 630,904 deaths from all causes.

⁴ Distressing as these figures are, they are dwarfed by those from the USA, which counts about 36,000 annual deaths and 2.7 million injuries. Of course, it is a much bigger country.

⁵ Compared with a total of about 6,900.

⁶ These figures are gleaned from the Office of National Statistics (ONS). The exact category into which a death is placed depends, *inter alia*, on the Reporting of Injuries, Diseases and Dangerous Occurrences Regulations (RIDDOR). Annual numbers are quite small, and given that each occurrence is presumably isolated, Poisson statistics apply and the variance equals the mean.

lines [7], a matter that is still being researched. At the other end of the scale, one might suppose that public libraries pose negligible risk [8].⁷ Tragically, every year there are a handful of fatalities in British schools. (Any building poses risks from fire or collapse.) Recent figures are hard to come by, but there seem to be about 5,000 deaths annually in English hospitals, where many complex interventions take place, due to nosocomial infections [9].

Another class of risks are those generated indirectly, especially by energy infrastructure. Exposure to the hazard of radioactivity from nuclear power plants presents a risk, albeit very small [10,11]. Chronic exposure to radon accumulating in poorly ventilated houses is estimated to be responsible for about 1500 deaths per annum (with an uncertainty of several hundred), mainly due to lung cancer triggered by the gas when inhaled. Air pollution from burning fossil fuels in electricity-generating plants results in a substantial number of excess deaths (due to shortened life expectancy); precise numbers are hard to come by; in the UK the matter is investigated by the Committee on the Medical Effects of Air Pollution (COMEAP), which produces reports on specific pollutants.⁸ The numbers are substantial, perhaps 30,000 to 40,000 excess deaths per annum in Great Britain. Here the risks are incurred entirely involuntarily, unless one deliberately moves to a district suffering from air pollution or nuclear radiation—although one should bear in mind that if *not* moving would result in more travel to and from work, that would likely present significantly more risk than living next door to a nuclear power station [10,11].

Returning to the quotation from ref. [3], one could conceivably compute some kind of average risk for all infrastructure, and then compare it with that posed by “grid-scale batteries”, but it would be largely meaningless because, as we have seen, infrastructure risks differ from each other both qualitatively and quantitatively. Hence, it is difficult to ascribe any cogent meaning to the first sentence of the quotation. The (anonymous) authors, presumably beholden to their paymasters (the three organizations publishing the report) are evidently at pains to reassure a concerned public that grid-scale batteries are safe. These batteries are collections of hundreds of thousands of lithium-ion cells, usually packed into shipping-style “20-foot” containers, which are used to store surplus electricity from solar photovoltaic panels and wind turbines, and release it upon demand. Since they also comprise inverters to convert the d.c. battery output to a.c., transformers and control equipment, they are usually called battery electric storage systems (BESS). Despite their many advantages for energy storage applications [13], lithium-ion cells suffer from the unfortunate propensity to spontaneously enter an autocatalytic self-heating process (called “thermal runaway”) that usually ends in fire [14], which can then propagate to the entire array of containers, as happened at Moss Landing in California in 2025 [15], with very severe consequences. In 2025 three BESS fires have been recorded in Great Britain (Table 1). The hazards mainly emanate from the large quantities of toxic pollutants released in a fire, which can last for many hours or even days.

Table 1. Reported BESS fires in Great Britain in 2025.

Name	Date	Size/MW	Size/MW h	Age/years	N^a	Duration
E. Tilbury	19 Feb.	300	600	0	1	24 h
Overhill Farm ^b	23 Feb.	50	100	0	1	3 h
Cirencester	28 Mar.	10	51	2.5	2	7 h

^a Number of containers (also called cabinets or units).

^b Near Rothienorman in Aberdeenshire.

⁷ Especially during the Covid-19 pandemic, the danger posed by libraries was examined with regards to the transmission of the SARS2 coronavirus.

⁸ See also, for example, ref. [12].

There were no fatalities at any of these fires, and no immediate injuries. Although the incident at Moss Landing resulted in a fire of the entire BESS, which had a total stored energy capacity of 1200 MW h, equivalent to 240 standard “20 foot” shipping containers filled with batteries,⁹ the British fires involved only one or two containers burning. Each standard container weighs about 40 t and typically contains about 400 kg of fluorine, mainly from the electrolyte (lithium phosphohexafluoride) with smaller quantities from the polyfluoroalkyl substances (PFAS) used to bind the electrode particles together. In the worst case, all of this fluorine will be released in a fire, probably mostly as HF [16] but smaller quantities as PFAS [17]. The question then is whether release of these substances, and others (there is typically a comparable mass of lithium, and probably ten times more (in mass) of aluminium and copper, with the balance made up by organic polymers (including for electrical insulation), electronics, and the steel structure of the container) and their subsequent inhalation (by human receptors and, in rural areas, by livestock) results in unacceptable health risks. In other words, does inhalation of hydrogen fluoride as well as the substances that will be produced generically in any electrical fire, such as copper and aluminium fumes and dioxins, at the anticipated concentrations, contribute to excess deaths? It is not easy to determine those concentrations. The total quantities released are large (it can be reasonably expected that essentially all the fluorine is released into the atmosphere). If heavy rain happened to be falling at the time of the fire, the plume’s contents would mostly be washed into the ground (potentially contaminating water supplies). Otherwise, dispersion of the plume depends on the vagaries of wind and weather (contrast a windless day in which the surroundings are blanketed in thick fog with a dry, gusty day), and one usually has recourse to finite element numerical modeling to characterize at least some of the possible scenarios.

Returning to the first sentence of our quotation from ref. [3], an even more basic question is what kind of danger is envisaged, and how it should be compared between one kind of infrastructure and another. We could simply count fatalities associated with a particular kind regardless of how pervasive it is. Excess deaths resulting from poor air quality constitute a well established metric, albeit requiring a lot of epidemiological work to establish,

although for only three fires it does not seem feasible to quantify those specifically associated with BESS.¹⁰ There is, furthermore, the psychological unease that will be felt by residents in the vicinity of a BESS, knowing that over its anticipated lifetime of several decades it is fairly likely that a fire will occur. The risk is significantly more palpable than that from a nuclear fission power station, which has been shown to be very small [10,11,18]. Indeed, without taking psychological factors into account, it seems impossible to understand the persistently excessive spending—typically by several orders of magnitude—on remediation of radioactivity associated with nuclear power generating infrastructure [18].

There is, of course, an important difference between BESS and nuclear power electricity generating stations. The latter are very few and far between, and usually sited somewhat remotely (e.g., at Dungeness), whereas there are presently about 2,000 BESS in the UK—more than one for each significant town or city. The latter are, therefore, palpable and pervasive, as are apprehensions concerning their safety.¹¹ The subjectivist (sometimes called Bayesian) theory of probability would use this degree of belief regarding the possibility of a severe BESS fire, rather than counting the fires that have occurred as would the frequentist. Of course, the degree of belief would be influenced by the statistics.¹² If we take the latest UK data (2025),¹⁰ there were three fires (Table 1) and the total installed capacity (at the end of 2024) was 6.8 GW (ref. [3], Table 1 and Figure 6). For a typical C-rate of 0.5, this implies a storage capacity of 13.6 GW h. Hence, for what it is worth, the annual probability of fire at a UK BESS is 0.22 GW h⁻¹.

Given that it is widely accepted that the probability of fire at an BESS increases with its size (for which the mechanism is explained in ref. [14]—in essence an individual cell has a certain probability of entering thermal runaway and converting that to fire, hence the more cells there are the greater this probability), it is somewhat disconcerting that at the end of the above quotation from ref. [3] a different metric is introduced, namely the annual probability of fire per installation. The problem with this metric is that undoubtedly the probability of a fire at a large BESS is greater than at a small BESS, and there is a great variety of installed BESS sizes. A further problem is that using the cited reference (to Modo Energy, a data source), one gets a different result from

⁹ E.g., the Sungrow Power Titan 2.0 specification.

¹⁰ If there were more than three fires, the others have not been reported.

¹¹ There is considerable current interest in deploying small modular reactors (SMR, typically delivering less than 300 MW, which would suffice for an individual city with 100,000–200,000 inhabitants, including its industries) or even microreactors delivering a tenth of that, for small towns of less than 10,000 inhabitants.

¹² As lucidly outlined by Gustav Bergmann [20], neither the frequency nor the subjectivistic theory has ultimate superiority.

the one claimed. The BESS result is compared with fire statistics from nondomestic buildings (i.e., business premises). There is of course some ambiguity in the identification of a building as “nondomestic”—there must be a non-negligible proportion of premises that are both domestic and nondomestic. (This could be taken care of by including an uncertainty in the final calculated figure.) Furthermore, as with the BESS, these buildings vary greatly in size and it is *prima facie* unreasonable to group them all together. At any rate, the given single significant figure implies an uncertainty of one unit in the first decimal place, hence (given the statistical origins of the data) it is unwarranted to say that 0.7% is lower than 0.8%. It is anyway even more incongruous to compare BESS with nondomestic buildings than with other kinds of infrastructure.

Given that intermittent renewable electricity generators engender a need for energy storage, it is reasonable to propose BESS as a candidate for such storage. One must, however, compare the risks posed by BESS with those from other energy storage infrastructure.¹³ Current policies for energy [22,23] do not privilege BESS over other technologies; indeed BESS, let alone lithium-ion batteries, are not even mentioned, whereas some space is devoted to pumped hydro storage and hydrogen storage. Even ref. [3] (p. 37, line 1) implies that lithium-ion batteries are only an interim solution for energy storage.¹⁴

The Clean Flexibility Roadmap [3] puts recurrent emphasis on household savings (pp. 8,9). For example, “Households with heat pumps could save more than £250 annually by shifting to a smart tariff...”. Given that a heat pump could cost 100 times more, this 1% return on investment seems barely worth mentioning. We are also told that, with a little effort, “shifting washing machine and dishwasher use [away from peak times] could save an additional £38 per year”. The publication “Clean Power 2030 Action Plan” also emphasizes savings in household expenditure, without mentioning specific sums [24]. All this simply illustrates the general air of unreality that pervades these reports. The economics of climate change have long been a preoccupation, hence in one sense it is not incongruous to highlight possible household savings resulting from adoption of the net

zero policy, but given that they are of the order of the cost a meal in a restaurant, there are evidently other ways of achieving similar savings without bothering about climate change at all.¹⁵

The “roadmap” suggests fairly interventionist regulation rather than letting a free market operate. Nevertheless, the rush to build BESS does not appear to be regulated. A recent House of Commons debate concluded with the resolution: “That this House recognises the unique challenges posed by lithium-ion fires in battery energy storage sites; and calls on the Government to bring forward enforceable national regulations for their design and construction” [25]. Despite the capacity of planned BESS now exceeding the target set out in ref. [3], (Figure 6), new projects continue to be proposed; many of them are not linked to renewable generation, but have a purely chrematistic purpose, to buy electricity when it is cheap and release it when it is expensive. Clearly such projects require especially close scrutiny regarding hazards and loss of amenity. Essential infrastructure, such as sanitation, prolongs life expectancy, with which its cost can be rationally balanced via the life quality index and the J-value [26]. If there is no general benefit, one has to be careful that the costs of a development are not borne involuntarily by anyone other than the developer.

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¹³ For this, the concept of macrorisk can be useful. In ref. [21] it has been applied to industrial installations with a view to optimally allocating regulatory resources.

¹⁴ This introduces a note of sobriety in a document that elsewhere verges on copywriter’s puffery—for example, in his foreword the Minister for Energy asserts that “Britain is a world leader in a range of exciting new clean flexibility technologies and services”. Alas, it seems that most of the lithium-ion cells for BESS are currently made in the People’s Republic of China. British BESS developers appear to expend significant effort on merely buying and selling sites and installations, which are generally equipped with turnkey systems purchased from overseas. It is, therefore, doubtful what kind of leadership is being exercised.

¹⁵ It is general problem for governments that many of the most effective measures to combat climate change, such as walking or using a bicycle instead of driving a car, are inimical to economic growth.

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