The impact of abrupt sunlight reduction scenarios on renewable energy production

Author details

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Abstract

To combat global warming, energy systems are transitioning to generation from renewable sources, such as wind and solar, which are sensitive to climate conditions. While their output is expected to be little affected by global warming, wind and solar electricity generation could be affected by more drastic climatic changes, such as abrupt sunlight reduction scenarios (ASRSs) caused by nuclear war or supervolcanic eruptions. This paper assesses the impacts of an ASRS on global energy supply and security in a 100% renewable scenario. National generation mixes are determined according to roadmaps for a global transition to renewable energy, with wind and solar contributing a combined 94% of global energy supply. Wind and solar generation are determined for a baseline climate and an ASRS following a large-scale nuclear exchange. While effects vary by country, overall wind and solar generation is expected to reduce by 59% in the first year following an ASRS, requiring over a decade for full recovery. Sufficient energy for critical needs for everyone, including water, food, and building heating/cooling, would require international trade, resilient food production, and/or resilient energy sources, such as wood, geothermal, nuclear power, tidal power, and hydropower.

Highlights

- Electricity generation from wind and solar is vulnerable to climatic conditions.
- Nuclear war or supervolcano could cause an abrupt sunlight reduction scenario (ASRS).
- In a 100% renewable energy system, an ASRS may reduce global generation by up to 59%.
- Prioritization of energy use for critical needs will be required for survival.
- With prioritization and resilient foods, energy may be sufficient to feed everyone.

Keywords: global catastrophic risk; nuclear winter; volcanic winter; renewable energy; resilient energy systems; energy security;

Word count: 6360 (excluding references)

1. Introduction

In response to concerns about climate change, many countries around the world are transitioning to renewable energy sources to reduce greenhouse gas emissions (Olabi & Abdelkareem, 2022). Solar and wind electricity generation are the fastest-growing renewable sources (Dalala et al., 2022; Joskow, 2019) and may account for more than 50% of global energy supply by 2050 (Lowe & Drummond, 2022; Mia et al., 2020).

However, electricity generation from solar and wind is, by nature, sensitive to climatic conditions. Generation can only occur when these resources are available: when the sun is shining at an appropriate angle, or the wind is blowing at an appropriate speed for the operation of wind turbines. These climatic sensitivities are managed in current electricity systems, as wind and solar comprise a small proportion of total generation, and locations are typically optimized for well-studied, stable climates (Lowery & O'Malley, 2014; Ribeiro et al., 2016).

The sensitivity of renewable electricity generation to climatic changes has been widely recognised, and research has investigated the effects of global warming and climate change on renewable energy systems. In the 21st century, global warming and climate change are expected to have little effect on solar electricity generation (Jerez et al., 2015). The impacts on wind generation are less certain (Gernaat et al., 2021; Russo et al., 2022), as wind energy is affected by many factors, including sunlight, terrain, and temperature, and the implications of climate change for wind patterns are less well understood than those for solar energy (Pryor et al., 2020; Solaun & Cerdá, 2019).

However, more drastic and rapid climate disruptions are possible, such as an abrupt sunlight reduction scenario (ASRS). A nuclear war, asteroid/comet impact, or supervolcanic eruption could release immense amounts of aerosol materials, such as sulphates or black carbon, into Earth's stratosphere, where they would remain for several years (Robock, 2010). The reduction in sunlight caused by these aerosols would decrease temperatures and cause rapid, widespread climatic changes (Robock et al., 2007). Previous research has shown a severe ASRS would be catastrophic for humanity and could push billions of people into starvation (Pham et al., 2022; Xia et al., 2021), but the impacts of an ASRS on renewable energy production are unknown. As the severity of these impacts will increase as the world transitions towards a renewable energy system, a comprehensive analysis of the effects of an ASRS on global renewable energy production is required.

This work investigates the effects of an ASRS on a global energy system with 100% renewable energy supply, and the implications of such a scenario for global energy security. A global climate model is used to assess the impacts of an ASRS on wind and solar energy resources, and national energy supply mixes are determined according to roadmaps developed by Jacobson et al. (2017) for a transition to a 100% renewable energy system.

The paper is structured as follows: Section 2 provides background information on renewable energy systems, Section 3 describes the methods used in this work, Section 4 presents the results of these analyses, and Sections 5 and 6 provide discussion and conclusions, respectively.

2. Background

Roadmaps from Jacobson et al. (2017) show global average power demand is expected to be approximately 11800 GW in a 100% renewable scenario, which, accounting for expected efficiency improvements, is similar to current levels. This stability in energy demand is attributed to population growth and increased per capita energy services, offset by gains in energy efficiency and electrification.

The following renewable energy sources are included in Jacobson et al.'s roadmaps: Onshore Wind; Offshore Wind; Wave; Geothermal; Hydroelectric; Tidal; Residential, Commercial, Government, and Utility Solar Photovoltaic (PV); and Concentrated Solar Power (CSP). Wind generation contributes 4400 GW (37%), and solar generation 6800 GW (57%), of average global power supply, for a combined 94%.

The intermittent nature of renewable sources, particularly wind and solar, will require energy system changes to account for uncertainty in supply (Mlilo et al., 2021). Three main strategies exist for managing these problems of intermittency:

- Oversize generation and spill or dump excess energy production (Rad et al., 2023).
- Increase demand flexibility by thermal storage (Arteconi et al., 2012; Bishop et al., 2023; Williams, Bishop, & Docherty, 2023), smart charging of electric vehicles (Dallinger & Wietschel, 2012; Williams et al., 2024), or other methods of demand side management (Gellings & Chamberlin, 1987; Williams, Bishop, Gallardo, et al., 2023).
- Storage, including pumped hydropower, compressed air energy storage, chemical batteries, hydrogen, or other energy storage methods (Khan et al., 2019; Koohi-Fayegh & Rosen, 2020).

The exact nature in which the problems of intermittency are addressed will vary between countries. However, it is expected all energy systems with large shares of demand met by wind and solar will require strategies to manage supply uncertainty. Demand-side management is widely regarded as the most cost-effective method to address the problems of supply intermittency and does so without introducing additional losses (Kazmi et al., 2018; Williams, Gallardo, et al., 2023), so is expected to be the primary method employed in most electricity systems.

3. Methods

We scale wind and photovoltaic to be 100% of the energy production for each country. This implicitly assumes the impacts of an ASRS would be the same for solar and wind as for other renewable energy sources. Some renewable energy sources would be less affected by ASRS, such as geothermal and likely hydropower, but concentrating solar power may be more affected by ASRS as it is dependent on direct sunlight. However, as solar and wind are expected to contribute the vast majority of energy supply in a 100% renewable scenario, the impacts of this assumption are likely to be minimal. The fraction of energy generated using photovoltaics in each country is shown in Figure 1, with the balance supplied by wind.

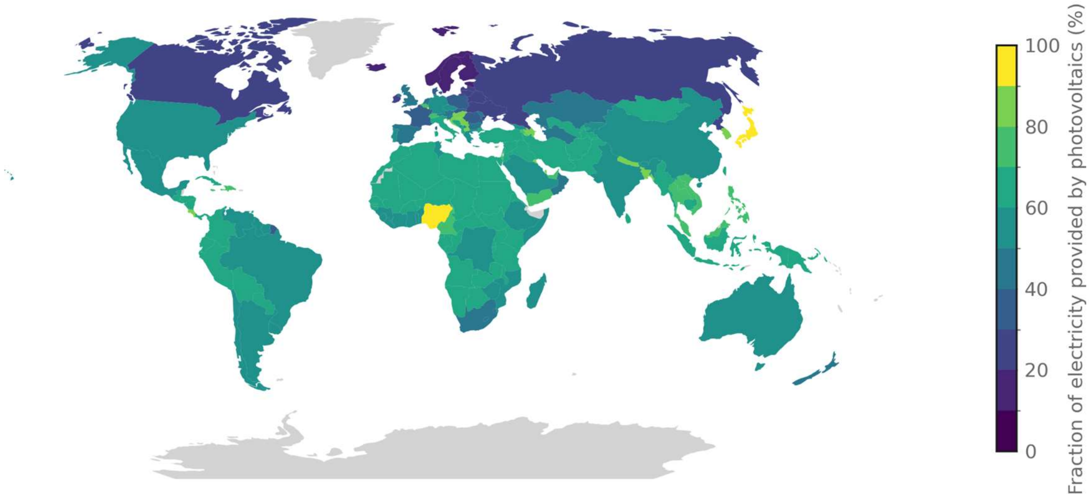

Figure 1. Percentage of energy provided by solar photovoltaics for baseline climate in a 100% renewable scenario.

We use climate modelling data from Coupe et al. (2019) to assess the impact of reduced sunlight on solar and wind energy production. Coupe et al. simulated the global climate response to a nuclear exchange between NATO and Russia, in which 150 TG (150 million tonnes) of black carbon are injected into the stratosphere. Although modelling the results of a nuclear exchange, this scenario also serves as a proxy for worst-case ASRSs arising from other causes. In this simulation, the nuclear exchange takes place in May; we designate the first complete calendar year after the nuclear exchange as "Year 1". We extract three physical quantities from Coupe et al.'s simulation results: downwelling solar flux at the surface, zonal (parallel to latitude lines) wind at the lowest model level (at a mean height of 60 meters), and meridional (parallel to longitude lines) wind at the lowest model level, all of which are provided with a 2° horizontal resolution.

To evaluate the production of solar power through the ASRS, we use monthly averages of the downwelling solar flux at the surface. We assume solar energy production is directly proportional to the solar flux received at the surface (with caveats described below). We query the climate model results at the locations of existing solar farms (Global Energy Monitor, 2024), for two scenarios: post-ASRS, and a reference year in which the sun is not obscured. The ratio of the solar flux in these two scenarios for a given month of the year yields the fraction of solar power available at each solar farm location compared to the baseline climate. This fraction is then used to calculate a time series of the solar energy available at each solar farm location, normalized according to the baseline climate case. These time series are then aggregated for each country, weighting each by the solar farm power capacity. Most countries are represented in the solar farm database (Global Energy Monitor, 2024), but for those that are not we randomly select 100 locations within each country's landmass to perform the climate data querying. Ultimately, a time series of solar power compared to baseline climate is obtained for every country.

For wind power, we use data of wind speed at three-hour intervals from Coupe et al.'s model (with some caveats described below). This finer temporal resolution is important for accurately assessing wind energy production, as wind turbine power output has a cubic relationship with wind speed, so modest reductions in wind speed can lead to large decreases in power generation; coarser temporal averages, such as daily or monthly means, would obscure these dynamics. We calculate the magnitude of wind speed from its zonal and meridional components at three-hour intervals, then cube this result to obtain a proxy of wind power. Resulting wind powers are averaged monthly, and then normalized using a baseline simulation in which the sun is not obscured. Wind farm locations are then queried, using a similar process to that described for solar farms, to estimate the impact of the ASRS on wind power production in different areas. Through this process, one time series of wind power compared to the baseline climate is generated for each country.

To assess the impact of the ASRS on total energy production, we weight the solar and wind energy results by their respective contributions to the total energy production of each country in the 100% renewable energy roadmaps of Jacobson et al. (2017). World averages are then calculated by weighting each country by Jacobson et al.'s national energy production forecasts.

The following assumptions and approximations are used in these analyses, and their implications are discussed in Section 5.5:

- No distinction is made between direct and diffuse solar radiation when calculating solar power.
- The effects of wavelength-dependent scattering and absorption of sunlight are not included.
- Wind turbine power output is assumed to be equal to the cube of wind velocity.
- Demand-side management is assumed to be sufficient to balance energy demand with uncertain supply from intermittent renewable resources, so the effects of large-scale energy storage are not assessed.

4. Results

A catastrophic scenario like a nuclear war will reduce sunlight, decreasing energy generation from wind and solar sources. Changes in wind and solar production for 12 years after a nuclear exchange between NATO and Russia are shown in Figure 2. Wind power shows considerable intra-annual fluctuation relative to production before the nuclear exchange, which is due to climatic variations throughout the year, and requires more than 10 years for full recovery. Solar power generation also requires more than a decade to fully recover but exhibits less intra-annual variability than wind. Combined wind and solar generation returns to baseline levels within 10-11 years, accounting for intra-annual variability.

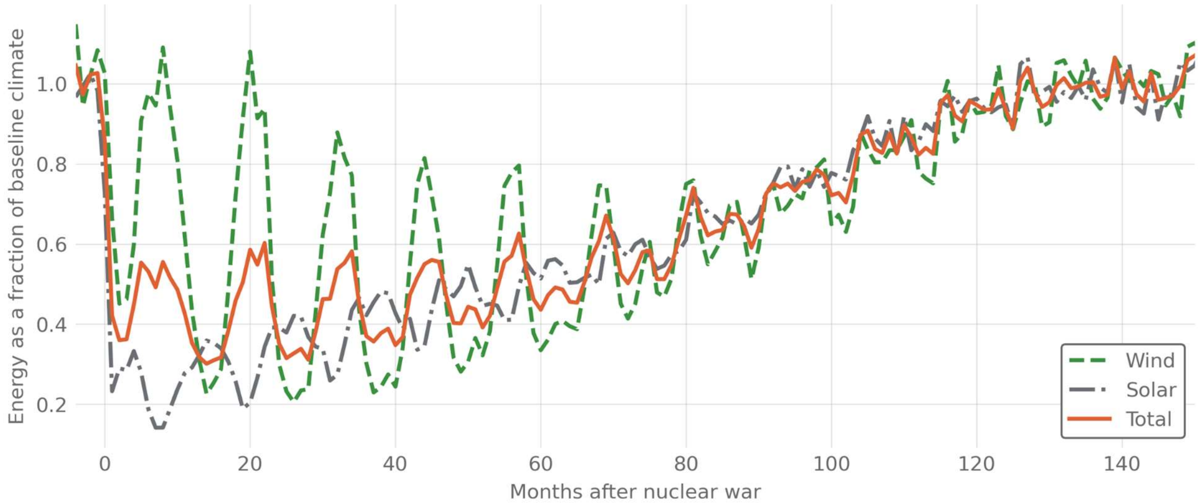

Figure 2. Global wind and solar production for 12 years after an ASRS caused by a nuclear exchange between NATO and Russia.

Figure 3 shows the percentage of remaining solar energy production in the first year of an ASRS compared to the baseline climate case. Sunlight levels in Northern Hemisphere extratropical regions are expected to decline, with these regions retaining 0-20% of baseline solar production. Reductions in solar generation in tropical regions are expected to be less drastic, remaining around 45% of baseline levels. This disparity arises for two reasons: (i) the sun is lower in the sky at higher latitudes, so sunlight must pass through more particles in the stratosphere, which attenuates the sun more in extratropical than tropical regions; and (ii) soot concentrations are generally higher in the Northern Hemisphere in this nuclear war scenario.

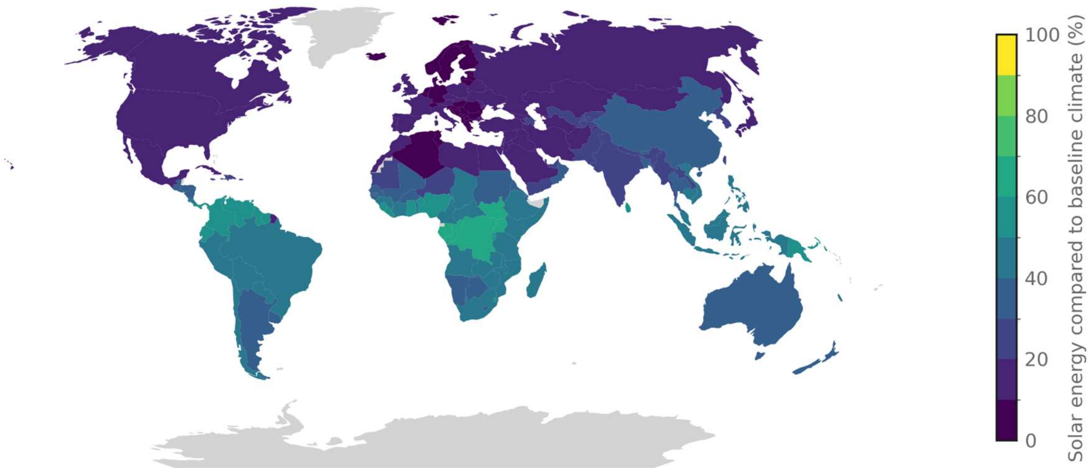

Figure 3. Solar energy generation compared to baseline in the first calendar year after nuclear war.

Changes in wind generation compared to the baseline scenario are shown in Figure 4. Reduced solar heating means temperature contrasts are reduced, causing lower wind energy in most regions of the world. In general, Northern Hemisphere extratropical regions are expected to retain roughly 65% of baseline wind power, while tropical regions are expected to retain around 40%.

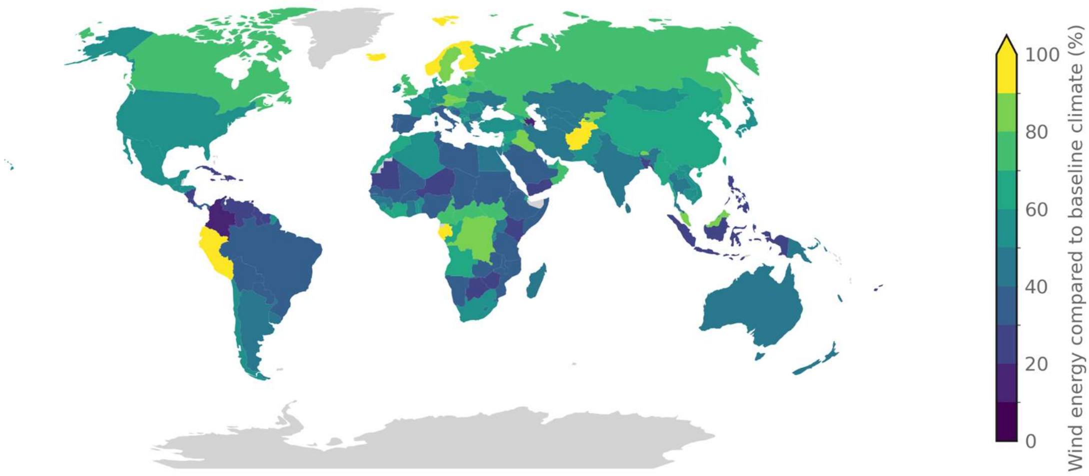

Figure 4. Wind energy generation compared to baseline in the first calendar year after nuclear war.

Change in combined wind and solar generation from the baseline scenario is shown in Figure 5. Global combined solar and wind generation is expected to reduce by 59% from baseline levels in the first year following an ASRS.

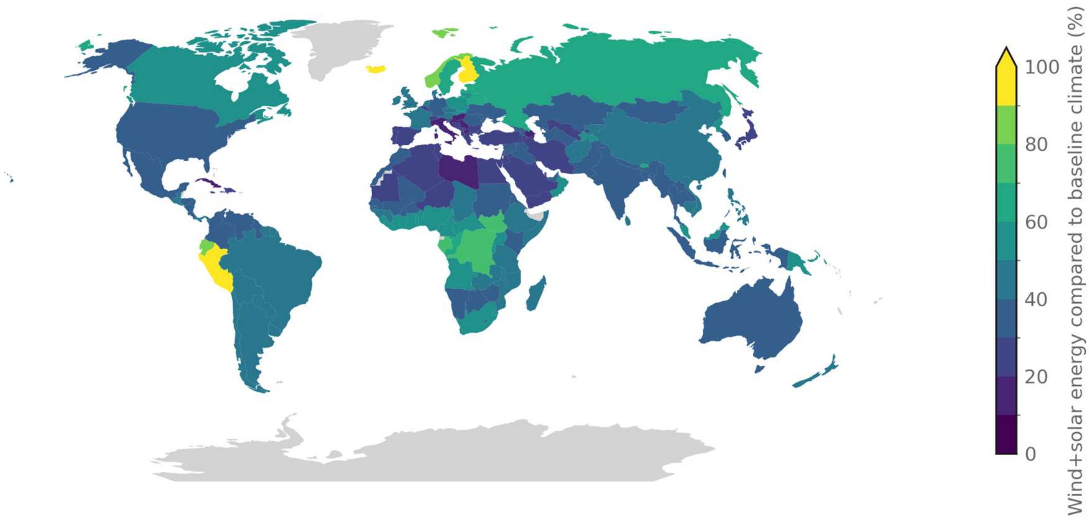

Figure 5. Wind and solar (overall energy) production compared to baseline in the first calendar year after nuclear war.

5. Discussion

A catastrophic ASRS, such as that resulting from a nuclear exchange between NATO and Russia, is expected to reduce global combined wind and solar generation by 59% in Year 1. Thus, an ASRS will considerably reduce total production in energy systems relying on renewable generation. Change in wind and solar generation is expected to vary between regions, with greater retention of solar generation in tropical regions and of wind generation in Northern Hemisphere extratropical regions, as shown in Figures 3 and 4. However, as shown in Figure 1, high-latitude countries tend to use more wind power and low-latitude countries more solar power, due to the greater intensity of wind and solar energy at higher and lower latitudes, respectively. Thus, the differences in pre-ASRS generation would mitigate the worst effects of an ASRS on renewable generation. However, despite these variations, renewable energy generation is expected to decrease in the vast majority of countries, as shown in Figure 5.

The impact of an ASRS on the current global energy system would be less pronounced. Wind and solar represent only 5% of current global primary energy consumption (Hannah et al., 2020). The primary energy from food biofuels is 0.7% of the total global primary energy supply. Since food would be scarce, food biofuels will likely cease in an ASRS, and this combined with a loss of 59%

of wind and solar due to ASRS would be ~4% of primary energy loss, which would not pose a catastrophic energy problem.

However, an ASRS would pose considerable challenges for a 100% renewable energy system, with only 41% of baseline energy production remaining. Thus, remaining energy should be prioritized to ensure critical needs are met, including water, shelter, and food. In the following sections, we calculate the energy requirements for critical needs and resilient foods, to estimate whether energy production will be sufficient for survival after an ASRS. The primary energy use of water and wastewater treatment and supply in the baseline scenario is around 4% of total generated electricity (Masłoń et al., 2020), or 0.7% of primary energy. This proportion is assumed for the 100% renewable case as well, and a similar framework is used for calculating the energy requirements of other critical needs.

5.1. Heating and cooling

Current heating and cooling demand require 43 EJ and 8 EJ, respectively (International Energy Agency, 2023c, 2023b), with space conditioning (combined heating and cooling) representing 12% of global energy demand. In an ASRS, cooling demand would decrease and heating demand increase, so total energy required globally for thermal comfort may remain relatively constant. However, these changing demands are likely to be unevenly spatially distributed, with some regions experiencing reduced, and others increased, space conditioning loads. Additionally, temperature reductions may cause freezing of some subterranean infrastructure, such as water and sewer pipes. Thus, additional energy would be required to protect these, such as by piling soil on top to raise the freezing level, or by heating the water going into the pipes (Lamilla et al., in preparation).

5.2. Food production

We estimate energy requirements for food as a percentage of current energy requirements, to approximate food requirements in a future 100% renewable energy system. Conventional food production currently requires approximately 6% of end-use energy, and the rest of the food system, including transport and storage, requires a further 16% (Day, 2011). However, conventional crop production could be reduced by up to 89% in an ASRS (Xia et al., 2022). We assume the food's energy intensity is inversely proportional to its yield, conservatively assuming the same energy inputs per hectare (although, in reality, low-yield land is unlikely to be farmed at all, so the overall efficiency decrease may be smaller). Current food demand is approximately 4.3 billion tonnes of annual dry caloric consumption (Food and Agriculture Organization of the United Nations, 2024) but is expected to fall in a catastrophe due to reductions in waste, and in edible food going to animals and biofuels. While reductions up to a factor of 2.5 could still provide adequate food to meet basic caloric requirements, conventional food would be insufficient due to reduced crop production in an ASRS (Rivers et al., n.d.), so resilient sources of food would likely be required to ensure sufficient food availability.

To account for decreased temperatures in an ASRS, crops could be relocated towards the equator to increase yields related to current locations. However, an ASRS is expected to decrease crop yields relative to baseline climate (Rivers et al., in preparation), so the net energy required for food production may increase. To increase food production, planted areas could be expanded to include current grasslands, young forests, and even desert areas that may become fertile in an ASRS (Monteiro et al., in preparation), but this expansion would require additional energy to clear and level the land. Another strategy for increasing food production with little energy investment involves the construction of greenhouses, which do not require heating or cooling and could be constructed from basic frames and polymer films, to extend growing seasons (Alvarado et al., 2020).

Further options for increased food security in an ASRS include alternative, resilient food sources, such as the following:

- **Seaweed**: Seaweed farming could provide additional food (Jehn et al., 2024), which would require the use of boats for harvesting and energy for rope production, seaweed drying, and other uses. For comparison purposes, we calculate the amount of primary energy required to feed everyone with a given food source, even though a variety of foods would be required. Since seaweed production requires approximately 70 MJ per kg of dry carbohydrate equivalent (4000 kcal/kg) (dominated by drying energy) (World Bank Group, 2016), feeding the global population with seaweed would consume 21% of global primary energy.
- **Cellulosic sugar**: Biorefineries, paper factories, and breweries could be repurposed to convert agricultural residues into cellulosic sugar (Throup et al., 2022). Since the lignin in lignocellulose (biomass) cannot be transformed into sugar, the boiler would burn the lignin and other waste products, which could produce net electricity, which may compensate for the energy required for transportation. These factories could potentially also produce leaf protein concentrate, which would contribute towards meeting nutritional needs (Donovan & Oppenheimer, 2018). Thus, cellulosic sugar is a good resilient food for energy shortage scenarios.
- **Single-cell protein**: In this 100% renewable energy scenario, natural gas wells would have been shut down. However, there may still be some biomethane production from landfills, wastewater treatment plants, and animal waste processing facilities, which could be used to grow single-cell protein (SCP) for human and animal consumption (García Martínez et al., 2022). The energy intensity of methane SCP is 90-130 MJ (natural gas)/dry kg and 15.8 MJ (electricity)/dry kg. To feed everyone, methane SCP would require 3,800-4,800 billion

cubic meters of natural gas and 870-910 GW of electricity total, equivalent to 90-115% of 2020 global natural gas production and 34-36% of 2019 global electricity consumption if it were to feed everyone. Since natural gas is 24% of global primary energy (BP, 2022), this food source corresponds to 31% of primary energy overall. Probably more scalable in the 100% renewable energy scenario is hydrogen SCP (Martínez et al., 2021), because hydrogen production is expected to contribute to a global renewable energy system (Ishaq et al., 2022). This would consume 6.5 TW of electricity, equivalent to 21.5% of 2019 global electricity consumption, to feed everyone.

- **Edible fat from petroleum wax**: Even in a 100% renewable energy system, there may still be some petroleum production for uses such as polymer and asphalt production. In this case, petroleum wax could be converted to edible fat, which would require 740-1,000 TWh of electricity and 28,000-34,000 TWh of fuels per year, or 3.3-4.6% of the 2019 global electricity consumption and 42-51% of 2019 global coal production to feed everyone (Martínez et al., 2022). Since coal is 35% of primary energy (Energy Institute, 2023), fat from wax would take 17% of primary energy. However, current paraffin wax production capacities would be insufficient to meet these requirements (Martínez et al., 2022).
- **Mushrooms**: Mushroom cultivation uses 2.7 MJ of electricity per kg of fresh mushrooms (Santos et al., 2023). White button mushrooms have ~310 kcal / kg (U.S. Department of Agriculture, 2021), or 36 MJ/dry kg. To feed everyone, mushroom cultivation would require ~60% of total 2019 electricity production, or ~10% of total primary energy.
- **Artificial light for food production**: Artificial light could be used to grow algae in bioreactors or vegetables in vertical farms (Denkenberger et al., 2019). Spirulina microalgae would require 140-500 MJ (electricity)/kg dry (Tzachor et al., 2022), while artificial light-grown vegetables would require about 4100 MJ (electricity)/kg dry (carbohydrate equivalent) at 0.4% electricity to calories efficiency (Nord & Bryson, 2022). Spirulina would then require 6.8-23.9 TW of electricity to feed everyone, or 133-466% of 2017 global electricity capacity or 230-930% of 2019 global electricity consumption. This is 40-160% of primary energy, even the lower bound of which would be infeasible in an ASRS because of other energy needs. Artificial light-grown vegetables would require 190 TW of electricity to feed everyone, or roughly 79 times the 2019 global electricity consumption. This would require ~1300% of primary energy if it were to feed everyone, which is obviously not feasible. Therefore, only small amounts of these energy-intensive resilient foods would be able to be produced in this limited energy scenario.

5.3. Increasing energy production

Another method to mitigate the effects of an ASRS on energy supply involves increasing energy production. Two broad methods of increasing post-ASRS energy production involve building the system to be more resilient before the catastrophe, and rapidly scaling up energy production after the catastrophe.

Figures 3 and 4 suggest strategic locations for the establishment of solar and wind farms. For example, regions like northern Europe and Canada would benefit from increased wind farm deployment, while regions like southern Africa and China, where solar energy remains viable even after a catastrophe, would benefit from increased solar generation, as these resources are expected to remain high in these regions after an ASRS. Integrating these data into energy infrastructure planning can optimize renewable energy resilience. However, this adaptive distribution of wind and solar generation may not be optimal from a business-as-usual perspective, so the costs of such a strategy may be high. Thus, other low-carbon forms of energy, such as geothermal, nuclear power, tidal power, fossil fuels with carbon capture and sequestration, and arguably, hydropower, could be prioritized over wind and solar because of their greater resilience to ASRS. However, these energy sources may be infeasible in some regions.

Lower-cost pre-catastrophe interventions would be more politically feasible and would not involve changing the energy system ahead of time, but instead preparing to respond well in a catastrophe. For instance, decreased renewable energy production in an ASRS could be addressed by constructing additional energy generation capability. However, since renewable production is expected to decrease rapidly following an ASRS, as shown in Figure 5, energy expenditure to construct additional generation capacity should be reserved for cases with minimal up-front and ongoing energy requirements.

An ASRS is expected to reduce conventional food production by up to 89% (Xia et al., 2022), so food production should be considered more critical than energy. Thus, energy solutions competing with food, such as using land crops for biofuels, should not be undertaken unless food needs are met. However, biofuel production may be feasible with crops such as seaweed, since people and animals can consume only a limited amount (and energy use may be low since the seaweed may not have to be dried). Production of cellulosic biofuel, such as from agricultural residues, would also be inadvisable unless food requirements were already met by other means, as the cellulose required for biofuel could be used to produce sugar to meet caloric needs.

Conversely, energy production from wood does not typically compete with food production. Thus, conversion of internal combustion engine vehicles to run on wood gas, as was undertaken during World War II, may help to mitigate energy shortages (Decker, 2010). Opportunities for wood gasification may be limited in a 100% renewable scenario, as this conversion requires an internal combustion engine and thus would not be feasible for battery electric or hydrogen fuel cell vehicles. However, vehicles with biofuel internal combustion engines and hydrogen internal combustion engines may be able to be powered with wood gasification. Wood could also be used to generate electricity via biofuel or hydrogen internal combustion hybrid electric vehicles powered by wood gasification. Alternatively, even non-hybrid biofuel or hydrogen internal combustion vehicles powered by wood gasification could run salvaged motors as electrical generators (Viloria et al., in preparation), and non-hybrid vehicles powered by wood gasification could directly provide shaft power to some loads, mitigating overall energy shortages. Similarly, wood could be used for home heating in fireplaces or wood-burning stoves.

If conventional electrical generation was scaled up following an ASRS, the focus should be on power plants with high energy return on investment (EROI). These high-EROI options typically include fossil fuel- and nuclear- powered plants, although the long construction time associated with nuclear power plants would reduce their feasibility for energy production immediately following an ASRS. Thus, while fossil fuel-powered power plants appear to be the best candidates for short-term scaling-up of electricity production after an ASRS, construction times may be longer than those currently expected, as the majority of mines and wells would no longer be operational in a 100% renewable energy system.

The energy payback times (the period required for a power plant to generate the same amount of energy that went into its construction, fuel production, and decommissioning) vary between different technologies. Wind farms typically have energy payback periods of 6 months to 1 year in current conditions (Marimuthu & Kirubakaran, 2013), but since the wind resource is reduced by about half in an ASRS, the paybacks would become 1-2 years. Solar PV systems typically have 1-4 year energy payback periods due to their energy-intensive manufacturing (Surek & Cameron, 1999), so the 70% reduction in sunlight in an ASRS would increase their payback periods to 3-12 years (though sunlight levels would largely recover before the upper bound). Hydroelectric power plants typically have energy payback periods of around 1-1.5 years (Smith et al., 2012), but additional generation capacity is limited, as existing power stations exploit the majority of hydroelectric resources in many countries (Smith et al., 2012). Concentrating solar power (CSP) typically has high energy payback periods of 3-4 years (Smith et al., 2012), which would be further increased by reduced sunlight levels, so would not be viable in an ASRS. Natural gas and coal power plants typically have energy payback periods of 6-12 months and 4-8 months, respectively (Smith et al., 2012), but reopening of gas wells and coal mines may be difficult if these have been closed following a transition to a renewable energy system. Instead, thermal power plants could be constructed to produce electricity from biogas and/or wood. Nuclear power plants typically have 6-14 month (Smith et al., 2012) energy payback periods once operational, but plant construction times can be prohibitively long. Geothermal power plants typically have payback periods of 3-6 months (Smith et al., 2012) but have limited ability to scale due to a lack of favourable locations.

Overall, while methods exist to increase energy production following an ASRS, considerations such as energy payback periods and the need to prioritize food production mean conventional energy sources, including typical electric power plants, are unlikely to be feasible. Thus, adaptive measures, including prioritization of critical needs and low-energy foods, will be imperative for energy system resilience. Further measures may include bolstering international cooperation to facilitate energy trade and the exchange of expertise between countries, and fostering robust policy frameworks conducive to the rapid deployment of backup energy production. Countries should also consider pre-emptive preparations, such as research into resilient food sources and infrastructure for the transportation of critical supplies, in the event of energy system shocks from a catastrophic ASRS.

5.4. Summary and key takeaways

Current annual energy requirements for basic needs are: (i) 51 EJ for space conditioning (International Energy Agency, 2023b, 2023c); (ii) 95 EJ for the food system, including production, transportation, and preservation (Day, 2011); and (iii) 17 EJ for water (Masłoń et al., 2020). Together, current global demand for basic needs is 163 EJ per year (20200 MJ, or 5600 kWh, per capita). In a 100% renewable global energy system, an ASRS causing a 59% reduction of combined wind and solar generation would bring global energy production to 153 EJ. Thus, energy production following an ASRS would be insufficient to meet current requirements for basic needs.

With reduced food production in an ASRS, additional energy expenditure would be required to produce resilient foods. Figure 6 shows current global energy requirements for basic needs, and the proportion of countries whose basic needs could all be met with resilient food production. This energy requirement is calculated by assuming the calories required to prevent malnutrition and maintain basic health (2100 kcal per person, or 8.8 MJ, per day (Joint, 1985)) are supplied with an equal distribution of mushrooms, cellulosic sugar, methane single-cell protein, seaweed, and petroleum fat.

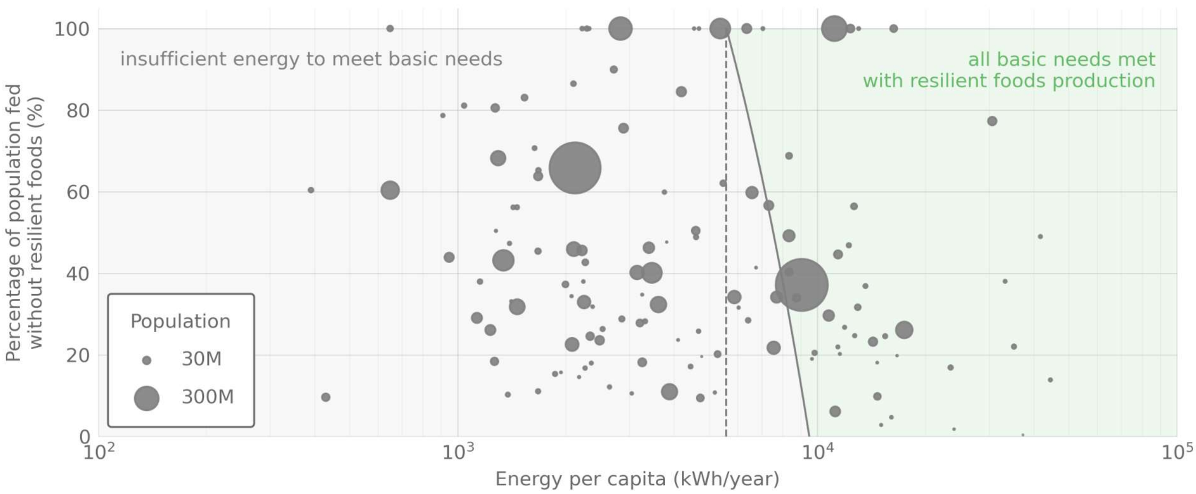

Figure 6. Percentage of the population of each country that can be fed without resilient foods, vs energy available per person during the first year of an ASRS. The dashed line represents current energy requirements for critical needs (20200 MJ, or 5600 kWh, per year, per capita), and the

solid line represents the amount of energy needed to fill the food gap with resilient food production, assuming calories are met by an equal distribution of mushrooms, cellulosic sugar, methane single-cell protein, seaweed, and petroleum fat.

Resilient food production would allow a greater proportion of countries to feed their citizens, but total energy production would be insufficient to meet basic needs around the globe. However, efficiency improvements and prioritization of basic needs, such as reducing waste in the food system and improved residential heating practices, could conceivably allow all basic needs to be met with the energy available following an ASRS. Furthermore, alternative energy sources would be available for some energy end-uses, such as heating houses with fireplaces and wood-burning stoves, rather than electricity (Jose et al., in preparation). While their effects have not been quantified in this work, such measures would ease pressures on energy supply and contribute towards global energy security.

As well as the prioritization of energy use, other measures, including international cooperation, will be required to ensure as many people as possible have their basic needs met, as highlighted in Figure 6. Figure 5 shows change in combined energy generation is expected to vary between countries, with generation in a small number of countries increasing and in others decreasing to less than 20% of pre-ASRS levels. Thus, ensuring provision of sufficient energy to provide critical services to as many people as possible will require energy trade between countries whose generation capacities are differently affected in an ASRS.

However, a catastrophic ASRS may reduce the likelihood of trade between countries, particularly as the vast majority of countries will experience a reduction in their energy production and will thus be struggling to meet their own citizens' needs. We also note the possibility of international energy trade is likely to be further reduced if the ASRS is caused by a nuclear war, as analysed in this work. Thus, individual nations should also implement measures to increase energy security in the event of a catastrophic ASRS, including strengthening international relations and establishing comprehensive contingency plans to mitigate the impacts of catastrophic events on existing energy systems, including the rapid scaleup of resilient food sources and backup energy supply systems. More expensive interventions include investing in resilient energy systems, diversified energy sources, strategic energy storage solutions, and resilient infrastructure to guarantee the uninterrupted provision of energy to essential services and critical facilities.

5.5. Limitations and future work

This study assesses only the high-level effects of an ASRS on wind and solar energy generation: decreased sunlight on solar panels, and changes in wind speed from variations to differential heating. Other potential effects of an ASRS, such as increased efficiency of solar panels and the accumulation of ice on wind turbine blades as a result of decreased temperatures, could further affect renewable generation. These second-order effects are complex and may counteract each other, so are not included in these analyses, and further research is needed to determine their nature and magnitude.

Solar and wind power are known to exhibit interannual variability with typical year-to-year variations around 10% (International Energy Agency, 2023a; Krakauer & Cohan, 2017; Kumler et al., 2019). Only one climate simulation is used in these analyses, so this natural variability cannot be separated from the effects of the ASRS, and variations on the order of 10% in a given country are best interpreted as within the range of expected natural fluctuations, rather than a direct impact of the ASRS. However, interannual natural variability over a global scale is much smaller (typically less than 3% for wind (Eoltech, 2023)), so these variations are less important for assessing the global impacts of an ASRS on renewable energy.

No distinction is made in this work between direct and diffuse solar radiation when calculating solar power. Because solar panels are typically not horizontal but tilted to maximize the capture of beam radiation, PV production could be disproportionately impacted by a reduction in direct radiation caused by atmospheric aerosols, which would likely occur for sulphate aerosols associated with volcanic eruptions. However, the black carbon in a nuclear winter absorbs, rather than scatters, sunlight, so direct radiation is unlikely to be disproportionately affected (Coupe et al., 2019). These analyses are conducted for an ASRS resulting from a large-scale nuclear exchange, so the results should be considered representative, rather than completely predictive, of ASRSs caused by other types of events.

The scattering and absorption of sunlight by soot is wavelength dependent (Coupe et al., 2019; Liu et al., 2018), so an ASRS could shift the overall distribution of solar radiation reaching the Earth's surface. Even if the total energy flux (integrated across all wavelengths) remains the same between the baseline climate and the ASRS, a change in the distribution may imply different solar energy outputs. However, to retain generalisability and avoid further assumptions, this effect is not included in these analyses.

In this study, wind turbine power output is assumed to be equal to the cube of wind velocity. With decreased wind speeds in an ASRS scenario, the efficiency of some wind turbines may decrease as wind speeds reduce below turbine cut-in speeds. However, efficiency of other turbines may increase as wind speeds reduce below the cut-out speed or from the saturated region to the cubic region (Lydia et al., 2014). Assessment of the magnitude of these effects would require the cut-in and cut-out speeds of specific turbines, which would limit the generalisability of these results.

The 2° horizontal resolution used in this work is insufficient to capture the varied local wind patterns experienced by wind farms, especially in regions with complex terrain. However, this study compares wind production in an ASRS with a baseline climate scenario using the same models of wind production, minimising the effects of these differences. Additionally, a similar resolution has been used in previous studies assessing wind turbine output in different climates

(Pryor et al., 2020), indicating the suitability of this assumption where more detailed data are unavailable.

Energy storage is not included in these analyses. Most methods of energy storage, such as batteries and pumped-hydroelectric storage, introduce additional energy losses and would further constrain supply issues in an ASRS. However, demand-side management, which does not introduce additional losses, is expected to be the primary means by which supply intermittency is addressed in future renewable energy scenarios, so the effects of storage losses are expected to be minimal. However, the presented methods are generalisable, and future work can use system-specific information to assess the effects of an ASRS on an energy system with large-scale storage.

6. Conclusions

Global end-use energy is expected to be around 370 EJ in a 100% renewable energy system, with wind and solar energy electricity generation expected to contribute 94% of global energy supply. For the worst-case scenario of the first year following a large-scale ASRS in a 100% renewable energy system, results show global energy production is expected to reduce by approximately 41% for wind power, 74% for solar power, and 59% for combined wind and solar. Combined production is expected to take over a decade to recover to pre-ASRS levels, with solar generation following a smooth recovery and wind generation exhibiting higher intra-annual variability due to changes in atmospheric circulation. Different regions are expected to be affected differently, with solar generation most affected in extratropical regions and wind generation most affected in tropical regions. The 59% reduction in energy production would decrease global energy security and necessitate prioritization measures to ensure critical energy needs are met, including food, water, and space heating/cooling. With conventional food production expected to decline alongside energy production after an ASRS, low-energy resilient food sources and low-energy practices, such as the construction of basic greenhouses, crop relocation, expansion of planted area, seaweed farming, and the utilization of agricultural residues for sugar production should be developed alongside system-level adaptations, such as reductions in animal feed, food biofuels, and food waste. With these changes in food production alongside efficiency improvements and international energy trade, sufficient energy may be available to meet food, water, and heating/cooling needs for the majority of the global population. Other post-ASRS interventions would help to increase energy security, including wood combustion for home heating and wood gasification for transportation and farm equipment. Additionally, pre-catastrophe interventions would increase energy security following an ASRS, such as strengthened international collaboration and other low-carbon forms of energy, including geothermal, nuclear power, tidal power, fossil fuels with carbon capture and sequestration, and hydropower. We emphasize the need for collaborative international efforts to address global energy security in an ASRS, but acknowledge the likelihood of limitations on collaboration and trade following an ASRS caused by an international nuclear exchange, which would leave many countries with insufficient energy to meet critical needs.

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