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Review

Quantifying Global Greenhouse Gas Emissions in Human Deaths to Guide Energy Policy

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Abstract: When attempting to quantify future harms caused by carbon emissions and to set appropriate energy policies, it has been argued that the most important metric is the number of human deaths caused by climate change. Several studies have attempted to overcome the uncertainties associated with such forecasting. In this article, approaches to estimating future human death tolls from climate change relevant at any scale or location are compared and synthesized, and implications for energy policy are considered. Several studies are consistent with the "1000-ton rule," according to which a future person is killed every time 1000 tons of fossil carbon are burned (order-of-magnitude estimate). If warming reaches or exceeds 2 °C this century, mainly richer humans will be responsible for killing roughly 1 billion mainly poorer humans through anthropogenic global warming, which is comparable with involuntary or negligent manslaughter. On this basis, relatively aggressive energy policies are summarized that would enable immediate and substantive decreases in carbon emissions. The limitations to such calculations are outlined and future work is recommended to accelerate the decarbonization of the global economy while minimizing the number of sacrificed human lives.

Keywords: carbon emissions; greenhouse gas emissions; global catastrophic risk; climate change; energy policy; human mortality; climate genocide

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1. Introduction

Despite repeated and ever more serious warnings [1] from the scientific community, global greenhouse gas (GHG) emissions and carbon dioxide (CO_2) concentrations in the atmosphere continue to increase as fossil fuel combustion increases [2]. It is now established with 95% confidence that anthropogenic global climate destabilization is occurring [3,4] and has potentially irreversible negative repercussions for global environment and the social and economic welfare of humanity [5,6]. Yet, despite these well-known facts, there has been a reluctance to apply aggressive energy policies to eliminate fossil fuel combustion. The reasons are both political (involving conflicting interests) and psychological (involving abstractions that may not be directly perceptible).

Climate change causes human deaths in diverse ways, which can be divided into direct, intermediate, indirect, and their interactions. Direct mortal effects of climate change include heat waves, which have already caused thousands of human deaths [7–9] by a combination of heat and humidity (wet-bulb temperature > 35 °C, such that the human body is physically unable to cool itself with perspiration). Intermediate causes of death (between direct and indirect) involve crop failures, droughts, flooding, extreme weather, wildfires, and rising seas. Crop failures [10,11] can exacerbate existing socially-constructed global hunger and starvation resulting in tens of thousands of human deaths [12–14]. More frequent or severe droughts [15–17] can lead to more frequent or severe wildfires [18–20] that also cause human deaths. Droughts lead to contaminated water, diseases, and deaths from dehydration [21,22]. The 2022 IPCC Report (6th Assessment Report) predicted that drought would displace 700 million people in Africa by 2030 [23]. Climate change can cause flooding and consequent destruction of property and crops, which also drives hunger and disease [24]. Climate change drives sea level rise and the resultant submersion of low-lying coastal areas and shoreline erosion [25,26], saltwater intrusion [26,27], storm damage to coastlines, and exacerbated flood risks [18,28–30]. These dangers are life-threatening for billions of people in coastal cities who face the prospect of forced migration [31]. Climate change increases extreme weather events (e.g., hurricanes), which indirectly kill and cause damage worth billions of dollars [32–34]. Extreme weather events kill in many ways including, for example, electric grid failures and power outages [35,36] that reduce access to electric-powered medical care. Indirectly, climate change increases the probability of conflict [37–41]. As the number of climate refugees increases [42–44], countries further from the equator might increasingly refuse to offer asylum. In a worst-case scenario, social collapse is possible [45,46].

For humanity, the most important consequence of climate change will be human deaths. The value of human life may be considered the foundation of all human values, as reflected by the universal legal importance of crimes such as murder, manslaughter, and genocide [47]. Therefore, when attempting to quantify the future harms caused by carbon emissions, the number of human deaths caused by climate change may be the most important metric. Philosopher John Nolt explained [48]:

> *Climate change will cause large numbers of casualties, perhaps extending over thousands of years. Casualties have a clear moral significance that economic and other technical measures of harm tend to mask. They are, moreover, universally understood, whereas other measures of harm are not. Therefore, the harms of climate change should regularly be expressed in terms of casualties by such agencies such as IPCC's Working Group III, in addition to whatever other measures are used. Casualty estimates should, furthermore, be used to derive estimates of casualties per emission source up to a given date. Such estimates would have wide margins of error, but they would add substantially to humanity's grasp of the moral costs of particular greenhouse gas emissions.*

"Casualties" can be deaths, injuries, or illness. In the medical literature these complexities are normally dealt with using the disability-adjusted life year (DALY), which is a measure of overall disease burden, expressed as the number of years lost due to ill-health, disability or early death [49,50]. DALYs have been found to be a useful tool for quantifying human damage from environmental pollution [51]. Since the World Bank first published the DALY concept in 1993, the use of life expectancy estimates, disability weights, age weighting, and discounting has evolved [52]. Unfortunately, as researchers in many fields have adjusted the equations used for estimating the DALY and have increasingly challenged assumptions underlying these calculations, comparing DALY estimates across different studies has become difficult. More concerning are studies that argue that the conceptual and technical basis for DALYs is flawed, its assumptions and value judgments are questionable as well as implications of age-weighting and discounting [53–55]. The stakes are high for the assumptions that underly a DALY because it is often used for cost-effectiveness analysis, which is used for funding allocations [56]. Rather than attempt to resolve that debate, and in agreement with Nolt [48], this review will focus only on human deaths caused by climate change, because they are more easily defined and categorically more serious than injuries or illnesses. In future scenarios of interest, death tolls are also likely to correlate with rates of injury and illness, making each of the three values an approximate measure or predictor of the other. This review aims to provide a clear guide for energy policy makers, which have historically not fully considered the ramifications of AGW on human deaths.

In the following text, published approaches to quantifying climate change in terms of human death tolls will first be summarized. After that, and on that basis, recommendations will be made for energy policy which are intended to be approximately applicable at every scale and in every geographic location.

2. Approaches to Quantifying Carbon Emissions with Human Deaths

2.1. The 1000-ton Rule

The 1000-ton rule says that a future person is killed every time humanity burns 1000 tons of fossil carbon. It is derived from a simple calculation: burning a trillion tons of fossil carbon will cause 2 °C of anthropogenic global warming (AGW) [57,58], which in turn will cause roughly a billion future premature deaths spread over a period of very roughly one century [59]. On the assumption that 2 °C of warming is either already inevitable (given the enormous political and economic difficulties of achieving a lower limit) or intended (given that the business plans of big fossil fuel industries make it inevitable), it can be concluded that burning 1000 tons of fossil carbon causes one future premature death.

The numbers "one billion" (for the total death toll at 2 °C) and "one thousand" (for the amount of carbon that needs to be burned to cause one death) are both very approximate (both are hardly more than order-of-magnitude estimates), but also consistent with diverse evidence and arguments:

- Before 2022, humans burned roughly 0.6 trillion tons of fossil carbon, causing a global temperature increase of roughly 1.2 °C. Incidentally, about the same amount of carbon is currently part of living things on this planet (550 billion T) [60].
- The carbon budget for 2 °C of AGW is about one trillion tons [61]. Thus, if humanity burns that amount altogether, the global mean surface temperature will rise by 2 °C. A more exact estimate is not necessary, because predicted death tolls will inevitably be even more approximate.
- About five trillion tons of fossil carbon are available in the Earth's crust. If humanity collectively burned all of that, global mean surface temperature would increase by up to 10 °C relative to the pre-industrial era [57,58] and could threaten human extinction [62]
- Dividing one trillion by one billion, one thousand tons is the amount of carbon that needs to be burned today to cause a future premature death in the future: 1000 tons.

It has been clear for a decade or more [63] that the final death toll due to AGW will be much greater than 100 million, or one million per year for a century—an extreme best case if current death rates from AGW miraculously remained constant at about one million per year (a level that may have already have reached). Conversely, the final death toll in a 2 °C warming scenario will certainly be much less than 10 billion, which is the predicted global human population in 2100 in the absence of AGW [64]. Although climate change clearly represents a global catastrophic risk to food supplies [65], only a small minority are suggesting that 2 °C of warming could cause human extinction [66]. Warming of well over 2 °C, however, could indeed cause natural climate feedbacks to get out of control, leading eventually to human extinction [66]. Between these extreme boundaries, it is likely more than 300 million ("likely best case") and less than 3 billion ("likely worst case") will die as a result of AGW of 2 °C. That prediction is consistent with detailed predictions of climate science summarized by the World Health Organization and their probable consequences for human mortality [67].

2.2. Convergent Evidence for the 1000-ton Rule

Although AGW is a global concern, some studies have looked specifically at a single country's emissions (USA) to illustrate the methods used. The 1000-ton rule is roughly consistent with two such independent studies from different academic disciplines—philosophy and economics. The authors of those studies arrived at their estimates of future death tolls by different methods but came to similar conclusions. First, an American philosopher John Nolt [68] concluded that the carbon emissions of the average American are causing the death or suffering of one or two future people. That is because the average American, in the course of a lifetime, causes (by her or his personal choices or participation in regular social structures) 1840 metric tons of CO_2 equivalent to be emitted. This corresponds to about 500 tons of carbon, so according to the 1000-tonne rule, those emissions are enough to kill half of a future person.

A more recent attempt at quantifying future deaths in connection with specific amounts of carbon was published by Bressler [69]. Coining an economically oriented term "mortality cost of carbon", he claimed that "for every 4434 metric tons of CO_2 pumped into the atmosphere beyond the 2020 rate of emissions, one person globally will die prematurely from the increased temperature" [70]. His predictions were confined to deaths from extreme heat when wet-bulb temperature exceeds skin temperature (35 °C). He acknowledged the importance of other causes of death in connection with AGW such as "infectious disease, civil and interstate war, food supply, and flooding", but considered them difficult to quantify—although taken together they may cause more deaths than direct heat. His estimate is consistent with the 1000-tonne rule, according to which one future person dies (for one of many reasons linked to AGW) whenever roughly 3700 tons of CO_2 are emitted.

2.3. The Temperature Niche

Xu and colleagues [71] have argued that "accounting for population growth projected in the SSP3 scenario, each degree of temperature rise above the current baseline roughly corresponds to one billion humans left outside the temperature niche, absent migration". That is consistent with the 1000-ton rule if it is assumed that long-term survival outside the ecological niche is unlikely. Specifically, for every additional degree of warming beyond 2 °C, roughly an additional billion deaths will be caused, leading to human extinction at very roughly 10 °C of warming [59]. At 2 °C of warming, roughly 2 billion people would find themselves outside the climate niche as defined by Lenton et al. [72]. If it is assumed that global warming will be the ultimate cause of death for half of those people (e.g., due to the inability to migrate), then 2 °C of warming will cause a billion deaths.

Ecologist George Evelyn Hutchinson has shown that a species faces extinction if it leaves its ecological niche [73], but that does not apply to humans with access to energy reserves. Humans without access to the capital to provide for those energy reserves, however, will die, particularly if limited resources from climate change result in 'climate wars' [74].

2.4. Marginal Carbon Emissions-Related Deaths

The estimates made in Sections 2.1–2.3 are very rough but provide a useful rule of thumb for gaging a first approximation. The 1000-ton rule makes it clear that there is a marginal human death cost to every amount of warming, no matter how small. Thus, every 0.1 °C degree of warming can be expected to cause 100 million deaths. Similarly, every 0.001 °C of warming will cause a million deaths. If humanity misses the 2 °C target or any of the more granular goals to stop 'dangerous climate change' [75], which appears likely according to AI models [76], rather than relax and accept it, all efforts to reduce carbon emissions can be viewed as lifesaving.

3. Results: Carbon-Related Deaths to Guide Energy Policy

3.1. Large Numbers and the Millilife

Understanding the large variability in the number of human deaths from climate change requires an accessible unit of measure for carbon footprints that is easy to understand and may be used to set energy policy to help accelerate carbon emissions reductions. Using the "1000-tonne rule" as a basis it is possible to convert any carbon footprint to human lives. A *millilife* is defined as a measure of intrinsic value that is equivalent to one thousandth of the value of human life. A millilife is roughly the same as a month in the richest countries, assuming a lifespan of about 80 years, but it is closer to half a month in the poorest countries, in which the lifespan is closer to 40 years.

The 1000-ton rule says that a millilife is destroyed when a ton of fossil carbon is burned. For example in Canada, which has some of the highest yearly carbon emissions per capita in the world at around 19 tons of CO_2 or 5 tons of carbon per person [77], roughly 5 millilives are sacrificed by an average person each year. As the average Canadian lives to be about 80, he/she sacrifices about 400 millilives (0.4 human lives) in the course of his/her lifetime, in exchange for a carbon-intensive lifestyle. Canada is one of the world's largest economies, currently ranked 9th [78]. Whereas the average gross domestic product globally is US$12,183/person, Canada generates US$51,988/person, more than 4 times the global average [78]. Canadians are thus not only wealthy by global standards but many already live outside of the human temperature niche. Climate change will likely benefit the Canadian economy in some sectors (e.g., agriculture and tourism), causing GDP to increase by up to 0.3% ($9 billion/year) [79]. Even if some areas prosper, however, others will face major challenges that could cause great economic harm (e.g., increased forest fires [80]). By contrast, the Global South will suffer the most negative impacts of climate change [81–83].

Parncutt assumed [59] for the purpose of the 1000-ton rule that an average future AGW-victim in a developing country will lose half of a lifetime or 30–40 life-years, as most victims will be either very young or very old. If the average climate victim loses 35 life-years (or 13,000 life-days), a millilife corresponds to 13 days. Stated in another way: if a person is responsible for burning a ton of fossil carbon by flying to another continent and back, they effectively steal 13 days from the life of a future poor person living in the developing world. If the traveler takes 1000 such trips, they are responsible for the death of a future person.

This concept can also be applied to large-scale energy decisions. For example, the Adani Carmichael coalmine in Queensland, Australia, is currently under construction and producing coal since 2021. Despite massive protests over several years, it will be the biggest coalmine ever. Its reserves are up to 4 billion tons of coal, or 3 billion tons of carbon. If all of that was burned, the 1000-tonne rule says it would cause the premature deaths of 3 million future people. Given that the 1000-tonne rule is only an order-of-magnitude estimate, the number of caused deaths will lie between one million and 10 million. Currently, 10 million tons of coal are being mined per year [84], equivalent to 7.5 million tons of carbon or 7500 sacrificed human lives. Many of those who will die are already living as children in the Global South; burning Carmichael coal will cause their future deaths with a high probability. Should energy policy allow that to occur?

3.2. Quantifiable Metrics Warranting Industry-Wide 'Corporate Death Penalties'

Many authors have considered the benefits of a "corporate death penalty" (judicial dissolution of a corporation by the government) for reigning in companies that do harm [85–90]. Pearce considered quantitative criteria for industry-wide penalties of that kind in the case of non-carbon air pollution deaths from the U.S. coal mining industry [91]. The USA consumed about 546 million tons of coal in 2021 [92], corresponding to about 400,000 future deaths according to the 1000-tonne rule (as the worst lignite is only 65% carbon whereas the best anthracite is 92% and these are short tons, which are about 900 kg, but the 1000-ton rule originally applies to metric tons (tonnes) which are 1000 kg).

Under what circumstances might a government ban or outlaw an entire corporation or industry, considered a legal entity or person—for example, the entire global coal industry? The Universal Declaration of Human Rights [93] suggests how this question might be answered:

1. Everyone has the right to life (Article 3) [93]. The right to life is the primary right, as it is necessary to be alive to enjoy any other right such as the right to work.
2. Everyone has the right to work (Article 23) [93]. Corporations promote this right if they offer employment.
3. Corporations are human inventions, created by law to benefit humanity. The law should only give corporations the right to exist if they are beneficial to humanity. In the simplest case, a corporation can be viewed as 'good' if it creates profit and jobs (benefiting humans), but not if the operation of the business infringes the universal human right to life.

Ideally, a company should not cause any human deaths at all. If it does, those deaths should be justifiable in terms of improvements to the quality of life of others. For example, a company that builds a bridge might reasonably risk a future collapse that would kill 100 people with a probability of 1%. In that case, the company accepts that on average one future person will be killed as a result of the construction of the bridge. It may be reasonable to claim that the improved quality of life for thousands or millions of people who cross the bridge justifies the human cost.

Fossil fuel industries are causing far more future deaths than that, raising the question of the point at which the law should intervene. As a first step to solving this problem, it has been proposed a rather high threshold (generous toward the corporations) is appropriate. A company does not have the right to exist if its net impact on human life (e.g., a company/industry might make products that save lives like medicine but do kill a small fraction of users) is such that it kills more people than it employs. This requirement for a company's existence is thus:

$$\textbf{Number of future premature deaths/year} < \textbf{Number of full-time employees} \quad (1)$$

This criterion can be applied to an entire industry. If the industry kills more people than it employs, then primary rights (life) are being sacrificed for secondary rights (jobs or profits) and the net benefit to humankind is negative. If an industry is not able to satisfy Equation (1), it should be closed down by the government.

Coal is primarily burned for electrical generation. Coal-fired power plants pollute the air with a combination of greenhouse gases (carbon dioxide and methane) [94], particulate matter, nitrogen and sulfur oxides, and heavy metals such as mercury [95–97]. The resultant poor air quality causes mortality and morbidity effects on respiratory, cardiovascular, urinary, nervous, and digestive systems [98–101]. In this way, the coal industry kills people by polluting the air that they breathe [102,103]. Fossil fuel-related air pollution was responsible for 10.2 million excess deaths globally in 2012 (due to PM2.5 from this source) with 62% of deaths in China (3.9 million) and India (2.5 million) [104]. In the U.S., about 52,000 human lives are sacrificed per year to provide coal-fired electricity [105]. Such death rates can be estimated from meteorological models that analyze emissions and pollutant concentrations. Concentration-response functions allow researchers to estimate the number of deaths that could be avoided if combustion emissions from coal were eliminated [105].

In the U.S., coal employed 51,795 people in 2016. Since the number of people killed is greater than the number employed, the U.S. coal industry does not satisfy Equation (1) and should be closed down [91]. This conservative conclusion does not include future deaths caused by climate change due to burning coal [106–108].

4. Discussion

4.1. Causation and Attribution

As the number of deaths from coal-related air pollution is quantified in epidemiological studies [105] the question arises: Why is coal still burned in the USA although 52,000 Americans die from coal-related air pollution (excluding carbon) each year? A possible answer involves attribution. It is challenging to establish a causal connection between a given coal plant and the death of a specific future person. To overcome this challenge, instead, the 1000-ton rule assigns responsibility in proportion to the amount of carbon burned. If a company burns twice as much carbon as another, it kills twice as many future people. That is, the marginal death rate from future effects of global warming that are attributable to burning coal is twice as high. The 1000-ton rule makes that proportionality specific. If the total number of deaths from climate change is known and the carbon emissions are known, the attribution is pro-rated in the same way as climate liability [109].

Clearly, if a billion people are going to die prematurely due to AGW, those deaths should be prevented. If that question were asked to people from all walks of life and to leaders of diverse countries, the answer would surely always be the same. There is also universal agreement that preventing deaths is better than regretting them afterward. Consequently, there should be universal agreement that humanity must *immediately* stop the killing of every individual future person, by *immediately* stopping the burning of every individual kiloton of carbon.

Those still profiting from emitting carbon might reasonably object that the chain of cause and effect between a carbon polluter's action and a future resultant death is complex. How can polluters be sure that they are the cause of a given future death? A similar legal question might be asked of a gunman who points a gun at a victim and pulls the trigger with the intention of killing the victim. The attempt may fail for a range of reasons, some of which are beyond the gunman's control: the gun might be faulty or not loaded, the gunman might miss the target, the target might suddenly move, the target might be injured but not killed, or the police may suddenly arrive, causing the gunman to flee. The gunman is nevertheless guilty of murder or manslaughter if two conditions are satisfied: the intent to kill can be demonstrated, and the victim dies as a result of the murder attempt. Similarly, fossil fuel industry leaders know in advance from media reports (even without reading this article, or other relevant academic literature) that their emissions will probably kill future people. That is true even if they do not intend to kill those people but are merely being negligent while maximizing their profits while providing a public service in the energy marketplace. Again, in that case, the chain of cause and effect is complex and can be interrupted in ways that are beyond the control of the industry. The industry's leadership is nevertheless guilty if it can be demonstrated that they were informed in advance about the deadly consequences of their actions or might reasonably have deduced those consequences themselves on the basis of publicly available information.

4.2. Energy Policy Implications

Several energy policy implications immediately fall from adopting a 1000-ton rule of analysis. The primary goal should be to decrease carbon emissions to zero. Anything that causes emissions should be eliminated. A first baby step toward that goal might be to ban advertising for fossil fuels, just as advertisements for tobacco and cigarettes are banned [110]. In general, advertising should be banned if it encourages deadly habits (such as flying) and addictions (given the similarities between fossil-fuel use and addiction), in particular when the advertising is deliberately misleading (such as greenwashing). Likewise, consumers should be warned about the consequences of excessive or preventable fossil fuel use. For example, airline flight tickets could have a warning label: "Whereas smoking a cigarette takes 10 min off your life, an intercontinental return flight takes 13 days off the life of a future person". Better still, the number of lost days for the specific flight in question could be calculated.

That raises another interesting issue. Whoever willfully causes 1000 tons of carbon to be burned, knowing the consequences in advance but doing it all the same, is guilty of killing a future person. Since it can be presumed there is no motive or intent to kill, this is not murder in a legal sense. If the polluter causes future deaths, they are guilty of manslaughter. Thus, measuring carbon emissions in human lives not only makes the numbers easier to understand—it also clarifies what the priorities should be on the policy front, as allowing a policy to cause manslaughter is intuitively unacceptable. One approach to rectifying this problem involves carbon emission liability [109,111–114]. Emissions bottlenecks have been recommended as liability targets to strategically reduce the greatest amounts of carbon emissions [115].

Another interesting approach could be applying asset forfeiture laws [116] (also referred to as asset seizure) to manslaughter caused by AGW. These laws enable the confiscation of assets by the U.S. government as a type of criminal-justice financial obligation that applies to the proceeds of crime. Essentially, if criminals profit from the results of unlawful activity, the profits (assets) are confiscated by the authorities. This is not only a law in the U.S. but is in place throughout the world. For example, in Canada, Part XII.2 of the Criminal Code, provides a national forfeiture régime for property arising from the commission of indictable offenses [117]. Similarly, 'Son of Sam laws' could also apply to carbon emissions. In the U.S., Son of Sam laws refer to laws designed to keep criminals from profiting from the notoriety of their crimes and often authorize the state to seize funds earned by the criminals to be used to compensate the criminal's victims [118]. If that logic of asset forfeiture is applied to fossil fuel company investors who profit from carbon-emission-related manslaughter, taxes could be set on fossil fuel profits, dividends, and capital gains at 100% and the resultant tax revenue could be used for energy efficiency and renewable energy projects or to help shield the poor from the most severe impacts of AGW. Future work is needed to determine over what time period should such laws be in force (e.g., seizure of past profits) and if additional penalties are necessary if companies purposefully misled the public to continue to profit from manslaughter (e.g., Exxon-Mobil's climate communication [119]). These laws would also apply to equipment manufacturers that enable fossil fuel extraction (e.g., pipeline equipment manufacturers). Such AGW-focused asset forfeiture laws would also apply to fossil fuel company executive compensation packages. Energy policy research has shown that it is possible to align energy executive compensation with careful calibration of incentive equations such that the harmful effects of emissions can be prevented through incentive pay [120]. Executives who were compensated without these safeguards in place would have their incomes seized the same as other criminals benefiting materially from manslaughter.

Energy policy designed specifically to mitigate climate change should be prioritized in the following three main areas [121]. In each area, the overriding need to save human lives justifies a reduction in fossil fuel burning that is both large and fast:

1. **Energy conservation**: Improved energy efficiency and the rational use of energy should be supported by government programs. This can include industrial [122], agricultural [123], transportation [124,125], sustainable cities [126], residential [127] and at the household level [128] energy efficiency in the developed world as well as the developing world [129]. Energy efficiency, however, is not enough to bring emissions to acceptable levels [130].
2. **Evolution of the energy mix**: Complete replacement of high carbon fuels (coal, oil and natural gas) by zero carbon content fuels (i.e., hydrogen, electricity, etc.) from renewable energy sources [131–133] like hydropower, wind, geothermal [134], biomass and most importantly solar, which can be scaled to provide a sustainable society [135]. It should be pointed out that renewable energy sources also can have adverse impacts on the local environment and should be minimized. Distributed generation (DG) with renewable energy should be encouraged as much as possible because many studies have shown DG customers provide a net benefit not only to non-DG customers but also to the overall electrical grid [136,137]. The value of solar studies [138] has confirmed that economic benefits surpass net metering rates and increasing the compensation for individuals investing in a renewable energy transition can be increased to at least meet this value. A broad range of policy tools have been introduced in countries and jurisdictions throughout the world that include [139]: tradable emission rights, tax credits, and subsidies, as well as regulations such as feed-in-tariffs for renewable energy production.
3. **Carbon waste management**: Development of techniques to devalue carbon-intensive fuel such as carbon taxes [140–142], and technical means for the capture and storage of CO_2 such as soil carbon sequestration [143].

The results of this study indicate more aggressive policies may be needed than the gradual decarbonization of the past: (i) instead of gradually increasing carbon taxes, ban the extraction of all fossil fuels [144], (ii) revoke the charters of fossil fuel companies and disperse their assets [91], (iii) retrain fossil-fuel workers en masse for renewable energy jobs [145], (iv) undercut fossil fuel regimes by giving renewable energy technologies to their citizens [146], (v) promote open-source technologies to erode the economies of fossil-fuel regimes [147], (vi) instead of complicated and time consuming rebates for energy conservation [148], make mass purchases of energy conservation or renewable energy technologies, and make them freely available to all citizens (e.g., nationalizing/buying/constructing/subsidizing insulation plants or provide free insulation to everyone that will take it), (vii) ban the sale of fossil fuel vehicles [149] or even ban all cars [150], (viii) instead of incentivizing heat pumps [151], ban natural gas stoves [152] or even boilers [153], (ix) only allow development of net zero buildings (or better yet—positive energy buildings [154]), (x) as profiting from manslaughter is illegal, tax all fossil fuel-related investments at 100%, or (xi) hold climate emitters as well as investors economically liable for harm caused by carbon emissions in the future [109].

Some of these energy policies may appear extreme in historical context. Expressing carbon emissions in human lives clarifies the argument. For example, an outright ban on mining coal would negatively impact coal workers as they would lose their jobs and coal investors, as they would lose their money. As there are both alternative sources of energy and alternative jobs, the cost and inconvenience of retraining coal workers for other types of employment and cutting unearned income for coal investors who have ignored decades of scientific warnings pales in comparison to the need to protect millions of human lives.

4.3. Limitations

Valerie Masson-Delmotte and colleagues warned humanity about the difference between 1.5 °C and 2 °C of warming [155]. On that basis, AGW of 2 °C was predicted to cause a billion premature deaths, spread across the next century or so. That raises the question of whether the number "one billion" is a reasonable estimate, or is it too high or too low? From a mathematical perspective, the number "one billion" is the peak of a rather broad probability distribution, within which the true value will fall—the number of people who actually die prematurely due to 2 °C of AGW. The distribution is assumed to be log-normal: normal (bell-shaped) and symmetrically relative to the logarithmic horizontal axis. The predicted number of deaths from 2 °C of warming can be broken down in various ways:

- Year: At present, the yearly death rate due to AGW is probably roughly one million. This figure is hard to estimate because AGW kills indirectly in diverse ways. The death rate was probably 300,000 per year in 2009 [156], and has been increasing steadily since then. In 2010, the Madrid thinktank DARA estimated that AGW would cause one million human deaths per year by 2030 [157]. At some point in the future, the death rate from various effects of AGW will overtake the number dying from air pollution—an independent negative effect of burning fossil fuels. Currently, some 7 million people are dying yearly from air pollution (either indoor or outdoor) [158]. Altogether, hundreds of millions will die in the coming decades as a result of fossil fuel burning, many of whom are already alive now. Further, hundreds of millions of future AGW victims have not yet been born.
- Age: Victims will die at any age, but they will be predominately (very) young or (very) old at the time of death, those two groups being more vulnerable [159,160].
- Location: UNICEF recently introduced the Children's Climate Risk Index as shown in Figure 1 [145,148]. The death rate relative to the population will be higher in climate-vulnerable countries such as Afghanistan, Bangladesh, Barbados, Bhutan, Costa Rica, Ethiopia, Ghana, Kenya, Kiribati, Madagascar, Maldives, Nepal, Philippines, Rwanda, Saint Lucia, Tanzania, Timor-Leste, Tuvalu, Vanuatu, and Vietnam.
- Proximal cause: The deaths will be caused only indirectly by AGW. More direct causes of death will include heat and humidity, rising sea levels, freak storms, changing precipitation patterns, disappearing glaciers affecting water supplies, ocean acidification, more frequent bushfires, loss of biodiversity, and so on. Many of these side-effects of AGW will reduce food supplies, causing famines.

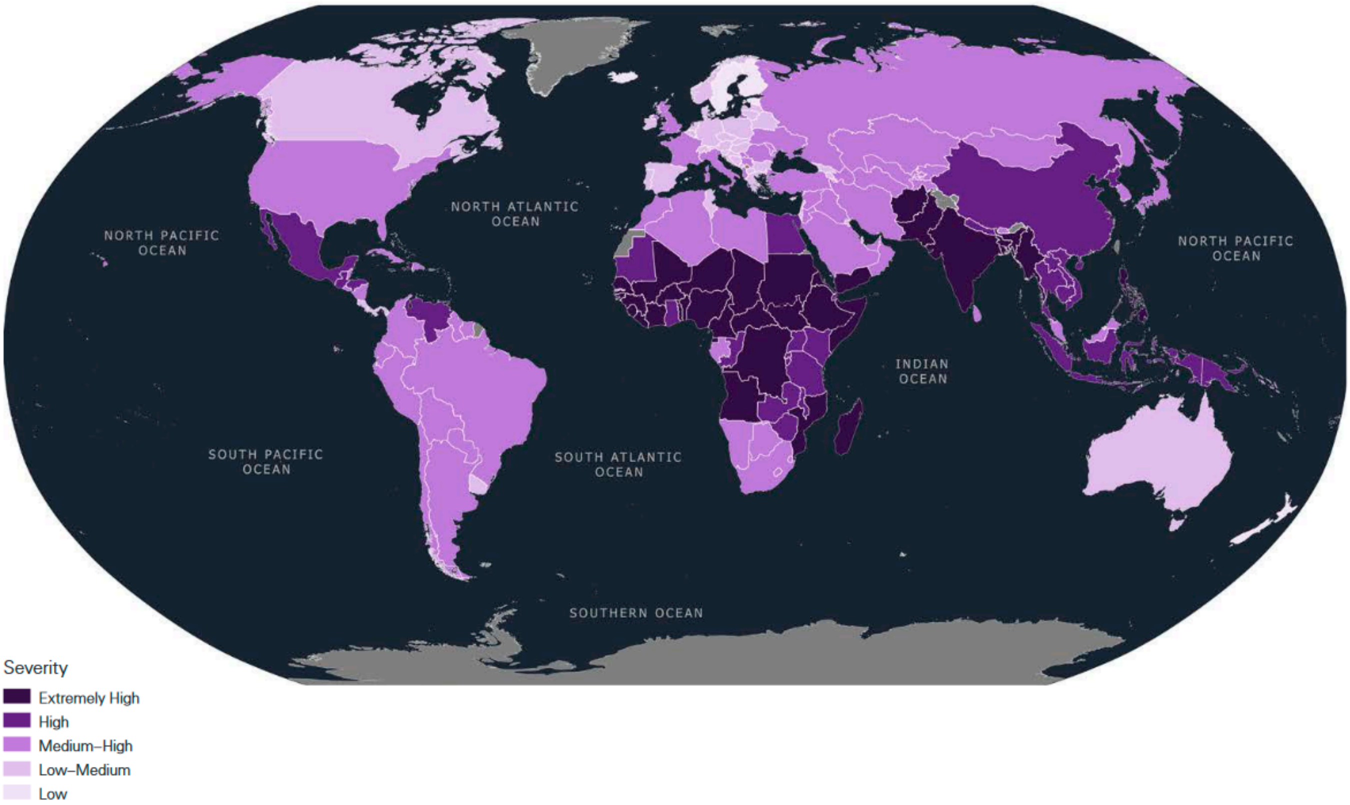

Figure 1. The Children's Climate Risk Index (CCRI) map of severity [161].

In August 2021, UNICEF warned that over one billion children are at extreme risk of the impacts of AGW [161]. According to the Children's Climate Risk Index (CCRI) [161],

- 240 million children are exposed to coastal flooding;
- 330 million to riverine flooding;
- 400 million to cyclones;
- 600 million to vector borne diseases;
- 815 million to lead pollution;
- 820 million to heatwaves;
- 920 million to water scarcity and
- one billion children to dangerously high levels of air pollution.

Looking at the problem from different perspectives provides convergent evidence for an estimate of 1 billion deaths at 2 °C of warming:

- The estimate corresponds to 10% of the projected future world population. All 10 billion humans will need food and fresh water to survive, and AGW will seriously affect both.
- Since CO_2 stays in the atmosphere for about a century, the prediction implies that, on average, 10 million additional deaths per year will be due to AGW.
- If the wet-bulb temperature exceeds skin temperature, perspiration can no longer cool the body. Already in 2022, this effect was life-threatening for a billion people in India and Pakistan [162]. In the same countries in 2023, maximum temperatures were consistently above 40 °C for over two weeks [161].

Future death rates are hard to predict because nothing of the kind has occurred in human history and the negative consequences of AGW as listed by the IPCC are diverse. They include hunger, disease, direct heat, extreme weather events (which kill not only directly but also because they cause long-term health problems), violence (e.g., wars over diminishing resources such as water), and immigration. In a first approximation, the various AGW-related causes of death will be added. It should be pointed out, there will also be interactions, so the whole will be greater than the sum of the parts [163]. For example, people are more likely to die during an extreme storm if they are already weak from years of famine.

As global temperatures increase, uninhabitable areas will grow (e.g., in the Middle East). People in those areas who cannot rely on air conditioning or some other cooling strategy (e.g., cool swimming holes) during heat waves, or cannot afford to buy food and water or protect themselves in times of conflict, will be forced to migrate. They will join the swelling tide of climate refugees [44], risking their lives to find a new place to live.

It has been estimated that there will be roughly one billion additional deaths for each degree of warming [59], meaning that 3 °C of warming would kill 2 billion people. That estimate is probably conservative if one considers the geographical areas that today occasionally suffer from deadly humid heat (with wet-bulb temperature exceeding skin temperature). Predicting the locations of such areas at different levels of warming using climate models, one might predict 3 billion deaths from direct heat alone at 3 °C of warming [164].

During the 21st century, the population of Africa may rise by a factor of three, from 1.3 billion to roughly 4.2 billion [165]. Those people will only survive if there is enough food. Along with other problems such as biodiversity loss and soil degradation, AGW will seriously affect food productivity. In the long term, it is challenging for Africa's food production to be sustainably increased to feed its growing population. In addition, food distribution will be affected by conflict (the 2022 invasion of Ukraine being an example). From what is known today about AGW, a massive, unprecedented, and seemingly never-ending catastrophe appears to be inevitable.

The calculations presented are conservative relative to some other published estimates of relevant death tolls. For example, Ziegler estimated that 35 million people die each year in connection with hunger [166]—much more than the estimate of 10 million deaths per year in connection with poverty that is used here. Ziegler's estimate is relevant because many of the people who will die prematurely in the future as an indirect consequence of AGW will die of hunger, and the estimate of "one billion" can be made on the basis of expected increases in existing death rates from hunger. Today around 9 million people die every year from hunger and hunger-related diseases [167]. This ethical challenge continues despite the global availability of more than enough human edible calories [168], but several studies have indicated that the entire human population could be maintained even with a loss of all conventional agriculture during a global catastrophe [169,170].

4.4. Causes of Death and Future Work

Causes of death often overlap. Intertwined effects include for example the effect of maternal mortality on neonatal survival rates [171]. Whether poverty is the cause of death in a specific instance is difficult to operationalize. If a life could be saved by spending a reasonable amount of money, and that money was not spent, and the person died as a result, one can argue that poverty was the cause of death. Based on World Health Organization data Pogge [172,173] estimated that:

> *Some eighteen million human beings die prematurely each year from medical conditions we can cure—this is equivalent to fifty thousand avoidable deaths per day.*

Moreover,

> *One-third of all human lives end in early death from poverty-related causes. Most of these premature deaths are avoidable through global institutional reforms that would eradicate extreme poverty. Many are also avoidable through global health-system reform that would make medical knowledge freely available as a global public good.*

UNICEF has estimated that as many as 22,000 children are dying daily due to poverty, or 8 million per year [167]. Another source claims that 35 million people are currently likely to die from hunger, presumably in the next few years [174]. In addition to poverty, AGW will kill humans in multiple ways. By about 2070, up to 3 billion people will live in places that from today's perspective will be too hot to survive in [175]. Storms and floods kill directly, but also indirectly, by causing epidemics. Droughts kill when drinking water or food runs out. Rising seas kill when people are forced to leave their land and become migrants. In all these cases, poverty and AGW combine to cause human deaths.

Mortality from direct heat will depend on wealth or poverty as much as it depends on temperature. People with money own air conditioners that work when they need them or have access to a cool refuge in thermal emergencies. If current trends continue, the most common cause of premature death in the coming decades and centuries will be a combination of two broad factors: AGW and poverty. People with money will mostly be able to adapt. Others will not, with fatal consequences.

In the academic literature, death from direct heat is normally (and somewhat misleadingly) called "temperature-related mortality". In fact, all causes of death in connection with AGW are "temperature-related", some being more directly or immediately related to temperature than others. Famines, floods, and fires are less directly temperature-related: AGW changes rainfall, wind, and temperature patterns, which in turn cause famines, floods, and fires. To be clear, it may help to regard deaths from such events as "second-order" or "indirect" temperature-related mortality.

The number of deaths from direct heat may increase non-linearly (although not necessarily exponentially) as the temperature rises. In that way, the increase in mortality will not be the same for each fraction of a degree of AGW. For example, the increase in mortality caused by a global mean temperature increases from 1.5° to 1.6 °C relative to pre-industrial temperatures will probably be less than the increase in mortality caused by raising global temperature from 2.5° to 2.6 °C. The 1000-tonne rule applies to global warming of less than 2 °C, and more work is needed to model possible non-linearities at higher temperatures.

Future work is needed to better attribute current death rates to AGW. The World Health Organization has estimated that between 2030 and 2050 climate change will cause 250,000 additional deaths per year due to malnutrition, malaria, diarrhea and heat stress [67]. The WHO used a bottom-up estimate, extrapolating from existing death tolls without considering unexpected or non-linear effects in the future. These, of course, are hard to predict. They include war (e.g., conflicts over limited resources like water), migration (due to rising sea levels and other catastrophic effects of AGW), and effects of unprecedented floods, water shortages, and storms). In addition, more accurate quantification of the impact of AGW efforts should be made using the up-to-date DALY concept and these results should be compared to the more simplistic total deaths used here.

For the past few decades, the global death rate in connection with poverty has steadily declined in response to international development aid and economic growth in the Global South. Unfortunately, the global number of deaths from hunger (starvation) is now increasing again [176]. The positive effect of economic growth in developing countries and international aid, which together previously caused mortality to decrease, is gradually being overwhelmed, not only by various negative effects of AGW (drought, flooding, fires, storms, disease spread, migration, conflict) but also by rising food prices linked to the emergence of global food monopolies; up to 90% of global trade in grain is controlled by just four corporations [177]. In addition, in 2020 and 2021, the COVID-19 pandemic caused an increase in death rates in connection with poverty [178]. Meanwhile, although the global death rate from malaria fell from 2010 to 2014, it increased again from 2015 to 2020, but the increase was partly due to changes in methodology for attributing cause of death [179]. Future work is needed to disaggregate different causes of death attributed to AGW.

Given the many negative consequences of AGW, combined with biodiversity loss and population growth, our grandchildren will not be surprised when in the year 2100 the death rate in connection with poverty has doubled relative to 2000, from roughly 10 million to roughly 20 million per year. From the vantage point of the year 2023, doubling seems conservative, given the number and diversity of disastrous climate events in the news and corresponding predictions in mainstream peer-reviewed scientific journals.

Future AGW death rates will depend on other population trends. The number of people that will be alive at a given time in the future (and therefore available to die from AGW) is hard to predict and can hardly be estimated more accurately than predicted death tolls in different warming scenarios, which are little more than orders of magnitude. In many developed nations the birth rate has dropped far below the replacement rate already today. For example, South Korea only has 0.8 children per couple [180] and even the USA is at 1.78, which is below the replacement rate [181]. If these trends continue to spread into other nations, there may be fewer deaths caused by AGW simply because there will be fewer people. These trends, however, may be interdependent: some couples are avoiding children because of climate concerns (1 in 4 childless adults in the USA) [182]. Overall, this review has made it clear there is far more work needed in this area to help guide appropriate energy policies.

5. Conclusions

This is the first review to analyze the substantial body of literature that enables approximate quantitative estimation of the human cost of carbon emissions, measured in lost human lives. The greatest risk to future human life is probably climate change, although biodiversity loss and nuclear war also pose enormous existential risks. It can be concluded from the results of this review, that as a rough rule of thumb, burning roughly 1000 tons of fossil carbon (creating 3700 tons of CO_2) causes one future premature death. Measuring carbon emissions in human lives not only makes the numbers easier to understand for nonexperts but also clarifies energy policy priorities: clearly, allowing a policy to cause manslaughter is intuitively unacceptable.

The high death tolls that can be attributed to current carbon emissions and that follow from this analysis have immediate and direct energy policy implications. The primary goal of all current energy policies should be to reduce carbon emissions to zero as fast as possible without causing additional deaths and to eliminate any policy that increases emissions or incentives future fossil carbon extraction. For this purpose, far more aggressive energy policies are warranted than are currently used in most jurisdictions. To save millions of lives it is ethically, morally, and logically acceptable to radically accelerate existing trends in energy efficiency, electrification, and the use of renewable energy, with the goal of powering global society without any fossil fuels at all. Future work is needed to flesh out the detailed implementation of such policies and make more precise estimations of future death tolls in connection with AGW.

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