Developing back-up plans to protect vital sectors in catastrophic pandemics

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Abstract:

Mass labor shortages in a catastrophic pandemic could pose a significant risk to the continuity of vital sectors, severely restricting the ability of countries to provide food, water, and other basic needs to their populations. In this study, we investigate vital sector preparedness by using Monte Carlo simulations to estimate the availability of and demand for pandemic-proof personal protective equipment (P4E), reviewing literature on vulnerabilities and response plans, and interviewing experts. The supply of rapidly-mobilisable P4E in the United States was found to be insufficient, with estimated vital sector demand for respirators far exceeding amounts available in stockpiles. This is expected to be the case for almost all other nations, given most respirators are produced in China and the United States. Key risk-areas were found across vital sectors, such as high-transmission environments in food processing and vulnerable demographics of vital workers leading to disproportionately high burdens of infection. To enhance response planning, we propose five priority measures: (i) develop P4E allocation strategies, (ii) improve adaptations to workplaces (e.g., air quality) and work processes (e.g., shift schedules), (iii) establish worker sequestration protocols, (iv) address socioeconomic vulnerabilities, and (v) develop contingency plans for meeting basic needs in the event of infrastructure collapse. This research underscores the urgent need for future research and policy efforts to increase pandemic preparedness in vital sectors and provides actionable recommendations to begin doing so.

1. Introduction

Severe worker shortages in a pandemic, whether from illness, quarantine, or fear of infection, pose the risk of blocking vital industries from operating and providing basic needs to the public (Esvelt, 2022). People cannot survive without food and water, so ensuring their continuity both directly, via the industries themselves, and indirectly, via supporting sectors such as energy, communications, and personal protective equipment (PPE) manufacturing, should be a critical priority. Staff shortages impacted operations during the COVID-19 pandemic throughout the food-water-energy nexus (American Water Works Association, 2021; ESCC, 2020; OECD, 2020), despite a reproduction number approximately a fifth of measles (Durrheim et al., 2021) and fatality rates an order of magnitude less than viral epidemics such as Middle East respiratory syndrome coronavirus and Ebola (Mathieu et al., 2020).

While these disruptions were managed, future pandemics could be far more severe in their downstream effects. During the 2014–2016 Ebola outbreak in West Africa, rice yields dropped by 12% nationally in Liberia, and by up to 25% in the worst-affected districts, largely driven by fears of infection (FAO, 2016). This was a situation with an extremely high case-fatality rate, but low prevalence in comparison to COVID-19 and Influenza outbreaks. Absenteeism from a novel pandemic with both extremely high mortality and extremely high transmissibility could therefore be catastrophic in its effects on maintaining labor-intensive aspects of vital industries.

Pandemic-proof PPE (P4E) provides a key layer of protection (Greenhalgh et al., 2024), yet a future pandemic more infectious than COVID-19 could render many forms of PPE ineffective. Recent analysis indicates disposable N95 respirators would be insufficient to keep indoor workers safe from infection in a pandemic as transmissible as measles and as deadly as the 1918 pandemic influenza virus, requiring more protective options such as elastomeric respirators (elastomerics), powered air-purifying respirators (PAPRs), or next-generation products (Blueprint Biosecurity and Gryphon Scientific, 2024). This scenario would be disastrous, but should not be considered an upper bound. H5N1 Influenza has a case fatality rate of ~50%, and has garnered recent concern over the potential of a pandemic should it develop efficient human-human transmissibility (Mallapaty, 2024; Restori et al., 2024). Risk assessment should not be limited to naturally occurring pandemics, either. The CDC lists Nipah virus and Hantavirus under its Category C Bioterrorism agents specifically because of their high case fatality rates and the potential for catastrophic consequences if pathogen engineering were to enable mass transmission (CDC, 2018). Given stockpiles and global manufacturing capabilities would likely be unable to produce enough P4E to cover vital sectors in such a scenario (Blueprint Biosecurity and Gryphon Scientific, 2024), there is a need for improved measures to protect these workers.

A combination of lessons learned from the recent pandemic and forward thinking have helped accelerate a number of pandemic preparedness initiatives that are crucial to the future security of vital infrastructure. Strengthening supply chains (OECD, 2020), developing and stockpiling next-generation P4E (Blueprint Biosecurity and Gryphon Scientific, 2024), advancing the state of germicidal ultraviolet light (GUV) interventions (Buonanno et al., 2020; Kleinwaks et al., 2023; Nardell, 2021), establishing globally-coordinated pathogen-agnostic early detection systems (The Nucleic Acid Observatory Consortium, 2021), and implementing nucleic acid synthesis screening (Wheeler et al., 2024) are a few of the highly valuable areas of work within this space to build a world resilient to future pandemics. However, if the world is not prepared when the next pandemic arrives, there need to be back-up plans in place to keep vital services functioning.

Adapting existing work on operational response plans for extreme scenarios presents a low-hanging fruit for increasing pandemic resilience. In comparison to many other biosecurity interventions which require significant resources and investment, response plans come with minimal burdens attached. Government and industry stakeholders may be more amenable to this, as it comes in the form of philanthropically-funded research bundled into recommendations to roll out only if a crisis occurs. As a first step, this requires profiling the risk area, and identifying the research gaps required to provide actionable recommendations.

In this study, we quantify P4E availability and requirements, identify vulnerabilities within vital sectors, analyze the requirements of operational response planning for catastrophic pandemics, and describe a plan of action to improve preparedness and ensure this research is translated into policy insights. We explore different adaptations to keep industry functioning where protective technology such as P4E is insufficient, and to meet basic needs in the event of localized or widespread infrastructure collapse. In doing so, we aim to provide a novel framework of pandemic resilience measures for vital sectors, focusing on multiple layers of protection to protect populations regardless of pandemic severity.

2. Methods

2.1 P4E availability and requirements

In order to evaluate the ability of P4E to be used to protect vital infrastructure, we set out to quantify the overall availability of all rapidly-accessible P4E, followed by the requirements needed to cover all vital sectors, followed by the minimum requirements needed to support production of P4E. Vital workers were defined as the minimum "workers who are necessary for the basic functioning of society and who likely cannot complete their work from home" (Blueprint Biosecurity and Gryphon

Scientific, 2024). Rapidly-accessible P4E was defined as P4E that could feasibly be distributed to vital workers quickly enough to prevent industry collapse. We focused on respirators due to previous work highlighting this as a bottleneck (Blueprint Biosecurity and Gryphon Scientific, 2024). Monte Carlo simulations were used for analysis to manage uncertainties, with key estimates defined as distributions between 90% confidence interval (CI) bounds. The analysis is available online (Mulhall, 2024) as a Guesstimate (2014) model, and allows a user to change input parameters if they have different assumptions than stated here.

2.1.1 Estimating availability of rapidly-accessible P4E

The core logic and assumptions used to estimate rapidly-accessible P4E availability are outlined below (Table 1), with full details available in the supplementary materials (S1). In brief, national stockpiles were estimated first as they should be readily set-up to quickly respond in a crisis. Military and local healthcare stockpiles were estimated next as adequate planning could enable redistribution if needed, such as in the case of temporary healthcare closures if staff cannot be protected. Finally, manufacturing and retail inventory was considered, along with units distributed throughout the private sector. A coordinated effort to gather and distribute these was deemed plausible. Other sources were excluded due to not meeting the *rapidly-accessible* requirement (e.g., respirators owned by individuals) or being assumed to only contribute a small amount of usable respirators (e.g., non-healthcare public sector organizations).

Table 1. Summary of sources and methods for estimating availability of rapidly-accessible pandemic-proof respirators. PAPR = powered air purifying respirator, CBRN = chemical, biological, radiological, and nuclear hazard respirators, JSGPM = joint service general purpose mask, SNS = strategic national stockpile, distr. = distribution, HHS = department of health & human services, PPE = personal protective equipment.

Category	**Type**	**Data source**	**Extrapolation and Assumptions**
National Stockpiles	Elastomerics	SNS purchase exploring national elastomeric deployment strategy (Haas et al., 2021)	● Stockpile numbers multiplied by normal distr. of 0.5–2
	PAPRs	Federal Coronavirus purchase contracts	● Normal distr. of 25–50% of purchases categorized as national stockpile, based on proportion purchased by HHS. ● Result multiplied by normal distr. of 0.5–2
Military Stockpiles	CBRN	Reported total fielded JSGPM masks (Hillman, 2023) and annual budgets (Office of the Under Secretary of Defense, 2024)	● Estimated as lognormal distribution between one year's purchase and half of fielded masks
Local Stockpiles	Elastomerics	Survey of healthcare PPE availability (Pillai et al., 2015)	● Normal distr. of 6–12% of hospitals stockpiled to normal distr. of 50–100% of pandemic requirements ● Normal distr. of 0–50% available for redistribution
	PAPRs	Survey of healthcare PPE availability (ASTHO, 2014)	● Estimated as a normal distr. between lower bound of PAPR availability and upper bound of annual purchases in survey ● Normal distr. of 0–30% available for redistribution
Inventory	Elastomerics	Market data for other types of PPE (Grand View Research, 2024a; Joskow, 2022)	● Estimated as normal distr. of 17–33% of N95 sales ● Resulting revenue dividing by unit cost ● Lognormal distr. of 50–75% with suitable filters ● Normal distr. of 30–80 days on-hand
	PAPRs	Market revenue reports (Grand View Research, 2024b; Straits Research, 2024)	● Estimated by dividing revenue by unit cost ● Normal distr. of 70–100% suitable ● Normal distr. of 30–80 days on-hand
Private Sector	Elastomerics	Survey of private-sector PPE usage (Doney et al., 2005)	● Estimated by extrapolating elastomeric-using employees from organization data ● Normal distr. of 58–99% employees use elastomerics (based on survey data) ● Lognormal distr. of 1–4 respirators per employee
	PAPRs	Survey of private-sector PPE usage (Doney et al., 2005)	● Estimated from number of PAPR-using employees in survey ● Lognormal distr. of 0.25–1 PAPRs per employee

2.1.1 Estimating P4E requirements

Demand estimates for the full vital workforce and the minimum P4E production workforce were quantified for the first three months of a catastrophic pandemic (Table 2), with full details available in the supplement (S2). This period of time was chosen as a crisis-buffer to weather the immediate stage of the pandemic and allow for ramp-up of response measures such as increased P4E production to help re-introduce additional essential services that may not be feasible in the short term (e.g., large-scale healthcare systems or critical supply chain inputs). Existing estimates were used to inform a range of realistic potential values for the size for the vital workforce; however, creating a detailed profile is outside the scope of this paper. McNicholas and Poydock (2020) estimated the number of US essential workers as 55 million, defined by executive orders during COVID-19. As the number of vital workers will very likely be lower than this, it provides a real-world data point to start from.

The upper bound of vital workers was informed by Blueprint Biosecurity and Gryphon Scientific (2024), who estimated vital workers for societal function in future pandemics by assessing individual job categories within critical infrastructure. This resulted in the inclusion of all agriculture and healthcare workers, 39.1% of industry workers, 38.4% of service workers, and 40% of military workers. For the U.S., which has 11 million essential agriculture workers, 17 million essential healthcare workers (McNicholas and Poydock, 2020), 22 million non-food industry workers (U.S. Bureau of Labor Statistics, 2024), 18 million non-food service workers (Deloitte and Datawheel, 2024), and 2.86 million military workers (USAFacts, 2024), this sums to approximately 45 million, or 82% of essential workers.

The lower bound estimate for vital workers was informed by the framework proposed by Gopal et al. (Gopal et al., 2023), breaking down essential workers into primary, secondary, and lifesaving workers. If only primary sectors are taken as vital workers in the first stage of a catastrophic pandemic, this leaves the provision of food, water, energy, communications, P4E, and law enforcement. For food and agriculture, in a minimal viable sector it was assumed that restaurants and retailers would be closed and food would be delivered to people. Therefore, all services, stores, and textile workers were removed to leave 5.7 million workers (USDA Economic Research Service, 2023). All 0.11 million essential water workers were taken. Given commercial needs would be much lower, half of essential energy and telecommunications workers were taken — 0.66 million and 1.6 million, respectively (McNicholas and Poydock, 2020). All 17 thousand current PPE workers were taken to cover P4E manufacturing (IBISWorld, 2024), and a reduced 20% of military workers were selected for law enforcement (0.57 million) (USAFacts, 2024). Finally, 20% of essential transportation, warehousing, and delivery workers (0.79 million); 10% of industrial, commercial, residential facilities and services workers (0.68 million); and 10% of essential critical manufacturing workers outside of direct PPE production (0.1 million) were assumed to be required to ensure delivery of basic needs. This sums to approximately 10 million, or 18% of essential workers.

Given the proportions suggested by these existing definitions, vital workers were therefore estimated as 18–82% of the essential workforce. For P4E production requirements, manufacturing, distribution, telecommunications, and energy workers were considered (supplementary materials; S2). Workers who work outdoors or alone may be protected by N95s, with all other workers requiring P4E such as elastomerics or PAPRs (Blueprint Biosecurity and Gryphon Scientific, 2024). However, due to concerns that fit failure may reduce effectiveness of all PPE, 70–100% of vital workers were assumed to require P4E. As P4E is reusable but may still occasionally need to be replaced, a lognormal distribution of 1–2 units per worker was assumed.

Table 2. Summary of sources and methods for estimating pandemic-proof respirators required to cover vital workers or support production of more respirators. PPE = personal protective equipment, P4E = pandemic-proof personal protective equipment, distr. = distribution, USPS = United States Postal Service, N95 = disposable N95 filtering facepiece respirator, telecoms. = telecommunications.

Category	**Sub-category**	**Data Source**	**Extrapolation and Assumptions**
All vital workers	Total workers	Previous estimates of essential (McNicholas and Poydock, 2020) and vital (Blueprint Biosecurity and Gryphon Scientific, 2024; Gopal et al., 2023) workers.	● Vital workers estimated as normal distr. of 18–82% of 55 million essential workers ● Normal distri. of 70–100% of workers require P4E ● Lognormal distr. of 1–2 respirators per worker
P4E production	PPE workers	US PPE workforce (IBISWorld, 2024)	● All 17,000 workers required
	Distribution workers	USPS workforce (US Bureau of Labor Statistics, 2024; USPS, 2024) and pre-COVID-19 N95 production (Joskow, 2022)	● Lognormal distr. of 5–20% of USPS workers required ● 67% are mail carriers and can use N95s ● 33% are warehouse/office workers and require P4E
	Telecoms.	US telecoms. workforce (Taylor, 2024)	● Lognormal distr. of 5–20% of 250,000 telecommunications workers required ● 50% require P4E ● 50% can use N95s
	Energy sector	Data on energy requirements of PPE production, distribution, and telecommunications.	● Estimated energy requirements make up <1% of total consumption ● Network effects may increase worker requirements ● Lognormal distr. of 1–10% of energy workers required

2.2 Profiling vital industry preparedness for extreme pandemics

2.2.1 Review of peer-reviewed literature, industry documentation, and media

A narrative literature review was conducted for each vital industry using academic literature databases, search engines, and targeted organization searches. With [vital industry] as a placeholder for variations of food, water, energy, PPE, or communications, key search terms included (COVID-19 OR pandemic) response plans [vital industry], (COVID-19 OR pandemic) preparedness [vital industry], (COVID-19 OR pandemic) adjustments [vital industry], (COVID-19 OR pandemic) operations [vital industry]. Academic literature was included for robustness of sources, whereas non-academic sources were included due to the wealth of information in industry and government documentation. Targeted organization searches were used to find key information on operations after identifying the major organizations within an industry.

2.2.2 Key informants

Key informants (n=8) were interviewed to gain additional insights for this study and provide sense-checks for researcher findings and theories of pandemic preparedness (supplementary materials; S3). These contacts were made up of workers with operations management experience in vital industries (n=4), academics specializing in vital industries (n=3), and one specialist worker from a non-governmental organization (n=1).

2.2.3 Evaluation of vulnerabilities and recommendations

Research findings from the literature review, interviews, and PPE analysis (Sections 2.1–2.2) were synthesized to identify key vulnerabilities throughout vital sectors, recommendations for response plans, and areas for future work. An evaluation framework was developed to aid in comparing the value of adaptations in an extreme pandemic (Table S1). This framework consisted of six criteria: (1) speed of deployment, (2) feasibility/scalability, (3) additional cost, (4) effectiveness (of maintaining industry function), (5) likelihood of effectiveness, and (6) adherence. An internal wargaming workshop was conducted to cross-evaluate rankings, and evaluate priority vulnerabilities and interventions.

3. Results

3.1 P4E Estimates and Sector Vulnerabilities

P4E availability was estimated to be sufficient to support the production of more P4E, but far below the amount required to protect all vital workers for the first three months of an extreme pandemic (Figure 1). P4E production would require 270 thousand (90% CI: 100–660 thousand) units of P4E, which could potentially be covered by national stockpiles which total 390 thousand (90% CI: 210–660 thousand) units. In contrast, all vital workers were estimated to require 29 million (90% CI: 11–64 million) units of P4E, far exceeding combined hospital, military, and national stockpiles ("all stockpiles") of 860 thousand (90% CI: 0.52–1.4 million) units. Adding all manufacturer, retailer, and private workplace stock to stockpiles ("all rapidly-accessible P4E") would still likely be insufficient at 6.6 million (3.7–11 million) units. There is a 1.3% overlap between this distribution and vital worker requirements. Assuming a lognormal 1–15% chance of this P4E being perfectly redistributed with current levels of planning, the probability of meeting requirements is 0.0000040%.

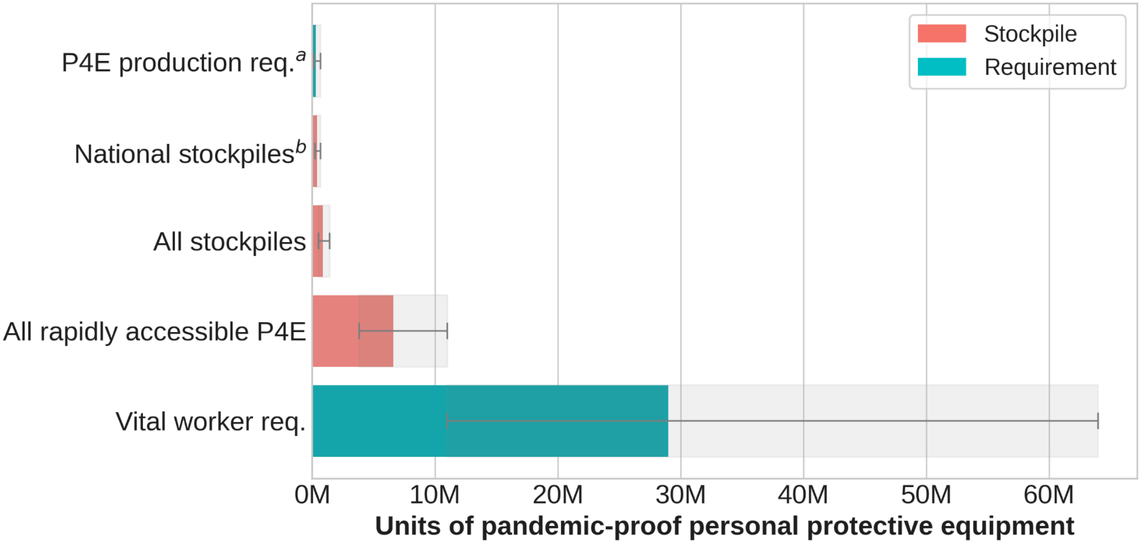

Figure 1: Comparison of P4E stockpiles and P4E needed in an extreme pandemic. P4E = pandemic-proof personal protective equipment, [a]Excluding law enforcement requirements, [b]Excluding military stockpiles, req. = requirement.

P4E manufacturing was deemed relatively more resilient than other sectors, given staff can be equipped with respirators produced in-house. However, repurposing other manufacturing facilities could increase transmission risks. Incidence rates (IRs) in 2020 of viral infections per 10,000 full-time workers in potential repurposed sectors, such as *textile and fabric finishing mills* (IR: 36.6), were higher than the range of averages for non-healthcare industries (IR: 5.0–25.4). In contrast, PPE manufacturing (*Surgical appliance and supplies manufacturing*) had a much lower IR of 7.9 (U.S. Bureau of Labor Statistics, 2020). As workers in the manufacturing industry work in close proximity for extended periods (CDC, 2021), facilities may need to ensure safety protocols are improved when repurposing to scale up P4E production.

3.2 Food Sector Vulnerabilities

Within the food sector, key transmission vulnerabilities were identified from farm to fork. Labor shortages of 1.9% were observed nationwide during COVID-19 in the US, alongside a 2.6% decrease in agricultural production in 2020 (Haqiqi and Bahalou Horeh, 2021). Ebola-induced labor shortages were associated with significantly worse impacts — rice yield shocks of 12% nationally and 25% in the worst-affected districts (FAO, 2016) — suggesting a catastrophic pandemic could result in even greater losses. Food processing was hit hardest, with a peak 40% drop in meat processing during COVID-19 (Ijaz et al., 2021). Workers operate in high-density plants where social distancing is impractical (Waltenburg et al., 2021) and loud conditions facilitate increased emissions due to shouting (Aday and Aday, 2020). While transportation roles, in contrast, can be lower-contact, the reliance of most regions on distant food sources (Marusak et al., 2021) renders them entirely dependent on specialized transport workers that are difficult to replace (Luke and Rodrigue, 2008).

Addressing this risk requires an understanding of farm worker vulnerability. Racial and ethnic minority food workers experienced a disproportionately high burden of COVID-19 infections and make up half of the agricultural workforce (Waltenburg et al., 2021). Moreover, undocumented farm laborers lack protection from the government despite making up 41% of the crop agriculture farm workforce (USDA, 2023). Workers often share modes of travel, increasing the risk of infections spreading through teams, and are often not granted paid sick leave or health insurance coverage, disincentivizing isolating when infected (Aday and Aday, 2020). Working in a low-contact environment cannot keep vital workers safe if they get infected outside of work, and improved planning will have to account for this.

3.3 Water Sector Vulnerabilities

During COVID-19, a third of US water utilities experienced staffing shortages and impacts on operations, exacerbated by 40% experiencing hiring difficulties (American Water Works Association, 2021). Staff shortages could instigate a number of failure points in future crises, from having insufficient workers to maintain supply, monitor and treat water, repair mains and pump systems, or keep payroll systems functioning to incentivize employees and vendors to keep working in a crisis

(Van Atta and Newsad, 2009). Operators, technicians, and drivers were identified as specific vulnerabilities due to criticality for continuity of operations (EPA Office of Water, 2022) and difficulty in hiring (American Water Works Association, 2021), suggesting these may also be bottlenecks in future pandemics.

Water also highlights the interdependence of vital sectors in maintaining and protecting the workforce in a future pandemic. A national moratorium on water shutoffs could have reportedly prevented half a million infections during COVID-19 (Jowers et al., 2021), while full utility disconnection bans could have reportedly reduced infections by 9% and deaths by 15% (Zhang et al., 2022). This links back directly to reducing vital worker infections, as nearly half (45%) of all COVID-19 essential workers are people of color, and half of essential sectors have lower wages than their non-essential counterparts (McNicholas and Poydock, 2020). Households with these characteristics are more likely to experience utility disconnections (Zhang et al., 2022), which could cause increased vital worker shortages in future pandemics.

3.4 Energy Sector Vulnerabilities

The energy sector has gained resilience through preparedness planning in response to SARS, H1N1, Ebola, Zika, and COVID-19 (North American Electric Reliability Corporation, 2020; Wormuth et al., 2020), though extreme scenarios may require greater efforts. Mission-critical control room operators and technicians still have to work in close-quarters. A single infection requires quarantine of the entire shift, meaning energy organizations could run out of these workers in a few weeks without sufficient planning (ESCC, 2020). Risks may be higher in areas heavily reliant on nuclear power, such as France where it provides 65% of electricity (IAEA, 2024). Nuclear plants require refueling every 18–24 months, involving hundreds of specialized workers in close proximity—a process challenging to maintain during pandemics (Korsnick, 2020). A collapse of the energy sector would induce catastrophic collapse of all other vital sectors, highlighting the need for additional failsafes where vulnerabilities remain.

For locations dependent on other sources of power, supply and demand fluctuations still stress the grid by overloading infrastructure. In particular, this may be exacerbated by inadequate forecasting of drastic changes in usage patterns causing transformer failure (Wormuth et al., 2020) and a lack of rationing plans. While gasoline rationing during World War II (Springate, 2023) and rolling blackouts during the 2000–2001 California energy crisis (Sweeney, 2002) mitigated shortages, not accounting for pandemic-specific rationing plans may be a further cause of sector vulnerability.

3.5 Communications Sector Vulnerabilities

Functioning telecommunications are required to maintain coordination in an extreme pandemic, but labor shortages may threaten this. Maintaining staff critical for operational continuity — operators and technicians, in particular — was an issue for the majority of data centers both before and during COVID-19 (Lawrence, 2020). These skilled worker positions are not easily replaceable, and even partial staff absences could cause losses of communication systems. Over 70% of all surveyed data centers outages were related to human error (Geng and Kajimoto, 2020), with labor shortages and tiredness leading to more outages and incidents. In order to safeguard against these effects, protecting key positions and cross-training workers on mission-critical tasks will be required in a global catastrophe.

The telecommunications industry plays a critical role in reducing vital worker infections by enabling remote work — a role that may be jeopardized by energy constraints. During COVID-19, quarter 2 of 2020 saw outages caused by lack of power increasing by 69% compared to quarter 2 of 2019 (Alotibi et al., 2022). While the impact of power outages can be mitigated by having back-up generators, this is dependent on both having generators and having fuel to run them. Operators without priority fuel delivery contracts may be unable to secure them post-catastrophe (Uptime Institute Intelligence Team, 2020), further highlighting insufficient backup power plans as an operational vulnerability that could have large effects on vital worker safety across industries.

3.6 Post-collapse scenarios

As long as vulnerabilities remain within vital sectors, industry collapse remains a threat. Without industrial agriculture, yields of major crops are anticipated to drop 15–37% in the year following a catastrophe (Moersdorf et al., 2024), before considering any reductions from labor shortages. Moreover, additional effects throughout the food supply chain could trigger famine in the event of a year-long industry loss event, even in countries such as the US with high levels of food production (Blouin et al., 2024). In response to these downstream threats from industry loss, vulnerabilities and potential solutions were explored.

Food processing, water treatment, and energy prioritization were identified as underexplored areas within post-collapse solutions, presenting vulnerabilities for extreme pandemics. Food processing is energy-intensive (Corigliano and Algieri, 2024) and high-contact (Waltenburg et al., 2021), which suggests it may be a bottleneck in meeting food needs in a post-collapse catastrophe. Additionally, while some people may be able to access natural water sources if pipes run dry, emergency guidance on the location-dependent scalability of different treatment options is lacking. A broader question remains, too, of how limited fuel reserves and wood gas should be used, balancing needs of necessities such as food production, distribution, water trucking, and backup generators for P4E manufacturing. Solving these uncertainties will add resilience to the current collection of resilience measures against industry collapse.

4. Discussion

4.1 Implications for response planning research

Through profiling vulnerabilities and existing response plans within vital sectors, five key areas were identified as priority recommendations for upcoming research and policy efforts to protect basic needs in an extreme pandemic — (i) allocate P4E, (ii) adapt workplaces, (iii) sequester workers, (iv) acknowledge vulnerabilities, and (v) develop collapse contingency plans. These are explored below:

(i) Allocate P4E

The modeling of P4E demand and supply shown in this study suggests rapidly-accessible P4E is highly unlikely to cover all vital workers, so P4E allocation strategies should be developed to minimize deaths caused by both infections (i.e., direct factors) and loss of basic needs such as food and water (i.e., indirect factors). This will require first creating a detailed profile of vital worker numbers to better understand how many workers need to be protected, and who is most at risk. Allocation priorities will have to carefully balance protecting lower-risk roles that provide vital services to the entire population — food, water, energy, communications, and P4E — with higher-risk roles that provide vital services to a smaller subset of the population, such as those in healthcare. Linked to this, our analysis suggests there are large volumes of P4E outside of traditional stockpiles. Figuring out how to efficiently redistribute respirators from manufacturing inventory and non-vital businesses to those who need it most has the potential to significantly increase resilience in a future crisis.

(ii) Adapt workplaces

Organizations will need to physically and operationally restructure workplaces to minimize infections and preserve labor supply. In the absence of ubiquitous, robust indoor air quality (IAQ) measures such as Far-UVC (Buonanno et al., 2020), response plans should provide guidance on rapidly ramping up alternatives such as upper-room GUV (UR-GUV), in-room filtration, and ventilation. A safe working environment would likely need to aim for at least an order of magnitude greater equivalent clean airflow rate per person than current best-practice systems such as ASHRAE-241, given they are designed around less-transmissible pathogens than considered here such as COVID-19 (Jones, 2023). Precursor studies should determine how existing infrastructure could be repurposed to improve IAQ in vital sectors, such as rapid construction of Corsi-Rosenthal type filtration units (Srikrishna, 2022), massively redistributing fans to increase ventilation, or expanding usage of UR-GUV solutions such as eggcrate-GUV in a crisis (Linnes et al., 2014). Most importantly, the relative efficacy of these options in reducing transmission should be included in analysis, accounting for combination-use with suboptimal PPE such as disposable N95s and surgical masks. Such work would inform how much vital worker safety could be improved during P4E shortages.

More general measures should start with best-practices learned from COVID-19, such as maximizing teleworking, implementing reduced shift schedules with no contact between crews, enhancing cleaning protocols (Ganesan et al., 2021), creating barriers and increasing distance between workers (Aday and Aday, 2020; OSHA, 2020), and ranking maintenance needs to determine which processes can be deferred. However, these plans should be built upon with stronger efforts to manage shortages. Adaptive staffing to switch from worker replacement to work distribution at the peak of an epidemic may double labor availability compared to replacement alone (Aguilar et al., 2021), and cross-training workers on mission-critical tasks can eliminate singular points of failure (EPA Office of Water, 2022; Furtado et al., 2020). In addition, all vital sectors should strive to have collaborative response networks in place, such as the Water/Wastewater Agency Response Network (WARN), to loan employees and resources to areas with high absenteeism (Van Atta and Newsad, 2009). Enhancing workplace adaptations to better prevent and account for severe shortages is a key recommendation for future pandemics.

Implementing response plans successfully will require strong communication plans combined with robust mental health and social support. Doing so can reduce drivers of absenteeism (Grigore, 2020; Mun et al., 2022), and accounting for cultural and language differences (Waltenburg et al., 2021) should reduce the chance of miscommunication driving transmission. Moreover, strong mental health planning will be critical to ensuring that response plans are adhered to and that laborers feel safe and engaged enough to keep working. This will be particularly relevant to more drastic measures, such as sequestering workers.

(iii) Sequester workers

In the absence of enough P4E to protect vital workers, a second line of defense is to sequester them to distance them from infected persons. Some facilities within vital sectors have rations and sleeping quarters to keep staff on-site in a crisis (Berglund et al., 2022; Morley et al., 2020), but this is far from ubiquitous. Future research should analyze the prevalence of sequestration facilities in vital sectors, the capacity of repurposed accommodation such as hotels and trailers, and the potential to rapidly construct additional facilities where required. However, providing facilities alone is not enough. Worker distribution will need to balance minimizing risks of outside transmission, by keeping workers on-site, with the potential risks of losing entire teams by having them isolated together.

(iv) Acknowledge vulnerabilities

The essential workforce is largely made up of lower-income and minority groups (McNicholas and Poydock, 2020), who are at higher risk of infection (Mora et al., 2021), and approximately one tenth are undocumented migrants with even greater risks (Center for American Progress, 2020). Given that vital workers are a subset of essential workers, it is imperative that response plans adequately address these vulnerabilities. One actionable finding is to ban utility disconnections during a future pandemic (Zhang et al., 2022), as they are likely to disproportionately increase infections amongst vulnerable workers. Beyond this, response plans should also ensure the provision of safe travel and (sequestered) accommodation options for workers to prevent infections outside of the workplace.

(v) Develop collapse contingency plans

Response plans should also include guidance on meeting basic needs in the event of local or widespread infrastructure collapse. As collapse is likely to occur in only the most severe scenarios, even localized loss of basic services poses a significant threat as neighboring regions or countries would likely be too preoccupied in protecting their own populations to provide any humanitarian aid or assistance. While developing P4E, IAQ, sequestration, and workplace adaptations is crucial to improving resilience, each is currently below the high levels of protection needed to ensure vital sectors are protected from future pandemics. Post-collapse solutions should therefore be viewed as another layer of defense against extreme pandemics, providing a safety net should first-line interventions fail to maintain vital industry function (Figure 2).

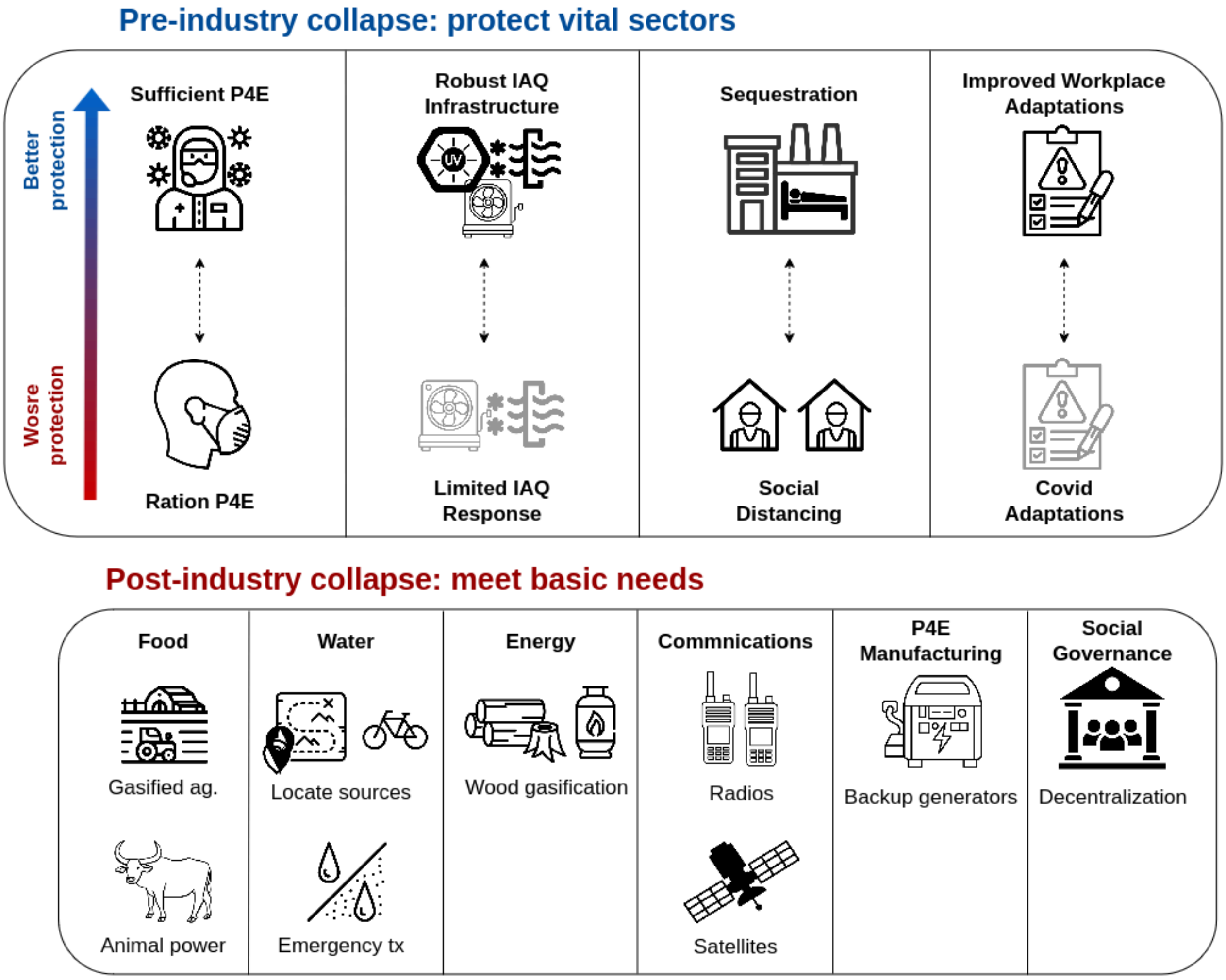

Figure 2: Layers of defense for meeting basic needs in extreme pandemics. P4E = pandemic-proof personal protective equipment, IAQ = indoor air quality, ag. = agriculture, tx. = treatment.

Existing literature has begun to identify components of this safety net. Wood gasification (Nelson et al., 2024; Vennard et al., 2024) or other biofuels could be used as an energy source, supporting industrial farming, transportation, water trucking, or generators for P4E manufacturing. In the absence of this, animal power and human-powered transport could provide alternative sources of power for agriculture and water distribution. Meeting water needs in this manner would also require assessment of the nearest suitable water sources for each population, and assessment of emergency treatment options available for different locations. For telecommunications, satellite phones and backup shortwave radio networks could potentially provide functional alternatives in the event of large-scale electricity loss (Denkenberger et al., 2021), and for social governance, local community networks could provide an decentralized alternative should traditional governance and law enforcement structures struggle to remain coordinated and functional. However, key questions remain unanswered. Further work should aim to fill gaps in the post-collapse portfolio such as food processing, water treatment, energy prioritization strategies, and decentralized social governance structures.

4.3 An opportunity for strengthening global pandemic resilience

Now is an opportune moment to develop resilience to extreme pandemics, with countries openly considering the reality of more severe crises. The World Health Organisation (WHO) has prioritized preparedness for novel outbreaks disrupting food and water since 2015 (WHO, 2015), and recent discussions of a "Disease X" 20x worse than COVID-19 at the World Economic Forum (Whiteside, 2024) showcase that global leaders are open to discussing mitigation strategies. Just this year, the White House released a memorandum to investigate resilience requirements in critical infrastructure (The White House, 2024). While our analysis focused on the US, the findings are broadly applicable — most other countries could also expect significant P4E shortages in a catastrophic pandemic given most respirators are produced in China and the US. With conversations on severe pandemics taking place at the highest levels, the pandemic treaty discussions ongoing (Johns Hopkins Bloomberg School of Public Health, 2024), and COVID-19 disruptions fresh in the minds of operations teams, there is an opportunity to engage key stakeholders across the globe.

In order to ensure research is translated into effective pandemic resilience, we recommend a three-pronged approach with a focus on adapting existing disaster frameworks. Firstly, research findings should be packaged into an additional "vital" extension of existing continuity of operations plans, taking into account the needs of the governments, industry groups, and organizations that would be involved in rolling out these plans in a crisis. Secondly, government stakeholders should be engaged to integrate extreme pandemics into critical infrastructure plans, such as via the National Security Memorandum on Critical Infrastructure Security and Resilience (The White House, 2024). Thirdly, industry groups should be engaged to provide vital sector organizations with this information, such as through the threat warning and risk mitigation capabilities of Information Sharing and Analysis Centers (National Council of ISACs, 2024). In doing so, existing communication networks can be employed to reach as many organizations as possible, maintaining a larger proportion of vital services should a catastrophic pandemic arise.

4. Conclusion

This study highlights significant gaps in vital infrastructure pandemic preparedness that could jeopardize the ability to meet basic societal needs in a catastrophe. Estimated shortages of P4E are expected to exacerbate existing vulnerabilities in the food, water, energy, communications, and P4E manufacturing sectors, threatening infrastructure collapse. However, targeted research on the topics proposed here can begin to mitigate this risk, and follow-on work from the wider community can greatly further this effort. By engaging researchers, policymakers, and industry leaders in a coordinated effort, we can better safeguard vital services and protect populations from future pandemics.

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