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Nuclear energy myths versus facts support it's expanded use - a review

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ABSTRACT

In order to promote a sound basis for considering the role of nuclear in climate change, this review spans the technical topics of social and political debate surrounding nuclear energy with a focus on the objective science of these issues including nuclear waste, accidents and overall risk. Novel aspects include the emergence of nuclear energy as being potentially renewable and the antithesis of Fukushima being an argument for the unacceptable risks associated with the use of nuclear energy. The purpose of this review is to present the facts about nuclear energy divorced from political, social or comparable bias. The results argue nuclear as effectively the most attractive option from almost every possible perspective in which common social discourse would have these painted as unfavourable if not horrific.

Introduction

It could be rightly stated that the mission of the modern engineer is to sustainably improve the standard of living for society while simultaneously reducing our impact on the environment. It is well known that standard of living is highly correlated with energy although it has been found that at the highest societal index, the trend becomes logarithmic due to the extended footprint of energy consumption from outside a countries borders (Arto et al., 2016) (such as the manufacture of items purchased from abroad by the more affluent countries). This means a high standard of living such as that in the USA is almost asymptotically approaching a constant thus highlighting the urgent need to develop environmentally friendly energy supplies to sustain the various forms of consumption associated with that lifestyle. Furthermore, the use of nuclear energy trending with economic growth and its satellite activity in society (generally supplied by fossil fuels) partially offsets the greenhouse gas reduction when this stimulated "affluent" activity is not also supplied with nuclear (Alam, 2013) or traditional renewables (Piłatowska et al., 2020). This unexpected trend helps explain the large energy consumption rates from all energy sources even when coupled with nuclear energy (Gralla et al., 2017). Depending on the availability of traditional renewables, complete conversion has been shown to not be currently feasible without nuclear energy (van Kooten et al., 2016) due to the current constraints on traditional renewables which effectively marries renewable success to nuclear.

Some of the primary features desired from any energy source are that they are sustainable (renewable), have a vanishingly small environmental footprint (from cradle to grave) and can replace our liquid fuel transportation sector. Couple this with safe operation, cost effectiveness and low overall risk and we have an almost dream solution. These benefits would increase further if they could provide industrial heat as well as carrying out carbon sequestration to not just stop greenhouse gas production but to forcibly reverse it. The extent to which nuclear fits all of these characteristics is of enormous social import.

When making electricity, nuclear energy creates extremely elevated radioactivity levels in the fuel as the primary hazard of concern. To start scaling this hazard, the typical distribution of radiation doses obtained by the citizenry of the USA (NCRP 2009) is shown in Fig. 1. Note that almost half of the dose comes from medical applications with all industrial sources combined being almost negligible overall (a small fraction of a percent which includes the use of nuclear energy).

The fear of radiological risks (e.g., accidents, waste etc.) from nuclear energy have effectively been argued the primary drivers inhibiting its use (Verbruggen et al., 2014) and can be attributed at least in part to the implicit negative bias against nuclear energy scientifically demonstrated to be present in the public (Truelove et al., 2014). This despite the dose to the public from nuclear energy being effectively negligible as seen in Fig. 1. Natural background (including radon) is almost equal to average medical annual exposures where the overall total is around 6.2 mSv y^{-1} with the highest average annual worker dose actually coming from particular air crews at 3.1 mSv.

Abbreviations: WIPP, Waste Isolation Pilot Plant; UNSCEAR, United Nations Scientific Committee on the Effects of Atomic Radiation; NCRP, National Council on Radiation Protection; LNT, Linear No Threshold; ALARA, As Low As Reasonably Achievable; ISFSI, Interim Spent Fuel Storage Installation; WHO, World Health Organization; DOE, Department of Energy; EPA, Environmental Protection Agency; EIA, Energy Invoermation Agency; BLS, Bureau of Labor Statistics.

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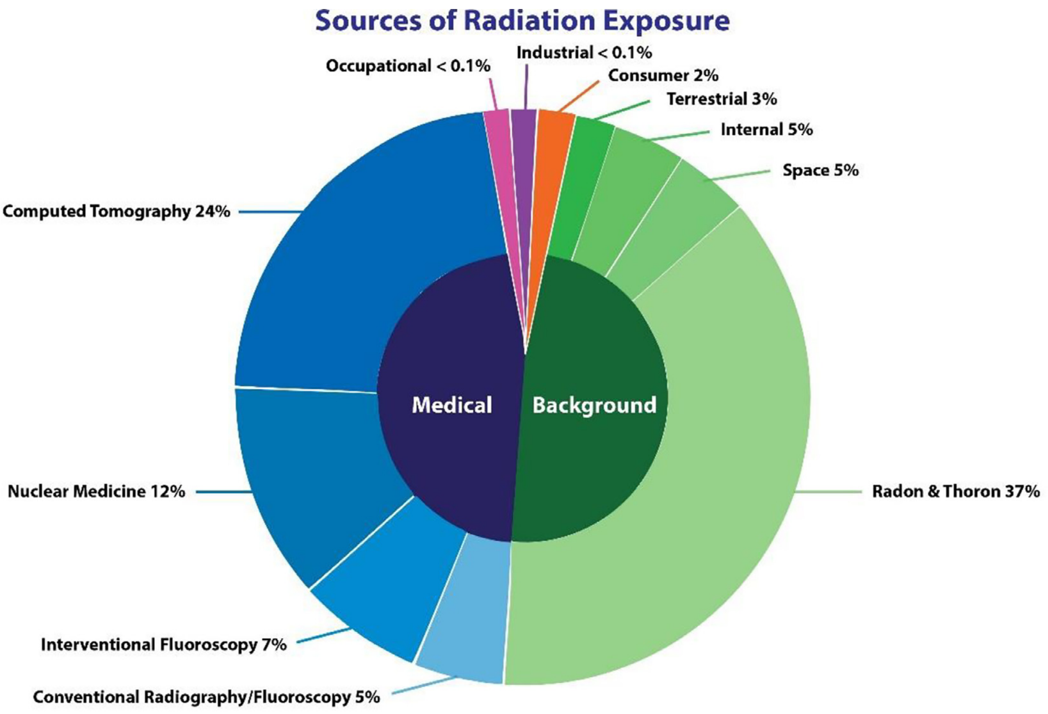

Average Annual Radiation Dose

Sources	Radon & Thoron	Computed Tomography	Nuclear Medicine	Interventional Fluoroscopy	Space	Conventional Radiography/ Fluoroscopy	Internal	Terrestrial	Consumer	Occupational	Industrial
Units											
mrem (United States)	228 mrem	147 mrem	77 mrem	43 mrem	33 mrem	33 mrem	29 mrem	21 mrem	13 mrem	0.5 mrem	0.3 mrem
mSv (International)	2.28 mSv	1.47 mSv	0.77 mSv	0.43 mSv	0.33 mSv	0.33mSv	0.29 mSv	0.21 mSv	0.13 mSv	0.005 mSv	0.003 mSv

(Source: National Council on Radiation Protection & Measurements, Report No. 160)

Fig. 1. NCRP dose category contribution to the average US citizen from all sources combined for 6.2 mSv y^{-1} on average (NCRP 2009).

This review includes consideration on how the clinical fear of ionizing radiation known as radiophobia (Myslobodsky, 2001) allows entire countries to spend hundreds of millions if not many billions of dollars to avoid a fraction of these natural background radiation levels to its citizens. What is perhaps the most surprising result found is that when using the established consensus based objective standards, that this radiophobia is the real obstacle in both converting the entire economy over to a renewable energy source (Pravalie and Bandoc, 2018) as well as doing this in a way that would drastically reduce the entire lifecycle environmental impact from energy consumption overall (Scott, 2013).

To the extent that public and political discourse against nuclear energy can be described by perceived risk, nuclear risk has to be first defined in terms of radiation exposure. With this, the popular societal narratives offered to argue undue risk exists with the use of nuclear energy are looked at on a case by case basis to consider how much money is spent averting various forms of nuclear risk even if risks avoided are already extremely low.

The potential available from nuclear vs fossil energy

The energy released in a single fission reaction is approximately 200 MeV whereas that for a combustion reaction is closer to 1 eV per atom. With (Truelove et al., 2014) more energy per reaction available from nuclear power, the amount of energy available or extracted per mass of waste generated, per fuel consumed, per construction materials etc., is all substantially larger with nuclear. This enables a favourable capability found in nuclear energy not present with any other commercial electrical supply source. A smaller amount of waste is easier to safely control, less materials per kWh is more environmentally friendly etc. This does not necessarily address public concerns with radioactivity as spent fuel and high level waste requires additional controls beyond that of toxic waste forms.

As a comparison, coal (like the rest of the earth) having generally a few parts per million concentration of primordial radionuclides concentrates these radionuclides in its ash while releasing the majority of this to the atmosphere during combustion (McBride et al., 1978). This primordial radioactivity in coal will vary from source to source which for European coals (Temuujin et al., 2019) were found to average 191±90%, 91±32% and 561±35% in Bq kg^{-1} for ^{226}Ra, ^{232}Th and (Till et al., 2017) ^{40}K. Note that these values do not include the parents of ^{226}Ra nor the rest of the progeny from the uranium and thorium decay chains. Depending on the source terms used for a coal fired power plant, it has been shown that the released radon alone can exceed the maximum permissible concentrations allowed for nuclear facilities (Papastefanou, 2010).

As we transition away from fossil fuels, the ability to comprehensively look at the demonstrable risks from nuclear energy divorced from radiophobic fear narratives must be embraced. If unfounded fears become a driver in decision making then well-reasoned solutions can become a hopeless goal. This paper attempts to review the popular arguments against nuclear energy from accidents, nuclear waste management and non-proliferation from an objective risk perspective. By defining radiological risk in terms of dose, the science for each of these topics then can be holistically addressed accordingly.

Risk management

If an individual insists that nuclear energy must be safe, this might readily be construed as equivalent to attaining zero risk. That nuclear cannot attain a zero risk has even been argued in the literature as a justification for its elimination (Ramana, 2009). Risk however has a technical definition and so a formal metric can be applied to compare and manage risks from ionizing radiation to any other sources of risk such as industrial, chemical, biological and security risks (although there are others such as financial, political and social). The technical definition of risk can be defined by the product of an objective outcome probability and the consequences of that outcome (Aven, 2016) according to Eq. (1). The consequences can be scaled according to various metrics but when those are established, a framework for risk management can then occur.

This means that the risk from using energy can never be brought to zero for any energy choice if it has any deleterious consequences without somehow making those individual probabilities exactly zero. Technically, the only way to make the consequences from a particular outcome have a zero probability is then to do nothing (as then the probability is by definition zero). Clearly doing nothing has its own set of alternative negative consequences for choosing not to use energy at all and so in a literal sense, zero risk is unattainable for any path demonstrating the importance for utilizing risk management in decision making.

$$Energy\ Risk = \sum_i Consequences_{\ i} \times Probability_{\ i} \tag{1}$$

When any design or process has the potential to impact public safety, the associated risks and benefits must be carefully considered according to Eq. 1. From this, risks with more severe consequences and higher probability should be weighed more heavily against any benefits from that activity relative to those with lesser consequences and smaller probability. Although it is impossible to fully eliminate subjectivity, this strategic approach enables ethical and regulatory decisions to be made with a balanced perspective on risks and benefits even when uncertainties are included.

In general, modern society has accepted that with appropriate regulatory oversight, the technological benefits from the properly regulated use of ionizing radiation outweigh the risks in many industrial, scientific, and medical applications. This is not quite the same case when it comes to civil nuclear energy (Verbruggen et al., 2014, Truelove et al., 2014, Myslobodsky, 2001, Pravalie and Bandoc, 2018).

Balanced risk management

When the metric from Eq. 1 has been assessed for all risks present, a desirable goal is to reduce the highest risks to be equivalent to the smaller risks. Still, some risks may be very inexpensive to reduce further and so will allow a cost effectiveness in lowering these particular categories below all others (Khan et al., 2015). In a generic sense, this would be to say that if risks from outcomes A_1 through A_N have energy risk metrics of B_1 through B_N, then if each of these risks can be reduced by amounts C_1 through C_N in risk reduction per $ (Note C_i is a risk reduction per $), then the optimal fraction of the monetary distribution K_D for option A_D in reducing all the risks would be found from the weighted average $K_D = (B_D \cdot C_D) / \sum_{i=1}^{N} (B_i C_i)$. If the total budget for risk reduction is then some value F, then the optimized $ to be spent on outcome A_D is then $F \times K_D$.

The fundamental intuition here being that you should not spend a large portion of money available on one of the already low risks B_i, when others are effectively ignored in terms of relative resources committed to their reduction unless it is extremely cheap to reduce that already low risk (e.g., C_i is very large). This review will further realize how, in the most important scientific metrics, the ionizing radiation aspects from nuclear energy currently are the lowest risk from this electricity source and yet attract the highest societal fear and so associated costs. The dichotomy resulting from this is that a large amount of money is being spent on a small risk accomplishing only a small risk reduction.

The weighting formula can also factor in subjective weights ρ_D. These could, for example, represent societal risk aversion metrics or even option preferences, not associated with physical harm, scheduling or cost. The weighted average could fold these societal biases into the individual option risks such that $B_D = \rho_D . b_D$ where b_D is the risk metric from the Dth option as described above. This approach could substantially change the resulting assessments accordingly depending on the values of ρ_D.

Radiological exposure risk

The primary categories for which public and political concern is expressed over exposures to ionizing radiation, are the risk from acute radiation syndrome, and the possibility of latent cancers. The most commonly used assumption for radiological risk due to latent cancers is that the probability increases linearly (NCRP, 2018) starting around at least 0.2 Sv at a rate of approximately 5% per Sv absorbed dose. The financial consequences from this risk avoidance can be cast into the cost per collective annual background dose avoided. The cost estimates in this way assume the linear no threshold hypothesis as a worst case scenario by ascribing it meaning all the way down to natural background levels or more specifically, how much money is spent to avoid an annual natural background dose equivalent for society.

The linear no threshold (LNT) hypothesis

Extended epidemiological follow-up of the Hiroshima and Nagasaki atomic bomb survivors, and many other exposed cohorts, have shown that ionizing radiation exposures in excess of 100 mSv are associated with statistically-significant linear increases in cancer rate probabilities (NAS, 2006). However, at effective doses below 100 mSv, the true shape of the dose-response curve is not known and much research is needed to shed light on the true nature of these exposures (Hall et al., 2017). Since occupational and public exposures are typically far below 100 mSv (by orders of magnitude), this lack of knowledge has led to debate over how radiation protection should be managed.

It has become fairly common for experts to sharply criticize the technical basis for the LNT assumption (Ulsh, 2018, Feindengen and Neumann, 2005, Scott and Thermalingam, 2019, Cuttler, 2016). That the LNT is the common assumption for radiation protection purposes is effectively nothing more than it's being more conservative in limiting acceptable levels than other models. This can be problematic in that LNT often is interpreted to ascribe risk at values which are small fractions of natural background (all the way to zero dose) suggesting even these levels might provide benefit if avoided. This can generate radiophobia from natural levels and even persuade some individuals to avoid necessary medical treatments (Brody and Guillerman, 2014).

Perhaps the most egregious use of LNT comes from the common practice of predicting cancer rates to large populations from a low dose, a practice forbidden by national expert consensus bodies (NCRP, 1997, NCRP, 2012) and even by those few experts who actually promote LNT (Boice, 2017). The kind of analogy used to describe this behavior for predicting cancer from collective dose is akin to arguing that if a jump from 20 m will kill an individual, then on average, if 20 individuals jumping from 10 cm do this 10 times, on average, one will die. Simply put, the use of LNT in predicting cancers from collective dose has been shown to be an egregious practice in drastically overpredicting cancer rates further promoting radiophobia (O'Connor, 2017).

As low as reasonably achievable (ALARA)

In addition to ensuring ionizing radiation exposures are justified and limited, the fundamental principles of operational radiation protection and their associated regulations (for example, 10CFR20) require optimization (10CFR835, 2022) - exposure-associated risks are to be kept ALARA. For stochastic effects like cancer, ALARA is the policy followed, consistent with the LNT hypothesis that has been assumed for radiation protection purposes. However, while the LNT model is convenient for regulators and those implementing radiation protection programs, it cannot be shown to describe the dose-response of excess cancer risk at exposure levels less than 100 mSv. Rather, there are examples where experimental radiobiology outcomes are just the opposite of LNT (Calabrese and O'Connor, 2014).

In one sense, ALARA can reasonably be enacted productively insofar as it is effectively a quality assurance tool for access to, and control of radiological materials. Trending ALARA parameters is intended as a reasonable metric even though current regulatory limits for public exposures are a fraction of average annual natural background levels (10CFR20, 2022). Current technology allows nuclear power operations to result in public exposures orders of magnitude below levels where statistically-significant negative health effects have been observed in healthy populations; and doses for nuclear and medical workers are also generally a fraction of these regulatory limits (NAS, 2006). As in any production environment, leaks and unexpected contamination or exposure are of interest to management for simple optimization and quality control applications.

It is important to emphasize the "reasonableness" of ALARA as to not unduly limit potential societal benefits or increase overall societal harm from extremely expensive actions taken to reduce exposures near zero. Zero risk, while desirable, is unattainable and contrary to the concept of ALARA. When determining "reasonableness" of actions intended to reduce exposure, associated secondary societal impacts and costs must be considered. For example, the decision to evacuate after release of radioactive material must be made in the context of the potential risk and negative health consequences resulting from ionizing radiation exposure and factors such as stress-related effects on evacuees, economic impact, traffic accidents, and direct health outcomes that may result from moving elderly or infirm people. Furthermore, without clear and understandable risk communication, the public's fear of radiation can compound any potential harm from exposures resulting in substantially elevated negative consequences.

Biological design specifications

Life on earth requires many things such as liquid water, unique geology (for elemental and mineral content) (Southam et al., 2007), cell design (it really is a fantastic machine) (Krakauer et al., 2016) and even all the way down to minimal genomic requirements (Lluch-Senar et al., 2015). It is reasonable to expect we will find more requirements but the key tenet being made here is that life as we know it really is designed specifically for our unique biosphere which has always included ionizing radiation.

Another way of looking at this in context of low level radiation doses due to background sources, might be to consider the requirement of potassium in our diet. That we would die without potassium (due to the need of this element in the sodium-potassium pump to get water in and out of our cells), a deficiency is known to create a large number of health issues if we do not ingest enough of it (Bueno-Orovio et al., 2014). These include a large number of cardiovascular diseases (Kanbay et al., 2013), as well as hypertension (Aaron et al., 2013) (where a balance of sodium and potassium is desired). This is of interest in that the naturally occurring (Till et al., 2017) ^{40}K has both a higher energy gamma and beta, than the dominant long term fission product gamma source of ^{137}Cs, and is in the same chemical family. Potassium content scales with muscle content so a small petite female may get only 0.1 mSv/y whereas a large muscular male can receive 0.4 mSv in a year from this self-irradiation source (NCRP, 1987).

Alternative models for low level exposure risks

Statistically-significant increases in cancer rates resulting from human uses of ionizing radiation at exposure levels below 100 mSv is sufficiently complex (Till et al., 2017), it cannot in general be resolved with current scientific detection means in support of LNT even as evidence mounts against it (Golden et al., 2019). This leaves room for various other dose response models including perhaps the most popular, hormeisis (Feinendegen et al., 2007) or alternatively the threshold model. The hormeisis model simply assumes that a little bit of radiation is actually good for you in stimulating your immune system, and placing it in the environment for which it was designed (Feinendegen et al., 2004). The threshold model simply assumes no radiogenic effects occur until some threshold near 100 mSv is attained (although this is currently the statistical detection threshold based on available population sizes and uncertainties in doses where permanent evacuation can be federally initiated (EPA, 2017).

The hormeisis model is argued compatible with a design specification based on when life began around a billion or so years ago, back then, life was bathed in a much higher background radiation field due to exponential growth of all the naturally occurring radionulcides in the earth. In forward time, radioactivity decays exponentially but going backwards in time, it will increase accordingly requiring life to endure under these terrestrially elevated radiological conditions (Parsons, 2002).

This argues that life is actually designed for higher background radiation levels meaning that if we add to the ambient background levels in the environment, we will bring the exposure level up to our design specification (Sacks et al., 2016). The question could then be asked if our design specification is that from the first living cell a billion years ago or the first homosapien, a few hundred thousand years ago (both would have different terrestrial background radiation levels).

The potential to evaluate health consequences from low doses of radiation has been studied for nuclear workers and found to have lower than normal cancer rates (Cardis et al., 2007). This is attributed to nuclear workers having a higher standard of living, including health care, which would identify precancerous lesions initiating mitigation of the same prior to full onset of the disease, lowering its eventual incidence (Cardis et al., 2007). This is called the healthy worker effect although others attribute this to hormesis (Fornalski and Dobrzyński, 2010).

In addition to this, many areas around the world have substantially higher natural background due to elevated combinations of uranium, potassium and thorium in the soil. Ambient dose rates in these areas can range all the way up to 132 mSv yr^{-1} without considering radon, and up to 260 mSv yr^{-1} with radon. That none of these areas show any increases in latent cancers (Aliyu and Ramli, 2015), can be attributed in part to the known dose rate factor (the same dose given at a lower dose rate has a smaller effect), and the fact that many of the higher dose rate areas have smaller populations making statistical significance more difficult to attain.

To potentially confound matters of low dose effects even more, recent evidence has shown that psychological stress from knowing you have been exposed to low level radiation is sufficient to reduce your bodies ability to combat the disease naturally (Wang et al., 2016), allowing for a self-fulfilling prophecy effect. This translates into stress alone generating a medical effect masking any radiogenic effect (meaning radiophobia has psycho-somatic responses) such that the body can't effectively fight a nonradiogenic cancer (Wang et al., 2016).

Acute radiation syndrome

Medical intervention for acute radiation syndrome (ARS) targets (Hofer et al., 2017) 2 Sv but ARS does not become significant until 4 Sv. Here, it becomes lethal to half the population within 30 days ($LD_{50/30}$) in the range of 3.5 to 5 Sv with no medical intervention (DOE 2017). Nausea and vomiting will occur at shorter delay times with higher doses due to the radio-compromised stomach linings inability to reproduce during the acidic digestion of its epithelial cells. Later effects also occur to the gastrointestinal tract where the epithelial layers again are not sufficiently replaced, potentially also allowing the E-coli to attack its supply, and even enter the blood. Depending on the health of the individual and the dose received, medical support can significantly improve survivability (Hofer et al., 2017).

ARS is effectively a condition where the body has a very poor immune system and so opportunistic infections of almost any sort can become deadly. Common medical treatments may include antivirals, antibiotics, antifungals and intravenous hydration. With medical intervention, the $LD_{50/30}$ level is in the range of 4.5 to 8 Sv.

Latent cancers

Possibly the greatest public fear of nuclear technology is that stemming from the known potential for large doses of radiation to promote cancer. With the average of all cancers combined being 40% for a US citizen to eventually contract the disease (Cronin et al., 2018), any increases above this average level is the contributor to popular radiophobia. Historical radiation exposures have demonstrated that acute exposures to ionizing radiation generate approximately a 5% increase in cancer rates per Sv absorbed whole body dose (NCRP, 1997). A dose rate factor is known to reduce acute exposure risks by at least a factor of 2 such that if the exposure is not acute and uniformly spread out over many weeks or months, a lower efficacy is realized (Hall et al., 2017).

The relationship for the number of individuals in a cohort to obtain a statistically significant result increases almost exponentially with decreasing dose (Brenner et al., 2003 Nov 25). At 100 mSv, the cohort would have to be $\sim 2 \times 10^4$ but around a dose of 40 mSv, the cohort would have to be $\sim 10^5$ and around a dose of 20 mSv the cohort would now have to be $\sim 10^6$ as described elsewhere (Brenner et al., 2003 Nov 25). Finding a million individuals who obtained such a small dose where all other confounding factors can be mitigated is not a trivial task and so the question remains open for low dose effects.

The general fear from nuclear energy might not be the radiation dose per se, but rather the unknown. When a nuclear accident occurs, and a researcher uses LNT to predict excess deaths worldwide, this latter effect appears horrific and intolerable, even through the doses may be many orders of magnitude lower than therapeutic radiation exposures or even less than natural background.

Public opinion and bias

It might seem reasonable to expect that educated citizenry would base their opinions toward any technology on facts and science alone. That it has been shown, that an individual's worldview actually has direct effect on their opinion of nuclear energy (Peters and Slovic, 1996), makes for less than objective expectations on this topic. It has been argued that this implicit bias against the facts come from the “birth defect” of atomic war and death (Slovic et al., 1991).

This societal worldview bias on science, falls back to an understanding, that anti-nuclear sentiments are tribalistic. This statement should not be seen as a condemnation or criticism of anti-nuclear perspectives. Rather, that all groups are naturally tribalistic (particularly in politics) has been shown to be inherently human (Clark et al., 2019), and so something we all experience in some fashion, it is natural.

Consider that tribalism is the same tendency to think your school or the sports team closest to where you live is “the best”, even when the facts contradict this assertion. It applies to commercial brands (Ruane and Wallace, 2015), vaccination (or an inhibition to receive them) (Attwell and Smith, 2017), climate science (Beck, 2012) and religion (Weissman, 2017). It has even been argued that this is the very effect in religion which can lead to terrorism (Cross, 2014). If you have ever seen a debate over who's team, religion or politics are best, you might understand the potential (or lack thereof) to have the facts change an anti-nuclear mind-set, irrespective of the facts. Given that it has been shown how anti-nuclear perspectives have become part of the very ethnography of those who oppose the use of nuclear science (Siemer, 2019), the inherent tribalism perspective will then bias the interpretation of the relevant facts accordingly.

Nuclear accidents

As with all energy technologies, it is not possible to say that any will have zero risk due to the definition given in Eq. (1). This means that an appropriate risk management perspective will consider all outcomes, with their probabilities, for objective risk assessment.

Along with a brief review of the radiological impact from each major historical nuclear accident, the cost per collective annual background dose will be concluded. From these, the risks can then be compared to other energy options. This will be found to drastically contrast with the common perception that a nuclear accident compares to an Armageddon event (Huhtala and Remes, 2017). In addressing these fears, the safety system costs, become exorbitantly large due to this over exaggerated perspective of the risks involved from nuclear. The following examples from major nuclear accidents readily demonstrate this characteristic.

Three-mile island

The core meltdown from Three-mile island (TMI) was the initial driver for requiring nuclear safety analysis to incorporate probabilistic safety analysis techniques as these would have readily identified the weakness in the TMI design that lead up to the release. This drastic change occurred despite the release from TMI being negligible from a public health perspective (Holzman, 2003). Based on Eq. (1) considering only stochastic effects, the radiophobic reaction was substantial. As in other nuclear accidents, the public doses offsite were estimated to be very low at 0.03 μSv (compared to 6 μSv as the average daily background from radon alone) (Gerusky, 1981). Despite this, the overtly negative reaction generated observable stress related physiological responses in the public (Chisholm et al., 1981).

The financial impact of the meltdown for TMI has been estimated at only 1 Billion US$ with a collective dose estimate of 33 person Sv (Aya et al., 1998). Using the normalized annual background dose of 3.1 mSv, this results in a cost per risk metric of approximately 100 kUS$ per annual background dose to an individual.

Chernobyl

It is not unreasonable to describe Chernobyl as the worst case scenario for any single nuclear reactor. That the graphite in the core combusted, allowing the radioactivity to loft uncontrolled, caused large scale contamination which would be difficult to surpass intentionally. The thyroid cancer increases were small but statistically significant, primarily in Belarus (Moysich et al., 2002). Although many of the thyroid cancers were successfully treated, survivors often have to take iodine pills for the remainder of their lives demonstrating one of many clear consequences from this event. Even with this, the thyroid cancers did not follow LNT and almost disappeared for exposed adults in the most impacted areas (Williams, 2008). Similarly, the leukaemia increases were small for children and below the detection limit for adults (Moyisch et al., 2002) speaking to the drastic lack of initially predicted cancers using LNT (Jargin, 2018).

Using the published cost estimates (Kinly, 2006) of 235 billion US$ and collective doses of 1.5×10^5 person mSv results in a collective risk per cost just under 5 kUS$ per annual background dose to an individual. Relative to the other nuclear power plant accidents, in these units this disaster looks cheap (largely due to the readily measurable consequences).

Although no leukaemia's were found in the emergency responders who did not succumb to ARS, the largest overall health consequence to date has turned out to be suicide for these individuals (Rahu et al., 2015). Likewise, the statistically-significant increase in thyroid cancers to Chernobyl fallout victims (WHO, 2016) was accompanied by a much larger statistically-significant increase in suicides, attributed again to radiophobia (Bromet et al., 2011). This is a profound finding, ignoring the many thousands of unnecessary abortions which occurred early on after Chernobyl, the number of self-inflicted fatalities has now outnumbered the number of radiogenic related deaths by at least a factor of 2 and all due strictly to the effects of radiophobia (Rahu et al., 2015). Apparently this accompanies a stigma where others look at those irradiated as "diseased" with those exposed having a tendency to blame any and all health issues to the radiation, creating a self-fulfilling and self-condemning cycle, leaving them without hope. This is a very profound result, the psychological effects from the Chernobyl event have now been found to be the largest public health consequence from the event (Bromet et al., 2011). It appears as though fear is the real enemy in nuclear accidents.

Fukushima

The Fukushima event could be described as a worst case scenario for a western design nuclear reactor and a primary public voiced argument, against the use of nuclear energy (Rogner and Weijermars, 2013). Here, there occurred multiple reactor core meltdowns with accompanied leaks into the environment.

Unlike Chernobyl, the typical doses to emergency workers were only in the range of 10's of mSv due to the reactor safety design features (such as a containment). At these low dose levels, an extremely large population (millions) would have to be given this dose to just see a statistically significant increase in cancer induction after the latency period (generally exceeding a decade). The increase at 10 mSv would only be 0.05% if LNT is correct at these levels. As a result of these small doses, this lead multiple bodies of international expert consensus teams to conclude that there are not any expected measurable medical effects from the entire Fukushima release, literally no discernible difference from natural rates and effects (Akiba, 2012). This consensus body was organized by the same international organization which assembled the international panel on climate change (IPCC), that being the United Nations.

That statement warrants some rather substantial scrutiny given the visceral reaction often accompanying the word "Fukushima". With such terror associated with the concept of Fukushima, and the overtly negative response incurred just at the name, to claim that all the radiation had zero measurable medical effects, is almost the very definition of cognitive dissonance to any anti-nuclear sentiment by well-meaning individuals. Can such a statement then be true? The World Health Organization (WHO, 2013), the United Nations Council for the Effects of Atomic Radiation (UNSCEAR, 2013) along with multiple subsequent review papers (Akiba, 2012, McLaughlin et al., 2012, Ishikawa, 2016, Akiba, 2012) have all come to this same conclusion, no measurable radiogenic medical consequences are expected from all of the Fukushima radiation emitted. Alternatively, there are substantial medical consequences from the stress of a high risk perception by the public from the event (Takebayashi et al., 2017).

To exacerbate this extreme contradictory concept created by radiophobia regarding the Fukushima disaster, it has now been shown that each and every death to a member of the public was fully attributable to the panicked evacuation (Hasegawa et al., 2016). Citizens literally risked and lost their lives to avoid an exposure that would not result in a single measurable medical effect (Hayakawa, 2016). Again, it would appear in the case of radiation, the thing we should really fear, is fear itself. It might even be argued that those who promote LNT are generating a meaningful public health hazard, literally killing people.

The evacuation criteria used in the United States is similarly very conservative, in that the US Environmental Protection Agency will recommend evacuation from radiological contamination worst case dose rates at as low as 10 mSv/yr up to 50 mSv/yr. These doses then range from that of an abdomen CT scan to a maximum legal radiation worker dose in the USA.

Other than the evacuation deaths, financial costs from the Fukushima event have now been estimated to range from 220 to 500 Billion US$ overall (Behling et al., 2019). The long term collective dose has been estimated (Smith, 2014) as 4.8×10 person mSv. From this, in units of annual background dose (3.1 mSv), this cost per risk is just over 300 kUS$ per annual background dose to an individual.

Eventual geological disposal of nuclear waste

The term "nuclear waste" itself is effectively another terror phrase to the public through its portrayal in common discourse (Pajo, 2015). It has even been considered a significant societal injustice for the fears from this term not being a driver in decision making without any quantitative risk consideration (Jenkins and Taebi, 2019).

According to the NEI (NEI, 2020), "after 7,000 shipments of used fuel by the worldwide nuclear industry since 1970, there have been no leaks of radioactive material or personal injuries". Given that there has not occurred a release of this kind in the United States from the legal (licensed) transportation of commercial nuclear waste, this provides an estimate for the bounding probability of such an event.

The US has received almost 20% of its electrical supply from nuclear for over 45 years (EIA, 2022). Despite this, according to the US Department of Energy (DOE, 2020b), "In fact, the U.S. has produced roughly 83,000 metric tons of used fuel since the 1950s—and all of it could fit on a single football field at a depth of less than 10 yards." Such a small volume for such an enormous output comes from such a high energy density found in nuclear power.

Still, in order to get the waste to a nuclear repository, it must be transported in properly licensed containers. According to the World Nuclear Association, "There has never been any accident in which a Type B transport cask containing radioactive materials has been breached or has leaked." (WNO, 2020) Even this is stalled by the Nuclear Waste Policy Act (NWPAA, 1987) which requires a licensed geological disposal facility to be built prior to consolidated interim storage. This results in a political barrier rather than a technical cause (Hadjilambrinos, 2006) being a hindrance to solving the nuclear waste issue.

Interim spent fuel storage installations (ISFSI)

With no licensed geological disposal facility (e.g., Yucca Mountain), the current inventory of spent fuel in the United States must be stored on the site where the fuel was utilized. Nuclear facilities have limited storage space in their cooling ponds for the spent fuel and so have had to construct a licensed ISFSI on site to hold the waste until another legal disposition path is found. Here, cost effectiveness warrants current construction of a large scale integrated ISFSI (Wegel et al., 2019). This concept of consolidating the multiple small ISFSI locations into a single large ISFSI, makes sense from an economy of scale perspective as a single security, safety and operation would reduce overall risk. Obtaining such a licence is not trivial and does require a comprehensive safety basis with concomitant reviews, potential revisions and only then, possible approval (Fischer and Howe, 1999).

Some situations have been found to require combined solutions (Seo et al., 2018) including changing fuel burnup cycles and fuel isotopics (azimi and Todreas, 1999). Despite all this, long term solutions will eventually require some form of consolidation as multiple small ISFSI locations are coastal and upon climate change flooding, will be subject to elevated risk (Jenkins et al., 2020).

Transportation of nuclear waste

When spent nuclear fuel, transuranic (TRU) or high level waste is to be shipped, the type B transportation and storage containers (Sanders, 2013) themselves undergo extreme safety and testing requirements preventing public exposures from exceeding regulatory limits even under hypothetical accident conditions (NRC, 2020,). Looking only at the nuclear weapons complex, there has not been a single detectable environmental release from transporting TRU wastes despite the standard suite of traffic accidents. Still, it is reasonable to expect that there have been Type A (e.g., very low level activity shipped in cardboard

Table 1
Hourly dose values radially perpendicular from the mid-plane of a spent nuclear fuel bundle with dose values for measurable medical effects.

Hourly dose	Radial distance	Medical Effects typical for the associated dose
234 Sv	0 m (contact)	Death from central nervous system failure likely within acquisition period
12 Sv	1 m	Death from central nervous system failure within 5 to 12 days
4.2 Sv	2 m	In the $LD_{50/30}$ range with ARS and more than 20% increase in future cancer post latency period.

Table 2
Hourly dose values obtainable from a location radially out toward the end of spent nuclear fuel bundle with dose values for measurable medical effects.

Hourly dose	Radial distance	Medical Effects typical for the associated dose
61 Sv	0 m (contact)	Death from central nervous system failure within a week
5.6 Sv	1 m	Upper range of the $LD_{50/30}$ from ARS allowing death within 2-3 weeks
2.8 Sv	2 m	Sunburn accompanied by mild ARS and more than 15% increase in future cancer post latency period.

boxes) transportation events which would have had leaks just from normal upset conditions in transport.

According to the state of Nevada website, there have been at least 4 incidents out of 72 where such contamination was detected which could not be demonstrated to have not been present prior to shipment allowing for the possibility of a leaking container (Nevada, 2020). Assuming these were all legitimate leaks, the relevant question still comes back to proper risk management, should one choose to increase the containment rigor of a transportation storage cask, how much cost is reasonable for the risk averted. Still, according to the US Nuclear Regulatory Commission, there has not yet occurred a nuclear waste transportation accident which has released any detectable radioactivity from spent fuel transportation storage casks (NRC, 2016).

The dose rates from a typical spent nuclear fuel bundle appropriate for shipping (Croff et al., 1979) are summarized in Tables 1 and 2. Along with these are the characteristic dose levels for various medical effects. In this way, the medical effect which would be incurred with a 1-hour exposure is shown for the position relative to the *unshielded* bare fuel bundle. Here it can be seen that unshielded dose rates on contact or very near the unshielded bundle, truly are lethal, particularly if exposures last on the order of an hour.

The key point from Tables 1 & 2 are that these could only be expected if the transportation cask holding the spent fuel disintegrated or was perniciously separated from the contents enabling direct public exposure or environmental release. By not spending an hour up close and personal with the bundles, the dose is reduced by an order of magnitude with only a 6-minute dwell time. Here, the worst case dose at 1 m would be around 1 Sv which is entirely survivable and only incurs a 5% increase in cancer rate probability after its latency period. Even this assumes a 6-minute dwell time at 1 m rather say 30 seconds which would decrease the dose by another order. The point being made is that although the radiation is deadly to be sure, it is not difficult to protect the public from harm (even if unshielded just by controlling time and distance). This is particularly true with shielding and containment.

Dose rates outside a transportation cask are required to have contact dose rates below 2 mSv hr^{-1} at the highest yellow III category without exclusive use provisions (10CFR71, 2020). At 1 and 2 m distances, the values would decrease accordingly.

Because of the applied shielding in approved transportation casks, collective doses from transportation are a very small fraction of background. Specifically, on a per shipment basis, this value would be 3.7 person mSv in total (Cook et al., 2013). Using an estimate of 9 MUS$ to manufacture a single storage transportation cask (Macfarlane, 2001) and a full year of usage of one shipment per day gives a cost per risk of 20.6 kUS$ per annual background exposure with the intent that this go to Yucca Mountain.

Given the political delays in allowing the licence application to proceed, interim storage has now started to become the more economical bridge for high level nuclear waste management (WHO, 2013). Multiple options for a consolidated ISFSI have been proposed but the current version of the law requires a permanent disposal option to be licensed first, and so how this will play out is indeterminate.

Natural nuclear reactors in the geological record

An unexpected analogue for the safe geological disposal of nuclear waste can be found in an ancient natural nuclear reactor[1]. As pointed out previously, by going back in time, the natural concentration of the primordial radionuclides increases exponentially. With the fissile isotope ^{235}U having a half-life of 704 Ma and the fissionable isotope ^{238}U having a half-life of 4,468 Ma, the ratio of $^{235}U/^{238}U$ effectively increases exponentially backwards in time. This means that around 2 billion years ago, the natural enrichment would be comparable to that used in commercial nuclear reactors today, just under 4%. Similarly, the enrichment at the earths formation (ca. 4.5 Ga), it would have been high enriched uranium being above 20%.

The only natural nuclear reactors known to have existed so far (Hidaka, 1999) were in the African Republic of Gabon and were associated with a modern uranium mine (providing the initial basis for discovery). It is now believed that the natural reactor would cycle active for 30 min (ejecting its moderating water) until trickle back would occur over a few hours allowing the critical chain reaction to reoccur. The significance here is in our ability to characterize how well an example geological media can retain fission products (Meshik et al., 2004). That we can now see the resultant transport of fission products from these events in the geological region is a strong validation of our ability to estimate these diffusive processes over geological time periods (Loss et al., 1984) to include water transport and geochemistry (Toulhoat et al., 1996). The reactions could have continued for over 100 ka with temperatures not exceeding 400 °C (when the water moderator is expelled) (Hidaka and Holliger, 1998).

It is an interesting novelty that the fine structure constant α (Eq. (2)) is obtained from Oklo through the fission product distribution implying the assumed fundamental forces have not changed over the past few billion years (Davis and Hamdan, 2015). This is highly significant from a cosmological historical perspective in that α is a function of some of the most fundamental physical parameters assumed constant since the big bang. Here, k is Coulombs constant, e is the electron charge, h is Planck's constant and c is the velocity of light

$$\alpha = \frac{ke^2}{hc} \tag{2}$$

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[1] Hayes, R.B., 2022. The ubiquity of nuclear fission reactors throughout time and space. *Physics and Chemistry of the Earth, Parts A/B/C*, *125*, p.103083.

Yucca Mountain

It has been shown that objective negative bias has been occurring in the media on nuclear waste to the extent that the anti-nuclear perspective is now literally part of the ethnography in the US (Siqueira et al., 2019). It should not be surprising then that for some individuals, nuclear waste issues are the dominant detracting issue associated with the use of nuclear energy (Taebi and Kloosterman, 2008) (akin to the tribalism of politics or religion).

The Yucca Mountain site is nestled within the Nellis Bombing Range adjacent to the former Nevada Test Site. It is approximately 110 km northeast of Las Vegas and almost 30 km northwest of Death Valley. With the geology of this site extensively evaluated, uncertainties remain associated with long term water infiltration effects (while recognizing transportation has the same public acceptance problems) (Tyler, 2020), with other considerations including rock mechanics due to heat stresses (Barton, 2020). This has been argued to be the most geologically studied piece of real estate on the planet.

Detailed technical analysis has now found that the Yucca Mountain repository would meet all the regulatory safety requirements (Swift and Bonano, 2016) (pending obtaining land and water rights requisite for construction and operation of the facility). That this fact is generally considered equivalent to having technical problems (when it is in reality only due to the politics of defunding the effort) is a common theme among review papers unfavourable to nuclear energy (Prăvălie and Bandoc, 2018), with others taking a more restrained approach to criticisms (Long and Ewing, 2004) (where uncertainties are emphasized).

The Waste Isolation Pilot Plant (WIPP)

The WIPP is the world's first geological repository for TRU waste. It is located in the southeastern corner of New Mexico. In February of 2014, a 55-gal drum of TRU waste from the Los Alamos National Laboratory deflagrated aerosolizing an estimated 7 Ci of ^{241}Am along with nitrate salts into the underground portion of the facility (Thakur et al., 2015). Current environmental levels outside the facility are indistinguishable from those prior to the event leaving them effectively within the natural variations of the past centuries global fallout content (Thakur and Ward, 2016). The resulting airborne dose potential validated for the entire ensuing release is shown in Fig. 2. Here the flags show the air monitoring stations used to validate the calculated plume contour potential (Hayes, 2016).

Prior to this event, the WIPP would report their annual releases of radioactivity as equal to the detection limits of all their radiological air monitoring assays (Ward and Basabilvazo, 2017). This in spite of the fact that their detection limits were substantially below natural levels of radon progeny in the air.

Post-event, the resulting release was monitored and characterized after the fact. Due to the safety features in place, the effluent was actually within their previously approved annual release limits (Thakur and Runyon, 2018) based on their radioactive material license issued by the US Environmental Protection Agency. The actual maximum dose potential on the public road (seen in Fig. 2 was 30 μSv assuming an individual stood there for at least 8 hours during the entire release. This is less than the dose from a single arm x-ray or a flight from New York to Los Angeles (HPS, 2022).

Needless to say, the event terrorized residents who lived over 60 km away where levels were far below detection limits (Zack, 2014). This is profound in that detection limits were able to see resuspended fallout particulate from atmospheric weapons testing in the prior century (WHO, 2013) (from Fig 1 which is less than 0.1% of average annual exposures).

The event placed the facility in a recovery mode for almost 2 years at an operational cost of approximately 0.35 billion US\$ yr^{-1} and with an infrastructure upgrade cost of 0.5 billion US\$. Assuming all residents did receive the full 0.1% of natural background for 30k residents gives a collective dose of 93 person mSv. From these, a rough estimate of the cost per risk incurred 13 million US\$ per person mSv.

Science, technology and policy

The applications for nuclear science and technology span almost all of modern conveniences and medicine to some extent or another (Hayes, 2017) with the largest hindrance tending to be public acceptance. Alternatively, the use of traditional renewables are almost universally accepted despite a suite of risks which can be very difficult to mitigate and predict including grid integration, worker safety, source material acquisition, processing and incentives (Ioannou et al., 2017).

Cost to the consumer is simply not the only lifecycle impact of concern as environmental impact is required to be minimized for sustainability. The lifecycle use of materials is just such an environmental point of interest when selecting an energy source. The US Department of Energy compared energy sources (Peters and Slovic, 1996) by total lifecycle material requirements as shown in Fig. 3. This metric is similar to total devoted land use as the footprint for the power station is not the only impact of concern. When considering the total amount of materials per energy obtained, the environmental friendliness of renewables looks to disappear completely in comparison with nuclear.

This dichotomy is only exacerbated by the need for traditional baseload energy to convert over to traditional renewables. The need for baseload in supplying the grid has been shown to make a complete conversion to traditional renewables impossible without a baseload supply such as fossil fuels (Blazquez et al., 2018) (or nuclear).

Greenhouse gas emissions supporting the grid

If a primary driver for energy choices is not simply that it be renewable but that it generate minimum greenhouse gas emissions per kWh produced, nuclear energy has been argued to be as good if not better than the other renewable sources. A significant result along these lines is shown in Fig. 4 from the US Department of Energy 2015 Quadrennial Technology Review (DOE, 2015).

Given the current climate crisis identified by the IPCC, the imperative to switch over to baseload capable energy for the grid should not only be a national security issue, but it has now been shown and recognized that nuclear has to play a much larger role than previously realized (Gattie, 2020). The same can be said for hybrid systems of coupled nuclear and traditional renewables, the combined benefit is clearly an option which should not be ignored (Suman, 2018).

If nuclear energy is coupled with hydrogen production to enable load following capability, the technology being fully developed would still require financial incentives due to the cost for nuclear not being considered low (Pinsky et al., 2020). However, when coupled with traditional renewables, the nuclear contribution can carry intermediaries allowing hydrogen production for fuel cells providing a direct transportation CO_2 mitigation capability (Orhan et al., 2012). Not a cost benefit incentive but clearly supporting climate sustainability.

Liquid fuel transportation energy supplied by nuclear

The largest contribution to greenhouse gas emissions is not the grid but rather transportation (EPA, 2022) and this due to the specific energy found in liquid fossil fuels. The solutions to replacing our transportation sectors addiction to fossil fuels are broad and innovative when coupled with nuclear energy (Forsberg, 2008). As a transition capability, nuclear could do full carbon capture from current and retiring fossil fuel plants to turn these emissions into liquid fuels (Middleton et al., 2009).

Simply by providing the energy (from nuclear) to create hydrogen from water, fuel cells can be used for transportation (O'Brien, 2012). Beyond simple hydrogen production, if nuclear is used for carbon sequestration from the atmosphere, to create organic liquid fuels, the process could become carbon negative. Alternatively, the nuclear hydro-

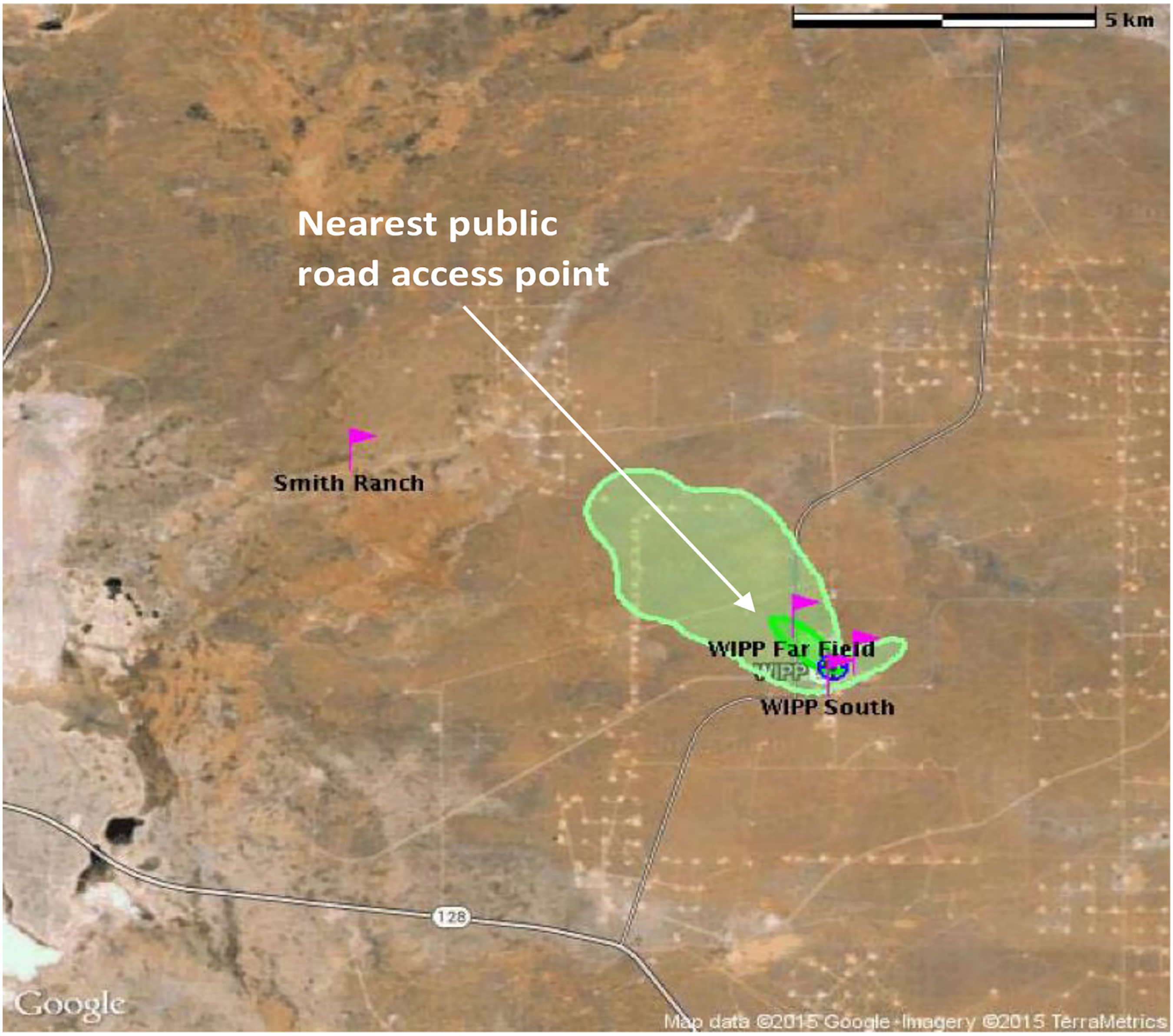

Fig. 2. Dose potential contours from the WIPP 2014 airborne release event (Hayes, 2016, Nasstrom et al., 2015). The outer contour represents 10 μSv and the inner contour (inside the stars) represents the 100 μSv level. The closest public road access to the site is shown by the inset arrow near one of the tagged monitoring stations.

gen could be coupled with biomass-to-liquid fuel production to utilize waste biomass in another version of a carbon neutral energy paradigm (Forsberg, 2009). Combinations of all these options is argued to be the optimal transition correction to mitigate various potential risks (Hori, 2008) through diversification. Note that in all of these solutions to removing greenhouse gas emissions from our transportation sector, nuclear energy allows this to occur in an overall carbon neutral or even a carbon negative manner with a small environmental footprint (Fig 3&4).

That nuclear has the ability to both replace liquid fuels for transportation, and provide dispatchable baseload (even load following capabilities) to the grid, does not dictate that this is the best energy for *all* sources. If the supply chain for nuclear energy was highly diverse so that single point failures in manufacture, procurement or distribution in any way were eliminated, *then* this would argue for nuclear to take a very large portion of our energy supply as its reliability, maintainability and availability would enable it to be highly robust.

Nuclear energy can now be renewable

It has long been known that the mineral content in fresh mountain spring water comes from leaching of the rocks through which the water trickles. More specifically, not just familiar minerals leach into surface water but all elemental constituents from the rock migrate into the water to varying degrees with the rock continually being replenished by plate tectonics. Plate tectonics replace the mountains and continents making these minerals renewable akin to hydro or geothermal in terms of natural replenishment sequences.

This basic geology theory applies also to the heavy elements such that the resultant uranium species being passively poured into the ocean each year is roughly 9x the annual total energy use rate of the United States (Palmer and Edmond, 1993). Currently this is precipitated out on the ocean floor with other sediments but could be diverted to safe nuclear energy as currently enjoyed by various nuclear energy suppliers. The technology to extract uranium from seawater is entirely passive,

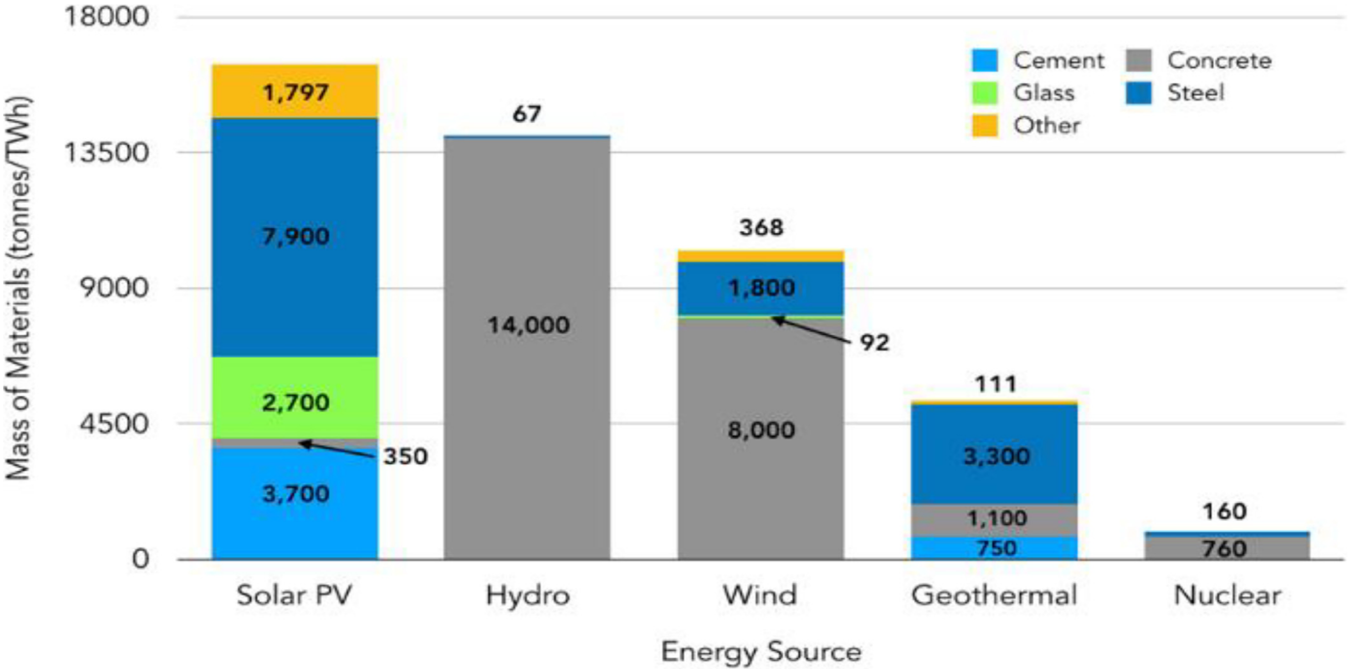

Fig. 3. Lifecycle material mass requirements for various energy sources per energy produced. Image generated by Environmental Progress (used by permission).

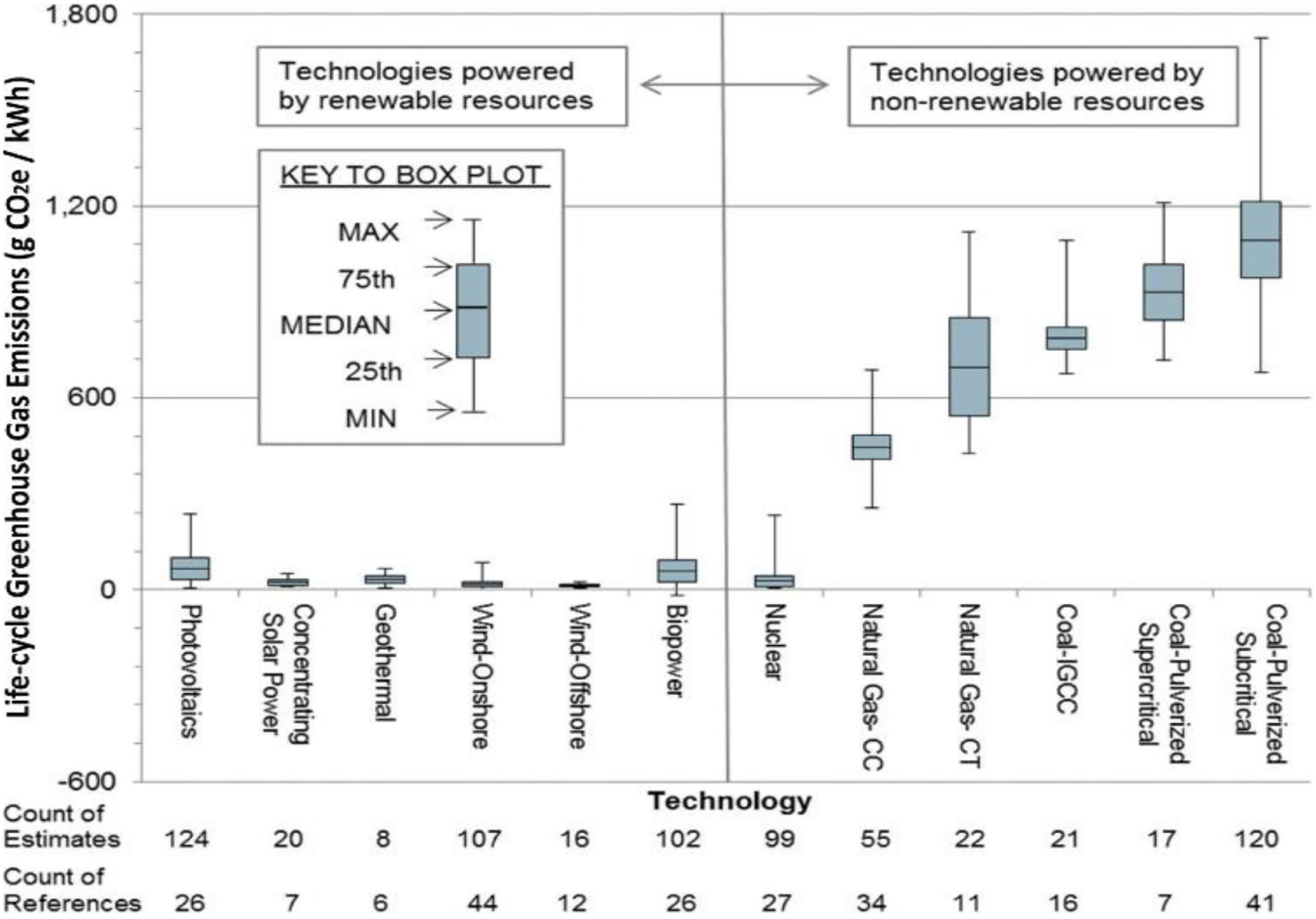

Fig. 4. Life-cycle greenhouse gas emissions per kWh generated from all energy sources (Figure used by permission 2020).

done by coating a frond array placed on the ocean floor (or floating on the surface) with a virtually inert resin which concentrates the dissolved U_3O_8 in seawater onto the resin effectively bypassing traditional mining and milling facilities.

The sun will eventually run out of fuel in some 7.6 billion years (Schröder and Smith, 2008). Geothermal is largely fuelled by the radioactive decay of primordial radionuclides (Dye, 2012) such as natural uranium, thorium and potassium. With the uranium alone having a 4.5 billion year half-live, this material will still be around long after the earth is a burnt cinder when the sun goes red giant. So although it is not being utilized as renewable in the way that geothermal energy is renewable, even though geothermal is indirectly nuclear (as are solar and wind). Traditional nuclear energy technically can be renewable, we need only change the material source to passive, sustainable ocean water extraction. Although this has not been realized on a commercial scale, recent research has now claimed novel methods which would be economically viable (Xu et al., 2020).

Water desalination

There can be no disagreement that water is one of the many features essential to life as we know it. Given population growth and habitability of arid regions being limited due to water resources, a large supply of water to these areas could turn desserts into breadbaskets and stave off drought and its associated suffering. What is desirable in trying to meet our ever increasing needs for desalinated water is sustainability, which is limited although conceivable using traditional renewables (Lior, 2017).

Others have argued that traditional renewables can, under idealized conditions, have a negligible impact in suppling every energy need (Jacobson and Delucchi, 2011), similar claims are more readily made by conventional nuclear. It has been shown however, that the traditional renewables (solar) have to displace the best croplands (Adeh et al., 2019) to attain these claims (and so displacing traditional food sources). This has also been shown to completely ignore any and all limitations based on energy storage needs to meet baseload demands drastically contradicting the same claims (Guozden et al., 2020).

The largest detractor from the use of traditional renewables in water desalination is the large overall land footprint associated with these energy sources. Due to the low power density from solar and wind relative to the very high power density of nuclear (van Zalk and Behrens, 2018), the latter has a much more environmentally friendly disposition in terms of this impact metric (Fig. 3). Still, traditional renewables have been argued for both wind (Ma and Lu, 2011) and solar (Chandrashekara and Yadev, 2017) to be able to meet this need with sufficient investment making them look quite attractive in niche markets (Alkaisi et al., 2017).

If water desalination capability and production is to be diversified to include nuclear, additional benefits can be realized. Specifically, it has been shown that using nuclear in water desalination, can more efficiently extract the natural uranium for fuel from the same seawater fed by natural runoff (Sodaye et al., 2009). This means desalination using traditional renewables or nuclear can be a source of nuclear fuel using the waste products from the desalination plant (another example of nuclear becoming renewable).

6.5. Nuclear non-proliferation

It is hard to overstate the importance of maintaining proliferation resistant nuclear reactor technology which helps explain the great strides towards this in western designs (Penner et al., 2008). It is not that nuclear energy in and of itself creates nuclear weapons any more than an iron mine creates guns but rather, that both require an infrastructure which typically is used for civil and social discourse among the nations. The current non-proliferation landscape has the US protecting Turkey, Germany, Belgium, the Netherlands, and Italy, should they suffer a nuclear attack (Kristensen and Korda, 2019). These countries would be given control of US nuclear weapons for retaliation of a nuclear attack on their country allowing them security and no motivation to develop their own nuclear arsenal and so limit proliferation in this way. This complicates complete disarmament, as many players have to agree unilaterally.

The technology for promoting nuclear non-proliferation has tremendously advanced to unprecedented levels. In the unclassified realm, research has demonstrated that thermoluminescence can be used on common red brick to make them behave like a retrospective low resolution gamma ray spectrometer at both high (Hayes and Sholom, 2017) and low gamma energies (O'Mara and Hayes, 2018). Optically stimulated luminescence has been demonstrated to turn an array of dosimetric material (e.g., electrical insulators or tiles) into a 3D gamma camera (Hayes and O'Mara, 2020) able to spatially resolve historical radioactive material. Applications then include retrospective assay of UF_6 enrichment (Hayes, 2019), using particulate from smears as dosimeters (Hayes et al., 2019) and even measuring an individual's dose at levels approaching natural background (Hayes and O'Mara, 2019). Adding to this electron paramagnetic resonance for ubiquitous organic materials (Hayes and Abdelrahman, 2016) which can be done nondestructively for common items (Hayes et al., 2019), the options to hide proliferant activity indefinitely are diminishing if at all extant. With radiological air monitoring research, this extends now to remote characterization of a release (Hayes, 2017) and now even in accelerated time frames mitigating radon progeny in an air sample assay (Cope and Hayes, 2019). There is ample nuclear forensic and attribution technology to deter and prevent effort going without detection.

Risk management for nuclear energy?

The use of probabilistic risk assessment is credited for having the ability to prevent a Three Mile Island type event (Gu, 2018) and so required today for licensing. The Three Mile Island event is attributed to why the US did not continue building nuclear reactors after the event in any great numbers and even stopped multiple units under construction. As seen in Figs. 3 & 4, were fossil plants to have continued being replaced by nuclear power plants to any extent, then this would have largely been equivalent to replacing the same with fully renewable energy sources. If the uranium would have been passively extracted from the ocean, then this would be fully renewable energy.

The difficult questions to answer include the number of deaths per greenhouse gas emitted along with logistics of transitioning all energy sources to renewables. The path of least resistance would be some combination of low cost, rapid transition and small overall footprint in terms of total land area impacted including mining, manufacture, deployment and disposal. Still, statistics are available to consider death rates per power generated from nuclear and traditional renewables from operations alone.

Observable fatality rate comparisons

The estimated probability of a major nuclear power plant release event has empirically been demonstrated historically to be 63% over a 30 year period assuming no improvements over historical characteristics (Ha-Duong and Journé, 2014). This also assumed the number of reactors operating remained unchanged so future deaths from any future events can reasonably be expected to be comparable such that with western designs, this should remain zero as with Fukushima.

The Chernobyl event is reasonably bounding for all commercial designs around the world given that it was comparable in effect to a successfully deliberate wartime or terrorist event. Here, it could be assumed that the statistically significant number of attributable radiogenic deaths is near 10^3.

Industrial fatality rates (non-nuclear) have been trending high in the US at 35 per million full time workers each year in 2018. In this same interval, US nuclear electric power generation demonstrated an order

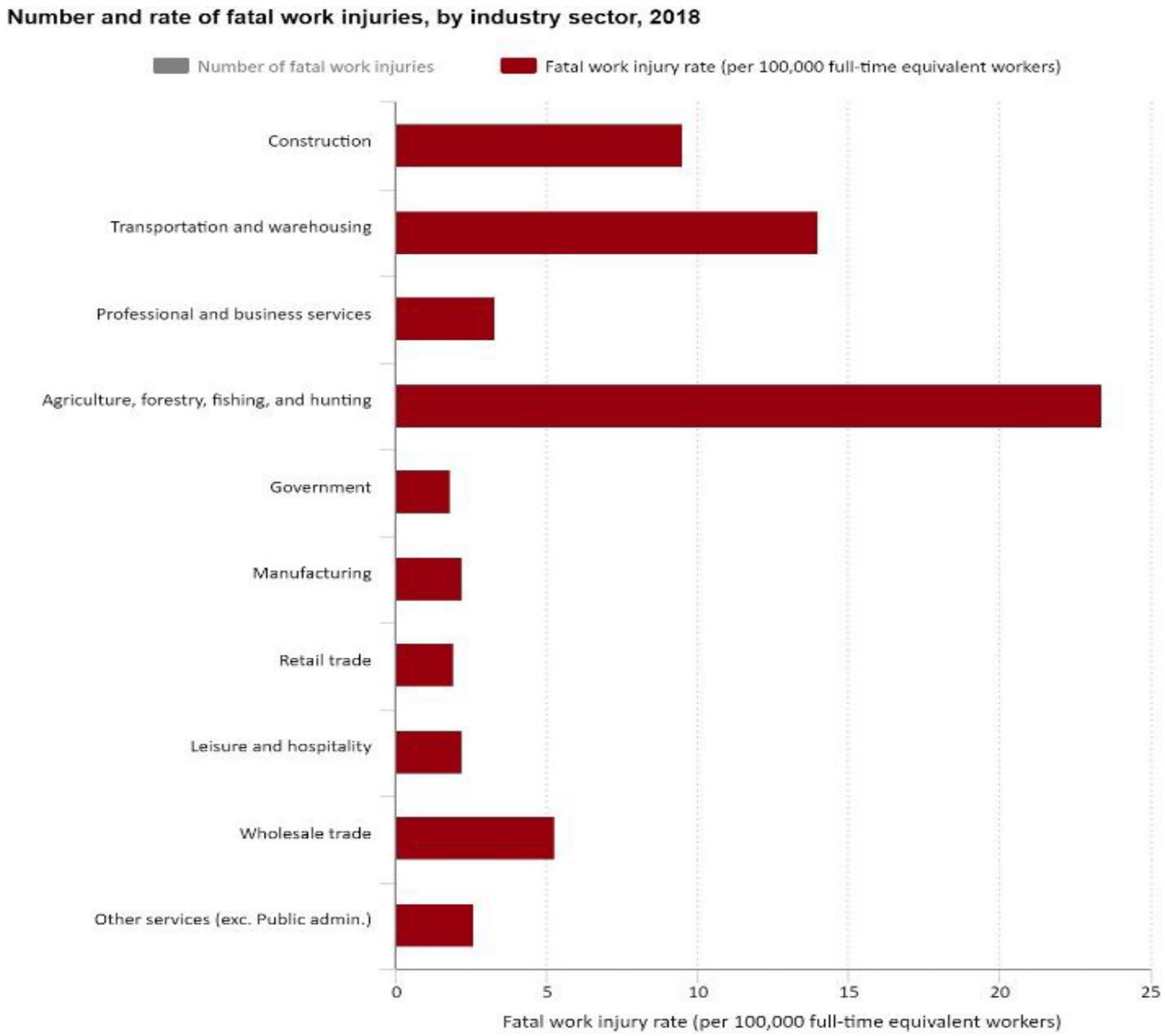

Fig. 5. Annual fatalities from occupational hazards in all US industries (note there were zero in nuclear power generation) (Injuries 2018).

of magnitude reduction of nonfatal accidents relative to all other industries (including private, state and local government) (Injuries 2018). The fatality rates from other industries shown in Fig. 5 might be a metric of socially acceptable risk from occupational or industrial endeavours ranging from 2 to 20 deaths per 10^5 full time workers each year.

Still, the appropriate comparison should be accidental deaths from traditional renewables versus that of nuclear during routine operations. As a comparison, wind farm workers were found to have a multitude of risks in operating and maintaining such large elevated turbines. These experienced an average of 4.4×10^{-5} fatalities per year (Aneziris et al., 2016) for a 0.014 GW wind farm which are small compared to the values in Fig. 4 but very high compared to nuclear. Using the value of 3×10^{-3} deaths per GW from wind, for the US nuclear capacity in 2018 of 8×10^5 GW, this would have been over 2500 deaths per year from nuclear energy production (and again, there were none BLS, 2018) at the same rate per energy produced from wind. Still, this was a Greek windfarm which may skew the results one way or another as Fig. 5 is US data.

It might be easy to think a death from doing something good like wind is ok, but a death from doing something bad like nuclear is not ok, allowing opinions to be unchanged (consistent with the definition of anti-nuclear now being part of our ethnography (Siemer, 2019, Davis and Hamdan, 2015). Similar disparities are found comparing renewable hydro to nuclear, where again, the traditional renewable (hydro) fares horribly compared to the safer option of nuclear due to dam breaks. This is reflected in Table 3 where both developing and developed countries are compared up to the year 2000 (Gordelier and Cameron, 2010). Here the deaths due to nuclear are due strictly to Chernobyl and then only the emergency responders who succumbed to ARS. This does not reflect long term effects. Under these assumptions, in the units of electric GWy, nuclear still fairs better than all other options (with hydro being the only traditional renewable considered).

The process for risk analysis has been covered by other authors (Wheatley et al., 2017) resulting in estimates assuming a human life is worth 6×10^6 US$ with the cost from Fukushima being in the billions

Table 3
Total fatalities from hydro, coal and nuclear generating stations up to the year 2000. Note that only the prompt Chernobyl fatalities are shown for the Non-OECD country results in GW electric year (GWey) output (Gordelier and Cameron, 2010).

	OECD			Non-OECD		
Energy Chain	Accidents	Fatalities	Fatalities/Gwey	Accidents	Fatalities	Fatalities/Gwey
Coal	75	2259	0.157	1044	18017	0.597
Coal (data for China 1994-1999)				819	11334	6.169
Coal (without China)				102	4831	0.597
Oil	165	3713	0.132	232	16505	0.897
Natural Gas	90	1043	0.085	45	1000	0.111
LPG	59	1905	1.957	46	2016	14.896
Hydro	1	14	0.003	10	29924	10.285
Nuclear	0	0	-	1	31*	0.048
Total	**390**	**8934**		**1480**	**72324**	

of dollars due to economic loss alone, demonstrating a clear contrast in risk management.

Geological disposal risk

The legal limit to a member of the public from geological disposal of high level waste or spent nuclear fuel is less than 10% of natural background at 0.25 mSv yr^{-1} in the USA (EPA, 2020a). The total money spent on studying Yucca Mountain to date is estimated (Conca, 2020). around 12 billion US$ and has not received any waste to date. The World Nuclear News estimated (WNO, 2020) the lifecycle cost to be around 100 billion US$ although over 10 billion US$ has already been spent for scientific studies and initial drilling efforts

The WIPP has a more restrictive limit than Yucca Mountain being 0.1 mSv yr^{-1} to the nearest dwelling of the public (EPA, 2020b) or 0.25 mSv yr^{-1} at the fence (or to the nearest uncontrolled access point for the public) or 1 mSv y^{-1} to a member of the public on site (DOE, 2020). The WIPP has been operational since 1999 and is technically over half full in terms of both volume or radioactivity limits allowed for disposal. Current WIPP annual costs (Woolf and Werner, 2021) around 0.4 billion US$ along with the estimated 1 billion US$ recovery expenses from the 2014 release event (Klaus, 2019).

Correct criticisms for nuclear energy

Although the deterministic effects from nuclear accidents on the public are generally negligible associated with the high engineering design and construction costs, this does not mean they always will be. The very fact that accidental releases have occurred, proves that these systems can attain a status of being uncontrolled. Like driving a car, being out of control is never acceptable, even for a moment. When loss of control occurs and no harm follows, this does not mean it was ok to have ever been “out of control”. That the safety systems for western designs have largely kept nuclear accidents in the range of negligible consequence, does not really address the physiological harm that comes from radiophobia as a real problem preventing societal benefit from this technology. This likewise drives up the cost for using this for electricity, due to the extensive safety systems required. Simply put, both of these issues are legitimate criticisms for using nuclear energy today.

Public acceptance

One of the difficulties in communicating complicated topics like comparative risks to the public in a comprehensive manner, is translating these concepts in a meaningful way, according to their own narrative. This has led to understandable shortfalls identified in the media when discussing the topic of nuclear energy (Kristiansen, 2017). Similarly, media coverage of the Fukushima disaster vastly overwhelmed comparable coverage of the Tsunami where the latter killed many tens of thousands of people (Mangano, 2004) (implying a harmless nuclear meltdown is substantially more interesting to media consumers than a natural disaster killing 10’s of thousands). Given that Fukushima only saw deaths from the panicked evacuation, the effects of media focusing on radiation releases can be argued to have only exacerbated public harm from our collectively intrinsic radiophobia.

The issue is likely exacerbated when experts in traditional renewables reject nuclear energy out of hand as simply being “too risky” (Oumer et al., 2018). The problem identified by others relevant to nuclear issues is the risk perception from an unknown generating a high “willingness to pay” even when it is known the risk is quite small (Hourdequin, 2019). This can also be described by a desire to not focus on false positives (Type 1 errors) but rather false negative outcomes (Type 2 errors) (Larry Heimann, 2010). In layman terms, this means we accept a “better safe than sorry” position, even when it is an exorbitant expense for a small risk.

Lifecycle costs and impacts

If the question of total financial costs are considered in units of power produced, the levelized cost of electricity (LCOE) is generally the default metric for this application. Given this, some have argued that were there to occur a nominal carbon tax, nuclear could become highly competitive fiscally, without taking credit for long term license extensions (Mari, 2014).

When considering such arguments, it should be noted that the LCOE approach for comparing energy costs has been sharply criticized due to its common application without consideration of its inherent sensitivities (Durmaz and Pommeret, 2020). Still, when evaluating various weighting schemes for important parameters in the LCOE (e.g., carbon emissions, capacity factor, location specificities including intermittency considerations) along with their uncertainties, nuclear energy has been shown to fair reasonably well overall, even though variations can be quite large (Larsson et al., 2014). Within the traditional renewable options, concentrated solar power appears to be the most attractive for potential dispatchable and baseload capability, if coupled with thermal storage (Dowling et al., 2017). As difficult as financing is for a nuclear power plant, diversification still offers hope under appropriate circumstances (Terlikowski et al., 2019).

The bulk of costs for a nuclear power plant are not so much the electrical connection to the grid or even the steam supply system as much as it is the nuclear reactor safety systems themselves. The licensing process requires that under worst case scenarios, the maximum dose to a member of the public at the fence cannot challenge 0.2 Sv, right there at the detection limit for radiogenic effects. Basically, the cost is in making sure negligible effects occur under a worst case accident (comparable to Fukushima). Any aspect which is credited for these safety requirements becomes safety significant and falls under nuclear grade quality requirements (ASME, 2019) making them very expensive.

When comparing the costs from all energy sources, the US Energy Information Agency concluded that advanced nuclear has more than 3 times the capital costs of onshore wind and more than double that for a large tracking PV array (EIA, 2016). Although combined cycle natural gas is about half that of PV and wind, the question then often asked is whether that saved cost of natural gas is worth it. The question should equally be asked about nuclear, whether the extreme safety is worth the added capital costs given that we tend to spend hundreds of thousands of dollars per background dose experienced in the most extreme worst case events? Can a background dose equivalent really be worth all that?

Discussion

The examples considered here were primarily those of the United States (US) with the exceptions of Chernobyl and Fukushima. The money spent by the US government is as much their choice as any other government to allocate their budget as they see fit. In order for money spent to mitigate radiological exposures to be considered sound risk management, consideration of the benefit per cost has to be practiced. Again both benefit and cost require metrics, but here, cost is in US$, and benefit or consequence is considered in dose equivalent to annual background.

Although multiple review papers outright advocate nuclear energy as a fundamental solution to climate change (Hejazi, 2017, Abu-Khader, 2009, Qi-Zhen, 2016), others see it as a balanced part of a diversified low greenhouse gas energy economy (Khan et al., 2019). With the large research investments in traditional renewables, others have argued we are now able to fully convert with minimal impact in our standard of living (Delucchi and Jacobson, 2011). When considering the cradle to grave of mining, manufacturing and then use and disposal, nuclear has likewise been shown to have met these target capability levels, although it remains highly stigmatized by many, even in academic circles due to the default criticisms of accidents, waste, costs and proliferation concerns (Mez, 2012).

Medicine analogy

It should be appropriate to say that our society recognizes how modern medicine is a wonderful benefit obtained from technological advancements. This despite the various risks from myriad side effects associated with all of the medical treatments and cures which are quite real (Smith et al., 2020). If we were to insist all vaccines, treatments and procedures had zero risk, we simply would no longer have medicine in any recognizable form (which would be harmful to say the least). To the extent that regulatory limits define expertly determined acceptable risk for adequate safety, any technology (including nuclear energy) meeting this mark, in an idealized society accepting of modern science, would presumably embrace the same.

Still, some might condemn these “anti-vaxers”, those who refuse medicines such as a vaccine due to its having various non-zero risks. This anti-vaxer social movement has been attributed to the use of identity politics (Attwell and Smith, 2017) which can be seen as another form of tribalism (Fukuyama, 2018) comparable to the anti-nuclear ethnography in society at present. (Siemer, 2019, Davis and Hamdan, 2015) A hope for these members of our society is that with a recognition of proper risk management being in place, a regulatory approved vaccine (or any medicine) when taken under professional guidance and control, is simply worth the risk. In their defence, it would be lovely to have zero probability of all side effects from any medical vaccination or treatment. Likewise true, it would be lovely to have zero risks from any energy source (including renewables), in all cases, this is currently not a possibility.

Future benefits and roles

With all the benefits offered by nuclear energy, the only real barriers to its deployment have been demonstrated to be rooted in radiophobia, largely attributed to the issues of nuclear waste, Fukushima and proliferation (Karakosta et al., 2013). Although these have been reviewed in this work, the reality is that public acceptance (or lack thereof) has driven nuclear to attempt to attain zero risk at exorbitant cost.

The potential to use excess heat in nuclear energy generation for water desalination would improve the efficiency of the system as a whole by not directly dumping the waste heat to the environment (Al-Othman et al., 2019). Similarly, the versatility and custom options coming available with the new small modular reactors (Mignacca and Locatelli, 2020) (SMRs) could bring about substantial changes to the nuclear energy landscape due to their diversity in potential applications (Black et al., 2015) while remaining economically viable (Black et al., 2019). Coupling this with desalination, carbon sequestration and providing industrial heat for manufacturing (Peakman and Merk, 2019), nuclear appears from these perspectives to truly be the climate solution we claim to be seeking.

With the improved passive/inherent safety found in SMR designs (Zeliang et al., 2020), the public acceptance might be expected to increase, particularly when the exclusion zone from an accident stays within the facility perimeter (Xuan et al., 2018). The lack of radiological harm to the Japanese does not alleviate the impact from the evacuation and so having new designs which remove that potential may reduce the ρ_D societal aversion metric mentioned in the introduction.

Some still believe that traditional renewables are the only preferred path to decarbonisation of the electrical grid (Jin and Kim, 2018). As argued elsewhere (Sadekin et al., 2019), this review has shown that in terms of the technological benefits to sustainably and renewably supplying the vast majority of our energy (including transportation and manufacture), when using nuclear, we can reduce environmental, public and worker risk altogether (Attwell and Smith, 2017). The requirement to see this appears to require not characterizing nuclear science and engineering as inherently bad, but rather to consider the objective facts so as not to interpret positive results in a negative light.

Typical ranges of dollars per life saved range from 19k USD up to 68k USD for health care, residential, transportation and occupational risks (Tengs et al., 1995). With nuclear energy, this has been argued elsewhere to be 2.5 billion USD for nuclear power plants and 220 million USD for radioactive waste management (Cohen, 1987) (assuming LNT) which are consistent with the present work.

The use of a fair metric for costs per risk avoided would clearly allow a much cheaper option for nuclear. Whether this would come at the cost of safety has not be evaluated but currently, there is clearly a great deal of leeway in utilizing this potentially sustainable, renewable and incredibly safe form of energy.

A comprehensive compendium on nuclear energy aspects relating to the entire world economy and energy needs would be a welcome addition to the scientific community. This work should help contribute to that literature.

Conclusions

Technically there should be no reason not to appreciate all the wonderful benefits, sustainability and progress afforded by the advancements being realized with traditional renewables. Whether this has taken place with nuclear energy is clearly in question by many. Proper risk management and consideration should be applied to all technologies accordingly, so that single point failures, supply disruption and any unique risks specific to each option are evaluated objectively. Implicit bias or any form of tribalistic narratives should be avoided by those taking an engineering or scientific perspective, so that informed recommendations and perspectives can be disseminated for the betterment of society in general. The final goal being a sustainable and ever diminishing risk to workers, the public and environment, aligned with good engineering practices.

This work finds that nuclear energy is akin to a climate savior, given the overwhelming utility, low risk and sustainability available from this technology. The only viable arguments against nuclear energy being rooted in radiophobia are theoretically able to be overcome with proper education on the relative risks associated with its use or rejection. The US should seriously seek to drastically expand its replacement of fossil fuels with nuclear energy to address both climate change and energy security.

Declaration of Competing Interest

The author declares no conflicts of interest.

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