Risk Analysis and Mitigation Strategies for Preventing Corrosion during Industrial Power Failure

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Abstract

Modern civilisation depends on many different sectors functioning well and concurrently to run smoothly. This includes the energy sector, the transport sector, and the information technology sector, to name a few. As such, the consequences can be catastrophic if these sectors were to fail and remain out of commission for 1 to 25 years, due to some form of power outage or disaster. Possible causes include a high-altitude electromagnetic pulse from a nuclear bomb or a solar storm, a pandemic worse than COVID-19 causing people to be too fearful to work in critical industries, a cyber-attack, or an extreme natural disaster. Some work has been done on what could happen if such sectors are disabled, but virtually none on how to cope or to prepare for the loss. First, estimates of how long such a power outage will last was calculated. Next, scenarios where there is a power loss in industry for at least 5 to 25 years was explored. The consequences of such a scenario with regards to corrosion was considered. Possible strategies for what can be done to prepare for such scenarios were also explored. It was found that considering the design, removing corrosive components, and using coatings and packaging were the cheapest ways to reduce corrosion risks.

Acknowledgements/Addendum

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This report will be reformatted as a paper and submitted to a scientific journal.

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1. Introduction

1.1. Background

The recent coronavirus pandemic has proven how ill-prepared governments are for large-scale crises. In the upcoming decades, there are greater risks that civilisation is not prepared for. One possible scenario is a long-term power outage lasting five years or more. In this type of scenario, it is likely that equipment and industries will corrode, although the rate of corrosion and how it happens are still largely unknown. Currently, research on corrosion mitigation during a power failure does not seem to exist. The closest research found was research that focused on specific scenarios after equipment failure [1], or research that only models power outages without corrosion [2]. The intersection of corrosion during a long-term power outage appears to have been unexplored.

1.2. Motivation and Significance

The motivation of this research is to shed light on possible corrosion scenarios that could happen during a power outage and their costs. With this information, governments and the people will be better prepared to handle such a situation. Since the possible damage of not being prepared for can result in large economic and productivity losses, it is important to do more to prepare for these scenarios. Furthermore, prolonged loss of electricity could cause the collapse of civilisation, from which we may not recover. This would negatively affect many future generations.

1.3. Objective and Scope

In this report, the definition of corrosion would be “the decay of materials by chemical or biological agents” [3], which includes not just metals but also other important materials. However, most resources available focus on metal corrosion; thus, most of the analysis and data presented here will be based on metal corrosion. Additionally, long-term failure is defined as a power failure lasting at least five years where large parts of civilisation have no access to electricity. Thus, solutions that can last for long periods of time are prioritised.

Under these conditions, this report aims to propose economical ways to reduce corrosion so that industries that were paused or stopped can be restarted as soon as possible. A broad, high-level overview of how this may happen was investigated. Deeper analysis into each sector is out of scope of this project, and can be built upon the foundation laid by this work.

In addition, not all industries were analysed; five critical industries that support modern civilisation were selected, and those were in turn chosen to be the focus of the analysis.

2. Literature Review

2.1. Causes of corrosion

Corrosion is defined as the decay of materials due to chemical or biological agents. Corrosion can occur anywhere there is a material exposed to a corrosive environment, and depends on what the material is and the characteristics of the environment. For the material side, the material used - such as stainless steel or carbon steel - will determine its susceptibility to attack. Stainless steel has self-healing properties due to various alloying elements such as chromium and molybdenum, while carbon steel is more likely to generate iron oxides (commonly known as rust). For the environment side, more corrosive environments are those that are near the sea (with more chloride ions and higher humidity), and also those in industrial areas, where more pollutants such as H_2S can be found. [3]

There are also many different mechanisms of corrosion. In metals, some mechanisms include:

1. Uniform/atmospheric corrosion, where an even layer of corrosion products coat the material due to electrochemical reactions on the surface in high humidity environments with relative humidity more than 70%.
2. Galvanic corrosion, where metals with different electrochemical potentials form an electrochemical cell with an electrolyte. The less noble metal with a lower potential will act as an anode and corrode, while the more noble metal with a higher potential will act as a cathode and remain uncorroded.
3. De-alloying, where certain components of alloys will tend to leach faster than other components, reducing the strength of the alloy.
4. Crevice and pitting corrosion, where corrosion occurs in crevices and pits respectively due to a difference in reactive species present.
5. Intergranular corrosion, whereby austenitic steel grains experience the diffusion of carbon towards grain boundaries and cause weakening of steel.
6. Physical stressors can also accelerate corrosion and lead to a few different related types of corrosion: stress corrosion cracking, corrosion fatigue, fretting corrosion (corrosion due to high-frequency, small-amplitude stress), erosion-corrosion and cavitation damage. [3]

With other materials such as polymers, oxidation can also occur and cause polymers to degrade, due to additives and the polymer chains in the material reacting with UV rays and oxygen. For wooden structures, they can decompose in humid environments and thus grow structurally weaker. These materials are also subject to fatigue stresses and the subsequent degradation caused by that. [3]

2.2. Consequences of corrosion

Currently, corrosion and work to prevent it - across both metallic and non-metallic materials - costs about 3-4% of world GDP annually, which is about US$2.5 trillion per year given 2015 estimates of global GDP [3]. If corrosion control best practices are implemented comprehensively, then up to 35% of the cost can be avoided, totalling to savings of between US$375 - US$875 billion per year. [4]

2.3. Corrosion prevention methods

To combat such degradation, many ways to prevent corrosion have been proposed by industry and researchers. The suitability of each method will depend on the budget of the facility owner and also what exactly is being protected.

Broadly there are six main ways:

1. The parts should be better designed. Higher-quality materials can be chosen for superior corrosion resistance. The thickness of material required to allow for adequate operational lifetime despite corrosion is also accounted for in this step. Other considerations include creating a design such that dust and rainwater cannot accumulate, reducing contact between different metals to avoid galvanic corrosion, and increasing ease of maintenance.

2. The environment of the equipment can be controlled. The humidity and pollutants present in the immediate surroundings can be reduced, such as with desiccants or with the enclosed dry air method, where the air in an enclosed space is circulated across dehumidifiers and filters.

3. Cathodic protection can be applied, where one metal is the sacrificial anode and forms an electrochemical cell with the cathode to be protected. There are two ways to do this, namely galvanic and impressed current. In the galvanic anode method, another metal (the anode) is attached to the metal to be protected such that the anode corrodes instead of the protected metal. In the impressed current method, an external current is applied to the material to supply electrons. This can be used in underground and maritime environments, where the soil or water is the electrolyte, respectively. There is a variant of this sort of protection called anodic protection, where the same is achieved in reverse - the metal to be protected is made to be the anode instead.

4. Corrosive components causing the issue can be removed. For example, draining chemicals from pipes or removing fuel from plane engines is one way to slow down corrosion when not in use.

5. Inhibitors can be mixed into the metal structure to be protected or mixed into corrosive liquids to reduce their corrosivity. For example, chromates are added to steel to reduce corrosion. Oxygen can also be removed from water in pipes.

6. The material can also be coated (with metal oxides, paint, or glass for example) and packaged well to separate it from corrosive environments. In the case of sacrificial coatings, the coating corrodes in place of the protected material. [3]

It is also possible to mitigate the impacts of corrosion instead of preventing them outright, for example ordering replacement parts once equipment has degraded, or in the case of aging dams, issuing warnings to settlements downstream in case of dam collapse.

2.4. Causes of power failure

There are a few ways that a large, long-term power failure can occur. A global catastrophic risk (GCR) is a risk that can affect a large portion of humanity to a severe extent [5]. An example would be a nuclear war. If nuclear bombs are detonated at high altitudes, it is possible to disable an entire electricity grid and most electronics connected to it. This is because of the high-altitude electromagnetic pulses (HEMPs) generated by such detonations [6]. Cyber attacks targeting the electricity grid would be another example. Other causes could be extreme solar storms damaging high-voltage transformers, or an extreme pandemic that causes people to be too afraid to show up to work in critical industries.

There are also some other risks that may cause a failure. For example, extreme weather events can cause flooding and loss of industry [7]. Another scenario could be a long-term lockdown (such as a war) that causes employees in industry to be unable to work, which can cause industrial equipment to lose maintenance. Another cause can be war and bombing of electric grids, which can cause a 6% destruction of industry with a 20- to 25-year recovery time [8]. Research has shown that such a war in the next 100 years has a higher probability than one would think, predicted to be about 0.62% per year [9]. However, in these scenarios only the specific locales affected will lose power.

2.5. Consequences of power failure

Modern civilisation depends on a large number of industries to continue functioning optimally. There are also many interdependencies between industries; if one of them is disabled due to a power failure, many other industries can be affected as well, creating a cascading effect [10]. Additionally, when industry is disabled for about five or more years, corrosion can cause issues for the various equipment used. Many examples of corrosion can be found in the oil and gas industry. The chemicals in the oil and gas industries are corrosive to commonly-used materials in the industry, such as steel [11]. When the plants are not maintained well in the case of power failure, they can incur long-term damage and high costs when they are commissioned again.

2.6. Power failure prevention

Back-up power options exist, such as diesel generators, batteries and renewable energy sources. However, in the case of a HEMP, everything connected to the grid is at risk of damage, including such back ups [6]. Even if only the grid is affected and not the back up power connected to it, poorly maintained diesel generators are estimated to have a 50% chance of failure within 48 hours. Even well-maintained diesel generators are estimated to fail about 20% of the time in two weeks, independent of HEMP effects [12].

There is also a possibility that these backup systems do not start in time to prevent damage or, even worse, not start at all. Arc flashes are likely to occur due to the HEMP and they can easily jump over the switch controlling such systems, even if the switch was an open circuit [13]. As such, while the backup systems themselves may not get damaged, the fragile electronics and switches controlling such systems might. [14] Thus, they may not be operable.

One solution to protect individual generators and renewable energy sources from grid failure is to operate them in island mode, where a battery provides power for the generator and the original grid controls are overridden [15].

Another solution for protection against outage is cable shielding, which can limit the induced current generated by EMPs [16]. However, it is unclear how common these shielded cables are, and how effective they would be against large changes in electromagnetic fields. It would also be very costly to do this everywhere.

There has been research done on whether it is possible to sustain the current human population in similar disaster scenarios [17]. However, no backup plan for preserving and restoring industry has been developed yet. It is also unclear how corrosive chemicals will behave without maintenance, and how much of a threat that poses to high-risk industries, such as chemical factories and nuclear power plants.

2.7. Industry and critical infrastructure

In order to understand what should be protected from corrosion during a power outage, an overview of industry and critical infrastructure is provided. For this report, industry is defined as all aspects of the modern economy. In particular, critical infrastructure (CI) is infrastructure that is essential to society's functioning [18]. These sectors ensure that society's basic needs are met. There are 16 such sectors which broadly cover food, water, shelter, energy, healthcare, finance, telecommunications, defence, and the manufacturing of equipment for these areas. These 16 sectors will be the most essential to protect in case of a power failure.

The 16 sectors, summarised briefly below in alphabetical order, are:

1. Chemical

This sector includes the production of basic chemicals (ethanol, sodium chloride), specialty chemicals (food additives, adhesives, explosives), pharmaceutical products, consumer toiletries and cleaning supplies, and fertilisers. [19]

2. Commercial Facilities

This sector includes all buildings used for public/commercial uses, such as mass media, hotels, stadiums, museums, libraries, real estate (office and multifamily residential buildings), and retail. [20]

3. Communications

This sector includes the information and communication technology (ICT) companies. This refers mainly to systems like the internet (mobile data and wireless), radio, satellites, and air traffic control. [21]

4. Critical Manufacturing

This sector includes the production of primary metals (aluminium, iron, steel), machinery, electrical equipment for power generation, components for vehicles. [22]

5. Dams

This includes provision of drinking water & pumping capabilities; hydroelectric dams, navigation locks, tailings dams (to contain mining waste), flood prevention levees. [23]

6. Defense Industrial Base

This includes military research labs, manufacturing, and other national security-related facilities and services. Also includes equipment, subsistence and clothing needed for military personnel. [24]

7. Emergency Services

This sector includes emergency response teams (disasters), the police, the fire department, and emergency medical services, and everything they need to operate. [25]

8. Energy

This sector includes electricity generation, the electricity grid, and oil and natural gas industries. Renewable energy sources are assumed to be part of the sector as well. Hydroelectric and nuclear energy sources are not a part of this sector. [26]

9. Financial Services

This sector includes facilities providing consumer banking services, credit facilities, investment products and risk transfer products. [27]

10. Food and Agriculture

This includes the production, processing and delivery of crops and livestock, for both domestic and export purposes. Restaurants and grocery stores are also included, as are regulatory organisations. [28]

11. Government Facilities

This includes government-owned facilities like labs, military-use buildings, housing for government employees, education, courthouses, repair shops, libraries, monuments. [29]

12. Healthcare and Public Health

This sector includes healthcare facilities and research centers, along with manufacturers and IT systems to support these facilities. Medical materials and mass fatality management services (cemeteries, morgues, funeral homes) are also included. [30]

13. Information Technology

This sector includes physical and virtual systems. Research and development (R&D), manufacturing, distribution, upgrades, and maintenance are part of the sector. Examples include internet services, cloud computing, domain name resolution services, smart devices. This can be thought of as a sector supporting the communications sector (sector 3). The scope of this sector is limited to the necessary systems needed to maintain or reconstitute the internet and its associated services. [31]

14. Nuclear Reactors, Materials, and Waste

This sector includes active and inactive nuclear power plants, along with those that are in the process of being decommissioned. The sector also includes research test reactors, radioactive material (medical and industrial purposes included), and fuel cycle facilities (produce fuel for military and commercial purposes). These do not include facilities managed by the US's defense or energy departments. [32]

15. Transportation Systems

This sector includes aviation, maritime transportation, freight rail, highways and roads, pipelines (for natural gas and hazardous liquids) and pumping stations, postal and shipping, and mass transit (public transport). [33]

16. Water and Wastewater Systems

This sector includes drinking water sourcing, delivery and storage. It also includes the digital processes required for the operation of these systems. The definition is similar for wastewater treatment utilities, and includes utilities that serve both industrial and domestic users. [34]

Within the 16 sectors, there are also four lifeline functions, namely, energy, water, communications, and transportation systems. These sectors are thought to be the most crucial sectors because they will affect the operations of all other CI sectors [35].

In Singapore, no specific critical infrastructure sectors are defined. They are termed as "essential services" instead, and are largely similar to the US's, except that transport is split up between the land, maritime and aviation sectors [36].

2.8. Research gap

While corrosion and power failure have been independently studied, no study on their intersection has been conducted, especially for power outages lasting more than five years. In current studies it is often assumed that industry will still be functioning normally when corrosion mitigation measures are implemented.

While the chances of such long-term power failure events happening is low, the severity of the consequences warrant more study and resources in this area. The chances of full-scale nuclear war is about 1 in 100 per year [37], which would be one possible cause of HEMPs. Alternatively, terrorists could co-opt the control of nuclear weapons. The World Economic

Forum also ranks cyber attacks - with a probability of 0.47% per year of success when targeting firms [38] - as among the top ten risks out of a list of 35 global risks [39]. One can extend this probability to large-scale infrastructure like electricity grids. While these chances are low, when added together, the chance of at least one of these events happening is not negligible. Such events can cause civilisation to halt and even reverse progress, since time will be needed to recover from the long-range and unpredictable damage caused.

Additionally, a search on ScienceDirect with the keyword "global catastrophic risk" OR "existential risk" OR "X-risk" OR "x-risks" OR "global risks" yielded 7,008 results [40], while a search with the keyword ‘shopping’ yielded 233,899 results [41] (as of 23 February 2021). One could argue that global catastrophic risks should deserve at least the same amount of attention as shopping does, since the former would have a more long-range impact on humanity’s future. Also, long-term power losses have not been studied in great detail; there is more interest in short-term power losses. Research on adapting to and recovering from such an event is also sparse, with only a few papers found discussing how to provide food [42] and non-food [43] needs if industry is disabled, and if the sun is also blocked causing a lack of solar energy and thus electricity to power our needs (in the case of nuclear winter) [44].

The coronavirus pandemic is a good example of the lack of research on such low-probability high-consequence events. Most research had been done only when the virus had started to spread - of the 26,508 results of a search of ‘coronavirus’ on ScienceDirect, 13,142 (or ~50%) of them were published in 2020 (as of 10 August 2020). The research may have been more useful if pandemic risks were considered and prepared for before the pandemic starts.

Furthermore, allocating more resources to preventing corrosion during a power outage would be prudent to reflect the severity of the possible damage from such events. If all of the current mitigating measures became ineffective in the event of industrial power failure (assuming no maintenance is possible because people will not be at work), corrosion costs will increase by 10.5% (see section 4.1.1 of this report). 80% of industry will also be lost at the 35-45 year mark without protection. Additionally, some of the low-maintenance corrosion mitigation methods can also be used in disaster-affected areas of the world immediately. Thus, there is value in undertaking more research in this area.

It is possible that plans for such scenarios have been prepared by governments but not released or published in journals, since they could affect national security. However, as seen from the recent coronavirus pandemic, the haphazard responses from governments show that they are not prepared to face sudden emergencies and bio-risks. Extrapolating to other risks, it is not far-fetched to assume that there is currently no plan for emergencies such as a long-term grid shutdown. While organisations that deal with these threats - such as the Electric Infrastructure Security Council [45] - exist, it is unclear if their recommendations have been implemented. Thus, there is value in exploring the consequences of such threats, and how to mitigate them. Research is lacking and governments are unlikely to have a plan prepared already.

Therefore, four main gaps to be covered in this report have been identified:

1. How quickly industry will corrode during an outage, and how long the power outage is likely to be.
2. Which sectors should be protected during a power outage.
3. How each industry will be affected by long-term corrosion.
4. Strategies to mitigate corrosion for the selected industries during an outage.

3. Methodology

For each gap listed above, different methods were used to tackle them.

3.1. Amount of time to protect industry

First, the extent of the potential damage was assessed. The rate of corrosion of industry over a long period of time without maintenance was first calculated. This calculation also serves as the control case where no protection is applied. Then, the amount of time taken for recovery given a certain amount of industry lost in disaster was calculated. A formula was also estimated for it. These details will inform the extent of corrosion protection measures to implement.

3.2. Sector selection

Which industries were more important to protect were also evaluated. Three factors were considered: the dependencies between a certain sector with other sectors, whether they were a lifeline sector, and also the valuation of the sector. To count the dependencies as found from literature, they were plotted with NetworkX [46]. The lifeline sectors were marked in red to bring attention to them. Other sectors were also considered and added to ensure nothing important was missed. For example, a sector may not be a part of the main network supporting the four lifeline sectors, but the impacts from that sector corroding may be large enough to warrant consideration as well. The sectors with the most relations and perceived importance were shortlisted. From this initial list, the sectors were further narrowed down by considering their annual valuation to determine their importance.

3.3. Corrosion risks for selected sectors

The corrosion risks to each sector was assessed, taking into account the environments that each sector operates in and the materials that are used in each sector. Each type of corrosion pathway was elucidated and the rate of corrosion per year (sector-specific) was also estimated based on the literature.

3.4. Corrosion mitigation

The six main ways of preventing corrosion were applied to the different industries, and cost estimates were calculated for each method. The breakdown and equations used for each will be included in the results section. The possibility of simply mitigating the impact of corrosion instead of the corrosion itself was also considered. Lower-cost and lower-maintenance methods were also considered. One last factor evaluated was whether the methods could be implemented even after the power outage occurs, in case no preparation was done beforehand. Finally, the methods were compared to one another and summarised.

3.5. Suitability of strategies for each sector

A chart was created to show which methods were suitable to be used for which sectors, and how much of each sector can be protected by a certain method. These are rough estimates to round out the findings in the report.

3.6. Summary of methodology

In Figure 1 the summarised version of the methodology is presented. There are many smaller parts which accumulate to form the overall structure of the report. shows how each part relates to one another. Arrows represent the flow of information or factors that contribute to each section. Grey, un-numbered sections represent information or tools from literature review, while black sections represent original work. The numbering represents which section will be discussed first. Section 6 (costs of protecting industry) will be covered as a part of section 7 (appropriate measures for corrosion prevention).

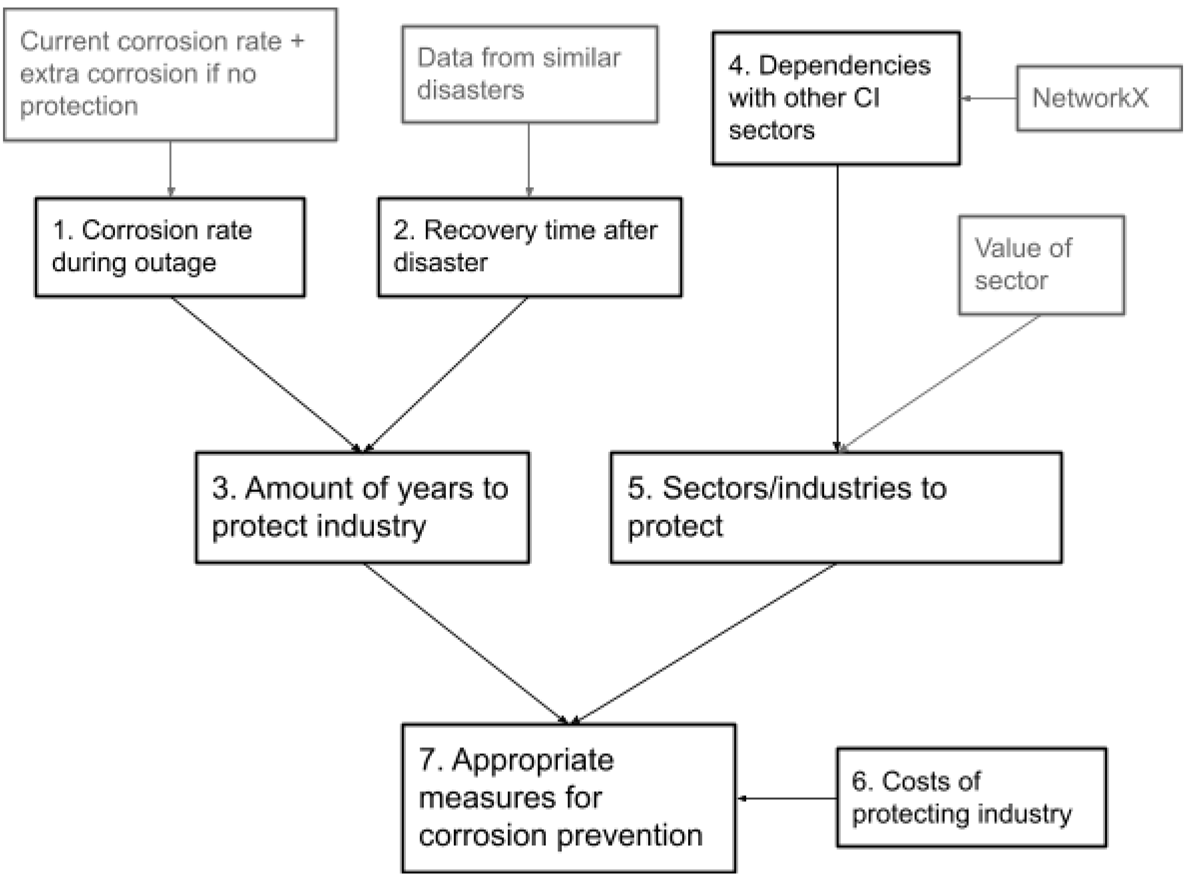

Figure 1: A flowchart illustrating the methodology.

4. Results and Discussion

4.1. Amount of time to protect industry

The amount of time is estimated from two factors - the corrosion rate without protection (how bad it will be if nothing is done, each year), and also the amount of time elapsed between the outage and the eventual restoration of power (and assumedly industry).

4.1.1. Corrosion rate during power outage

A few terms have been defined in Table 1 to aid in calculating the corrosion rate if no prevention methods were used.

Table 1: Definitions of numbers used in calculations to follow.

Term	**Definition**
$T_{D, unav}$	Current annual total unavoidable cost of corrosion damage, where no mitigation measures exist for it.
$T_{D, av}$	Current annual total avoidable cost of corrosion damage
T_D	Current annual total cost of corrosion damage
T_P	Current annual total cost of corrosion protection
T_C	Current annual total cost of corrosion. $T_C = T_D + T_P$
T_{av}	Theoretical annual total cost of avoided corrosion due to protection measures
F_C	Future theoretical annual cost of corrosion if there is no protection

From the literature, it is seen that in the United States in 1998 [47], about $121 of $276 billion USD of the corrosion cost was spent on preventative measures. This proportion can then be extrapolated worldwide. Thus, it is reasonable to assume that

$$T_P = 0.438T_C,$$

and

$$T_D = 0.562T_C$$

The literature also mentions that 35% of T_C can be reduced if corrosion mitigation measures are implemented [3]. Thus,

$$T_{D, av} = 0.35T_C$$

and

$$T_{D, unav} = T_D - T_{D, av} = 0.212\, T_C$$

In the case where there is no corrosion protection, while T_P will drop to 0, $T_{D, av}$ will increase. In an example for aircraft, corrosion protection can increase the lifetime from 17 years to 23-25 years [48]. Taking the lower end of the range, a modest estimate would be that

$$T_{av} = \frac{23}{17} T_P = 1.35\, T_p$$

Without T_P, the annual cost of corrosion will be

$$F_C = T_{D,unav} + T_{D,av} + T_{av}$$

$$F_C = (0.212 + 0.35 + 1.35(0.438)) T_C$$

$$F_C = 1.15 T_C$$

One last consideration is the amount of corrosion that is decreased due to a reduction in usage. At lower levels of usage, fretting corrosion and corrosion fatigue will decrease or reduce completely. Given that fatigue causes about 2% of failures in copper pipes (generalised to all industry) [47] and we allow for 2% more reduction because of lower fretting corrosion, the corrosion rate would thus be

$$F_C = 1.15 T_C \times 0.96 = 1.105\, T_C$$

As such, without protection, the estimated loss rate of industry would be about 3.31-4.42%, which is roughly 10.5% higher than currently reported rates of 3-4%. The amount of industry *I* in percent remaining after *t* years with *x* corrosion rate as a fraction of 1 would then be

$$I = 100(1 - x)^t$$

Figure 2 shows that the amount of industry remaining drops quickly, with about 40-50% industry remaining after 20 years. Both proposed scenarios show that at least 80% of the value of industry will be lost after hitting the 35-45 year mark. This assumes the rate in loss of value stays constant. It may be higher as a threshold amount of corrosion could reduce the value of a piece of equipment to zero. However, it may lower over time as the structures very resistant to corrosion (e.g. concrete dams) remain. For 50% of industry to remain after 25 years, the rate of corrosion needs to be reduced to about 2.73%/year, and for 80% to remain, the rate needs to be reduced to around 0.88%/year. This would entail a 17.5%-38.2% or 73.4%-80.1% decrease in corrosion rates, respectively.

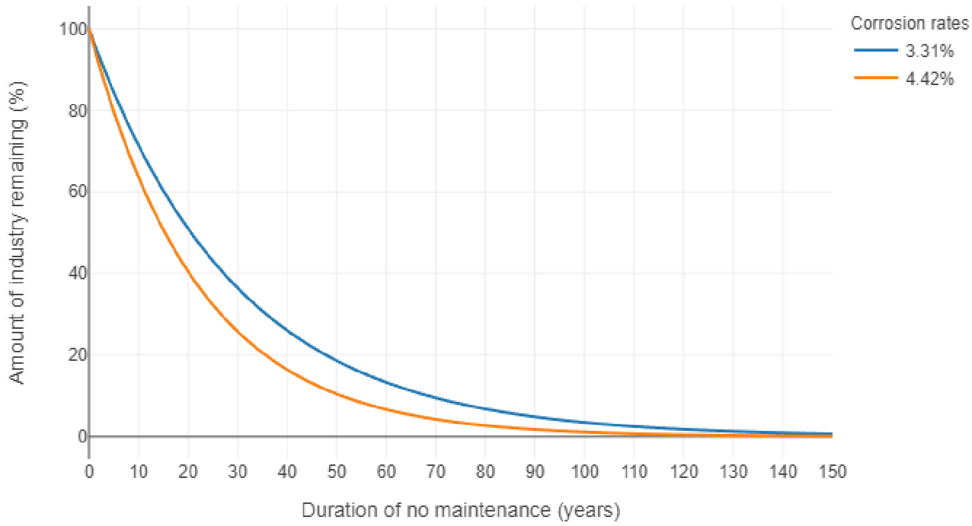

Figure 2: A graph showing two possible scenarios of losses with different corrosion rates.

4.1.2. Estimated recovery time

The estimated recovery time is shown in Table 2 below. Some values were taken from sources and others were calculated based on estimates from the sources.

Table 2: Estimates of time taken to recover industry. Bolded numbers are extrapolations.

Risk	Non-nuclear war	HEMP	Cyber attack on grid	Extreme pandemic	Extreme natural disasters
% chance per year	0.62 [9]	1 [37]	0.47 [38]	3.3 [49]	1 [7]
% of industry lost	6 [8]	13.9[1] [50] [51]	1	8.3 [52]	0.095[2] [53]
Initial recovery of essential CI (years)	**3**	3[3] [54]	0.5-2[4]	2[5] [55]	**5**
Time taken to full recovery (years)	20-25 [8]	**23-29**	4[6]	6-10 [56]	15 [57]

Other models suggest a mean of 0.4% - 3% chance per year for a 10% loss in industry, with a mean of 0.09% - 0.3% chance per year for an almost-full loss of industry. [58] The estimates presented here are in the same order of magnitude as these figures, though it was attempted to break down the causes of industry loss and find loss of industry per cause.

In the HEMP scenario, a nuclear bomb detonation above the United States that generates a resultant magnetic pulse big enough to cover parts of Canada and Mexico as well was assumed. This would likely be the worst case scenario for such a detonation, although estimates are still highly uncertain. [59], [60]

For a cyber attack on the grid, the amount of industry lost is about 1%, based on the economic loss by firms affected by past cyber attacks. Software-based attacks are likely to be unable to cause large-scale damage, since they are resolved within 15 hours normally [61]. The recovery time for power outages - even including grid damage - is likely going to be shorter than that of natural disasters, since most buildings will be standing instead of destroyed as will be the case in a natural disaster.

In the short term, it takes about 1.5-5 years for displaced communities to resettle after a natural disaster [53], [62]. The main barriers to recovery include destroyed infrastructure

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[1] Assuming Canada, the US and Mexico were all affected, and 50% of industry was disabled in those countries. The total GDP damage (if it were 2019) was about 22% of the global economy.
[2] Assuming around 5 countries affected, with 3.5% (number from source) of industry affected in each
[3] The time in the source mentions a maximum of two years, however here a 1.5x multiplier was applied to account for general chaos and incoordination when such an event occurs.
[4] Based on how quickly firms' economic performance resumes after an attack.
[5] Estimated based on COVID-19 situation - essential industries have returned to normal, and cases generally are reducing
[6] Since physical infrastructure damage would likely be localised, most of the impacts of cyberattacks would likely not linger beyond four years. The 1% loss in industry would also largely be due to economic losses.

such as buildings [63], which may not happen as extensively if the damage is mostly electrical and from the grid. However, other infrastructure damage (such as broken power lines) may occur and unforeseen complications may arise; thus, it is reasonable to conclude that the rates of recovery will be similar. Therefore, estimates of initial recovery range about 0.5-5 years, depending on the type of disaster.

Longer-term, post recovery work still continues about 15 years after natural disasters [57]. It appears that recovery roughly follows a logarithmic pattern, where most of the essential work can be completed early, while the more difficult restoration work will be eventually completed. It also appears that full recovery may not be possible, since there always appear to be some areas that are left behind [62]. However, the exact parameters differ depending on the cause of the loss of industry. Thus, it becomes difficult to create one single formula for recovery rates across all different causes of loss of industry. Also, the estimated amount of time taken for recovery does not seem to differ much at lower-digit percentages; it is unclear if the relationship between recovery time and how much industry was lost would be exponential at higher percentages or remain stable. The tipping point is assumed to be at ~40% value in terms of GDP, since that is the point where the five most important critical infrastructure sectors would have all been disabled (according to valuation, see Table 3). Thus, a possible formula could be

$$t_{recovery} = 18.8\, e^{x},$$

where *x* is the value of industry lost as a fraction of the total value of industry. This would apply at least for HEMP impacts, based on figures from non-nuclear war. The constant 18.8 was obtained by finding the value that will result in roughly 20 years of recovery time with a 6% loss of industry, as seen in Table 2.

Figure 3 below shows the predicted trend for recovery time as a function of the amount of industry lost. The model has some limitations. The model may only apply for disasters due to wars or with other infrastructure damage, since trends may be different for different kinds of disasters. For example, in the case of pandemics and cyber attacks, the damage to industry in this case would mostly be economic, leaving infrastructure intact. Thus, the recovery may be relatively quick compared to other disasters.

There is also a lack of data to create a more complete model. At low levels of industry loss, the predicted time taken to recover tends to be slightly higher than actual times. Also, at high levels of industry lost, the model underestimates the amount of time taken to recover. At levels of industry loss below 100%, it is possible that another part of the world unaffected by the disaster will be able to help with recovering industry. However, at 100% loss of industry, the recovery time is not likely to follow the trend and may be much longer, since there is no possibility of outside help from other regions unaffected by the loss.

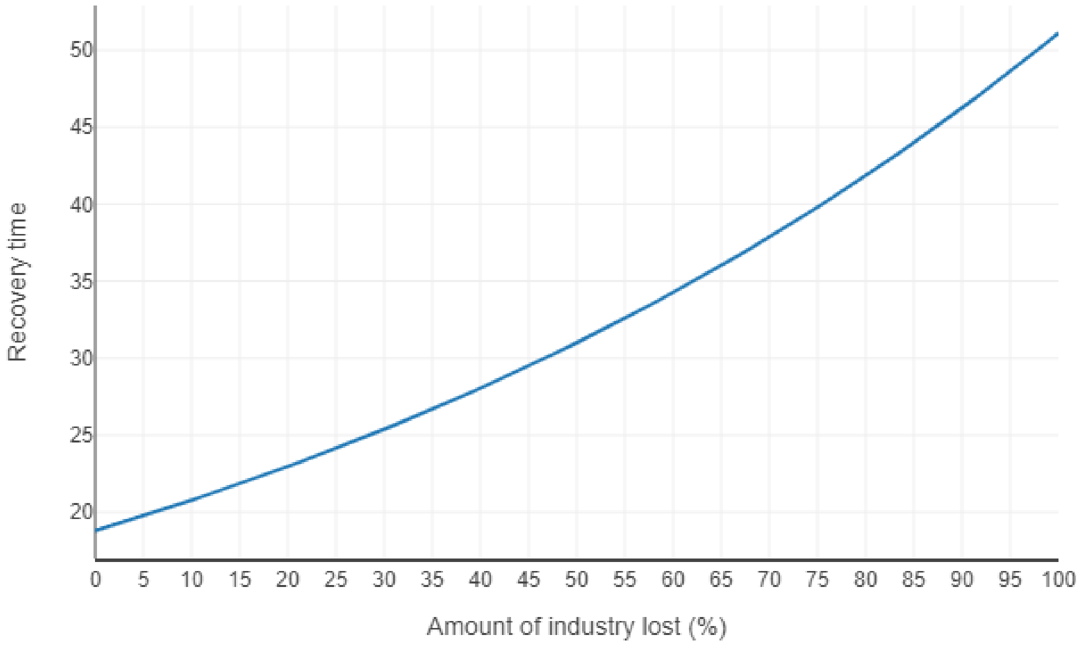

Figure 3: Given a certain amount of industry lost in catastrophe, the recovery time is estimated.

As such, solutions that are offered for corrosion will be in the range of 5-25 years without maintenance, since within 5 years, it is unlikely that extensive corrosion damage will occur due to existing corrosion prevention mechanisms. After 25 years of no maintenance, it is likely that what is left is not important enough to warrant corrosion protection. Some of the solutions may also be able to last longer than 25 years if so needed, and if better preparation was done beforehand.

4.2. Sector selection

The graph of dependencies between the 16 CIs obtained is as follows in Figure 4.

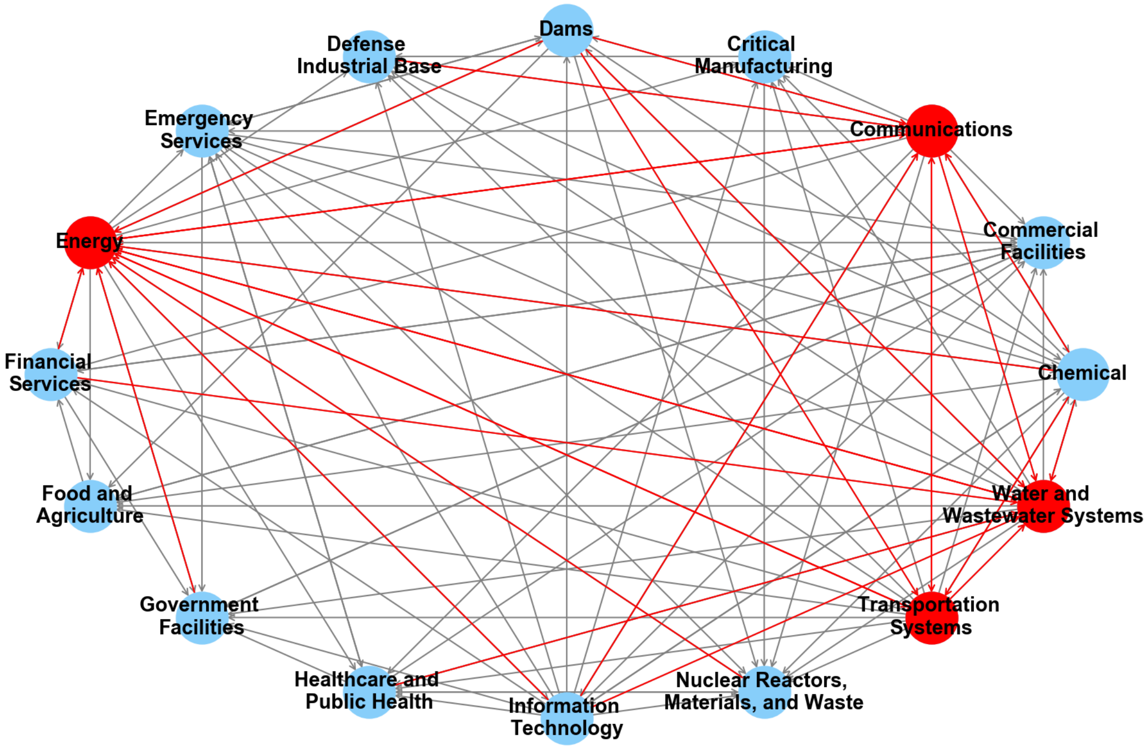

Figure 4: General overview of the 16 CI sectors and their dependencies. Red lines denote sectors that the four lifeline functions (red circles) depend on.

For a clearer view of the important relations, only the dependencies of the lifeline functions were kept in Figure 5.

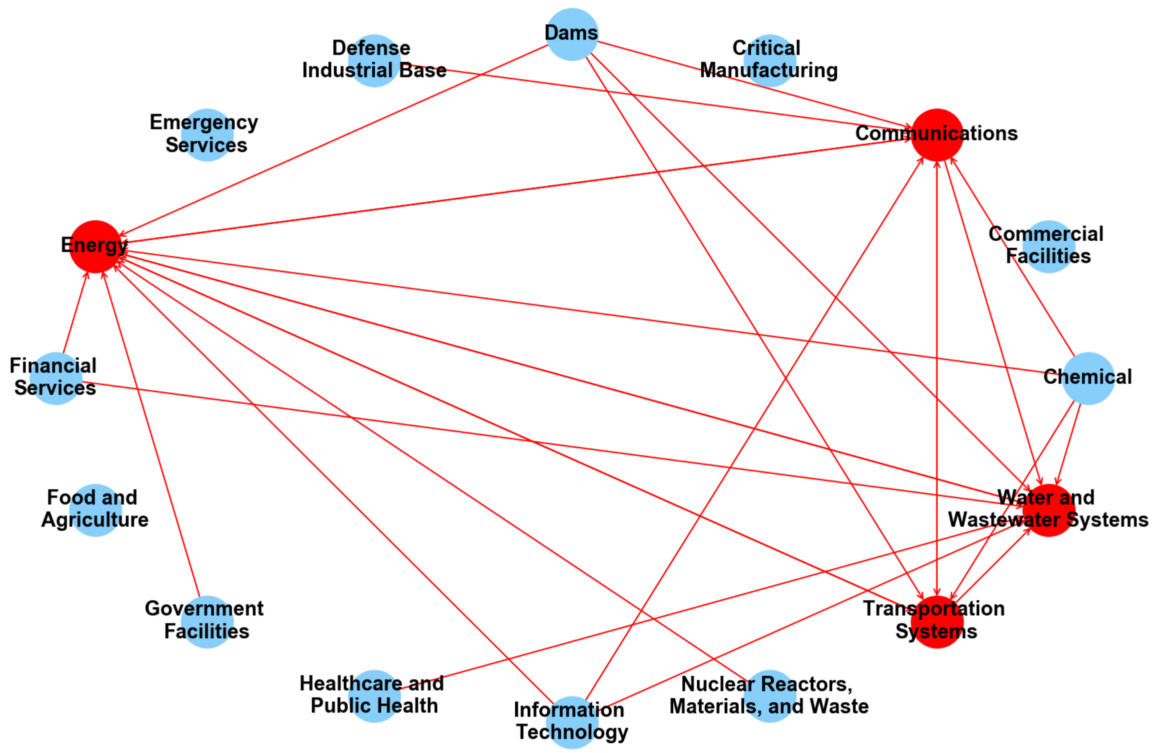

Figure 5: The same graph in Figure 4, with the lifeline functions' dependencies drawn only.

The sectors that the lifeline functions rely on are largely the Dams sector, Information Technology sector, and Chemical sector. The lifeline functions are also highly dependent on each other, as denoted by lines that are double-headed (one example is between Communications and Transportation Systems in Figure 5).

Food and Agriculture was also considered because without it, people would starve. However, it was removed since most of the equipment was designed with harsh environments in mind and did not require protection to begin with. Furthermore, equipment can be moved indoors to barns or other structures, which can provide protection as well.

While the Nuclear Reactors, Materials, and Waste Industry does not have many links with other industries, an accident in that sector can have potentially serious and unique consequences owing to the radiation; thus it was also included for the initial analysis. Nuclear reactors are generally inspected every two years [64]; assuming a lack of maintenance for five years, there could be potentially dangerous consequences.

The initial shortlist to analyse for corrosion risks contains these industries:

1. Chemical
2. Communications
3. Dams
4. Energy
5. Information Technology
6. Nuclear Reactors, Materials, and Waste

7. Transportation Systems
8. Water and Wastewater Systems

The capital value in USD of each of the eight sectors globally is in Table 3 below, as sourced and from estimates. For values that were obtained in years other than 2019, the inflation rate [65] was accounted for but growth rates of the industry were ignored, since predictions may have been unreliable.

Table 3: Value of each shortlisted sector in USD.

Sector	**Value in 2019 (original year in brackets)**
Chemical	$5.81 trillion (2018) [66]
Communications	$407 billion (2018) [67]
Dams	$4.21 trillion (2018)[7]
Energy	$7.50 trillion (2018)[8]
Information Technology	$12.3 trillion (2016) [73]
Nuclear Reactors, Materials, and Waste	$116 billion[9] (2019)
Transportation Systems	$6.18 trillion (2019) [76]
Water and Wastewater Systems	$530 billion (2019) [77]

As shown in Figure 6, the top five valued industries - Information Technology, Energy, Transportation Systems, Chemical and Dams - account for $36 trillion USD, which is 97% of the value across the eight sectors (about $37.05 trillion USD). Thus, corrosion risks for those five sectors will be analysed.

These five industries combined also account for about 44.5% of global GDP, assuming that world GDP is $80.9 trillion GDP [72].

[7] Calculated based on hydropower estimations: 1283 GW capacity in the world total [68] at $3.22 million/MW in 2018 prices [41], adjusted from $2.8 million/MW [69] in 2010 USD prices
[8] $3.3 trillion in revenue from oil and gas drilling [70], and $4.05 trillion in revenue from electricity (assume 5% [71] of $80.9 trillion world GDP [72])
[9] Calculated by adding $101 billion of nuclear energy-related industries [74] and $15.4 billion from nuclear-related uses in medicine [75]

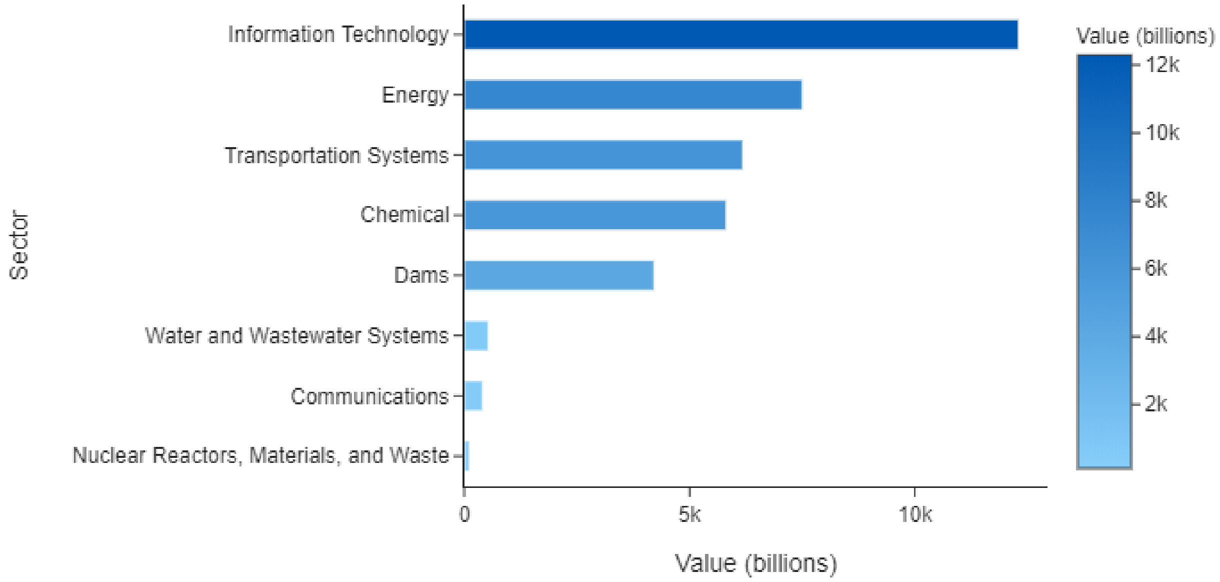

Figure 6: A graph of the value of shortlisted sectors in USD.

4.3. Corrosion risks for selected sectors

4.3.1. Information Technology

In the Information Technology sector, some types of corrosion would not be an issue because most equipment will be in enclosed environments (until the environments leak) and will not be running during a power outage. One such equipment type considered was data centres. Data centres are mainly affected by atmospheric pollutants such as hydrogen sulfide, sulfur and nitrogen oxides, chlorine, and ozone, leading to atmospheric corrosion [78]. Any such corrosion will be slowed down since the data centres will no longer emit heat, and thus will not experience elevated temperatures even as cooling and power systems fail. Also, atmospheric pollution will generally fall with a loss of electricity.

Humidity will be a bigger problem for the IT sector in a power failure. This can either be a lack of humidity or too much humidity [79] (anything outside the range of 20-80% [80]). If humidity is below 20%, it is possible for static electricity to build up. The resulting static discharge may damage pieces of equipment by short-circuiting them, especially when the protective epoxy is worn away or otherwise corroded [81].

Under humid conditions (50-80% relative humidity), water vapour forms an electrolyte that facilitates corrosion of circuits found in printed circuit boards (PCBs), which may render them unsalvageable past 6 months' time in moderately-corrosive atmospheres [82]. However, it can be observed that personal computers are able to last about five years [83] under normal use in similar atmospheres. Considering additional protection from outside elements (PCBs are generally contained within individual machines in data centres, for example), the relevant equipment is unlikely to undergo significant corrosion in about five years' time without protection, especially when it is not in use. It is also reasonable to expect a reduction in pollutants in the atmosphere, since industry will have partially or wholly stopped and thus fewer waste products would be produced. The time until significant corrosion is thus likely to be about 10 years or longer. As such, the rate of industry degradation would be about 10% per year.

The batteries used in uninterruptible power supplies for information technology products are also vulnerable to corrosion. Their cathodes and anodes may corrode, and they will also self discharge. With proper storage, lifetimes range between 3 and 10 years depending on the type of battery, and they will have discharged about 20% - 100% without maintenance [84], [85]. Thus, for the next 10-15 years, the biggest threat will be self-discharge leading to a semi-permanent loss of capacity. The low charge can cause corrosion product build-up in the battery and thus reduce capacity. Corrosion products can also build up and leak out of the battery if the battery remains inside a closed circuit/other electrical contact during storage.

4.3.2. Energy & Chemical

The energy sector mainly consists of oil and gas industries, their pipes, the coal industry, the electric grid and renewable energy sources. Each of them have slightly different corrosion risks due to their different environments. The chemical sector generally consists of plants that are somewhat similar to oil and gas plants; thus, they will be analysed together.

We first start by analysing the oil and gas industry. In oil-producing countries, the energy sector contributes the most to corrosion costs [3]. Thus we can posit that the energy sector faces a substantial threat due to corrosion. In the case of a power failure, the biggest risks would be a lack of maintenance. While the sector can be active in combating corrosion, some of the corrosion prevention methods require maintenance, constant power and surveillance. As such, when there is no maintenance, these methods may not be effective and corrosion could accelerate. A reduction in pollutants and heat in the environment surrounding equipment due to reduced activity will also be considered in the analysis.

During a power outage, it is assumed that the environment in outdoor equipment such as cooling towers is the same as when equipment is turned off. In colder climates, cooling towers may collapse if ice accumulates on the tower over time and thus collapse in one particularly bad winter, and pipes may burst if any water remains in them when they freeze. Typically protection for pipes is also meant to last around 10 years; therefore it is likely that the corrosion will worsen only after 10 years. As for indoor equipment, the situation is slightly better; it will be protected from the elements for at least about 25-30 years. This is assuming the buildings are similar in structure to shipping containers, which can last for that long without much maintenance [86].

Given the large amounts of steel used in these industries, steel corrosion would be a serious problem in the industry. To save costs, a lot of the vessels used in the oil and gas and chemical industry are made of carbon steel. The various forms of corrosion mentioned above in the literature review would apply to steel, along with sweet corrosion (corrosion due to the presence of carbon dioxide). However, due to the reduced temperatures experienced, corrosion rates will likely slow down, even though common contaminants will likely still be present in such scenarios. Thus, the main threat will be atmospheric corrosion. The contaminants present - such as SO_2 and H_2S - will still be present and likely accumulate if they are not allowed to vent from the vessels inside the power/chemical plant, or stay trapped within the relevant buildings before leaching out over the years. The rate of corrosion of steel in industrial environments ranges from 40-160 μm/year [3]; the lower end of 40 μm/year is taken since industry will not be running in the event of a power outage, reducing temperatures and therefore corrosion rates.

For the electric grid, the main threat will be to the wires and transmission cables. However, they would be expected to last at least 10-24 years, since the maintenance cycle is 5-12 years [87] and missing one maintenance cycle is unlikely to cause the transmission cables to corrode extensively.

It is important to preserve the machinery in the chemical industry since they can be retrofitted to use in case of other disasters that may occur together with power outage, such as a food crisis [17]. As such, extra care should be taken to ensure the preservation of these industries.

4.3.3. Transportation Systems

In countries that do not produce oil, transportation systems incur the most corrosion cost [3]. This is likely because transportation systems require a lot of metal for the various vehicles used in modern life. Pipes transporting gases and chemicals - also included in this sector - would likely face similar risks as above. Due to the reduced strain on transportation systems in the event of industry being disabled, this would reduce certain factors that contribute to corrosion, such as heat and pollutants.

For roads and other similar structures, it will depend on what type of road or railway it is. For gravel and dirt roads, they should be able to be maintained easily during an industry breakdown if the need arises. Thus there is little risk of corrosion for these two types of roads. Other roads that may be more susceptible would be roads or structures that contain steel in their structures, such as asphalt and concrete roads. The asphalt and concrete may also contain steel slag to improve the resistance of the steel within it to corrosion [88].

In the harshest marine environments, the corrosion rate of steel in asphalt/concrete is found to be about 50 μm/year, and small cracks in the concrete and rusting become apparent in about four and a half years [89]. Given that urban and industrial environments are about 50% and 75% as corrosive as marine environments respectively [3], we can estimate the average rate of corrosion to be about 25-37.5 μm/year, and for corrosion to become apparent past 6-9 years. With this, it can be predicted that in about 5 years, underwater tunnels may collapse at the points where it may come in contact with seawater, or with different soils, thus creating oxygen cells for the structures to corrode and fail. For railways, the rate of 40 μm/year of steel in air can be assumed to still apply, with more obvious effects manifesting past 5 years or so.

For individual vehicles such as planes, buses, trains and ships, they would largely face atmospheric corrosion. For vehicles that use tires, they may deflate slowly over time at a rate of about 1-3 PSI per month. Given that tires range in pressure from 35-42 PSI, and losing about 25%-50% of the air can make them unusable, vehicles are only able to be moved to a storage space within the first 1.5 years of the catastrophe. [90] The average lifespan of vehicles including cars and planes are about 10-25 years [91], [92], while that for a train is about 30-50 years [93], [94]. The vehicles are therefore assumed to last past a short catastrophe if they are kept in proper storage.

Ships in particular would face marine and coastal environments, which would accelerate the rate of corrosion. Carbon steel corrodes at a rate of 1250 μm/year in natural aerated seawater, much faster than in air. Extrapolating from the previous section on roads and railways, the effects of this without protection would likely be observable in just two months.

Fuel tanks may also corrode specific parts of vehicles, and have been shown to hasten corrosion of the contact structural elements in ships [95].

4.3.4. Dams

Usually, dam capacity is designed with safety factors in mind - namely, the probable maximum precipitation and probable maximum flood [96], [97]. Spillways - gated or ungated - will also be present to accommodate extra water from flooding. Even so, floods may be able to structurally damage the dams - especially poorly constructed ones - and cause significant effects on groups living downstream in the flood basin [98]. Corrosion may make such a collapse more probable.

One difference between this and the transportation systems sector is that the stresses on dams will not decrease in the event of a power outage, since they are mostly passive structures that depend more on geography than human usage. However, some types of dams can be more at risk than others. For example, pumped-storage hydroelectricity may be one such type, since a pump is required for operation, and that pump can be corroded over time, since it is submerged in water (presumably still, when not in operation).

Another vulnerable system could be the Panama Canal, due to the high maintenance levels required for it. Extreme flooding and seal breakage due to high amounts of pressure and flow are some issues that it will face in about 15-20 years without much maintenance. A more immediate cause could be eroded land filling up the canal, which can increase the corrosion rate due to a higher pressure and higher flood risk in the dam [99].

However, dams and flood control systems - such as the Thames Barrier in London - are commonly designed to last for at least 40 years from the onset [100]. Thus, some such structures may still be operational after 25 years of low maintenance.

One last unique threat that can arise from dams is that those used in generating electricity can still operate even if the power grid is damaged in some way. In that scenario, the electricity delivered from dams cannot be dissipated. As such, there can be excess electricity that is wasted in the power grid and it can contribute to heat and extra load on the grid. This may damage the grid even further over a longer period of time, causing casings to deform or melt and therefore short circuits on the grid.

Another crucial part of the dams would be the control systems. These may be the ones that are the most damaged from corrosion, with corroded components that render dam control impossible. In this case, the risks would be similar to the ones for the information technology sector, since some of these controls are similar to the equipment in that industry.

4.4. Corrosion mitigation

The best way to ensure corrosion does not happen is to ensure enough mitigation measures such that power failure does not occur. However, in the event that a power failure does occur, strategies exist to minimise the damage to systems.

The strategies and costs will be benchmarked against the current global annual costs of corrosion, which amounts to $2.5 trillion per year (about 3-4% of GDP) as mentioned earlier [3]. Beyond controlling corrosion using chemicals, coatings and cathodic protection, other ways to control it can also be considered. Facilities can be 'mothballed' - or, kept in storage - while the power is out. For mitigation measures requiring energy and moving of equipment, more preparation beforehand would be required, since systems (such as normally disconnected PV systems) need to be set up before the power outage. Some of them may still be implementable in the 24 hours after a disaster, provided that UPS systems or other backup systems can keep services running for a short while after the disaster. Finally, some passive strategies can be employed at any time during the disaster.

In the case of pre-set up normally disconnected PV systems, the control systems should be shielded such that they are more likely to survive some of the scenarios detailed in Table 2. Furthermore, these systems should ideally remain unplugged from the grid so that they are not affected by any shorts or electrical surges in the main grid.

Some of these mitigating measures can be used concurrently to create even more effective corrosion protection solutions.

4.4.1. Design considerations

The best and lowest-cost way to prevent corrosion is through designing equipment in a sensible manner. One of the most important ways to improve the design by using better materials, such as replacing carbon steel with stainless steel. Stainless steel has higher pitting corrosion resistance than carbon steel, and does not undergo significant uniform corrosion. Thus, it can extend the life of equipment created with it.

Beyond designing for normal operating conditions, some more thought can be put into designing for scenarios where maintenance would be difficult if not impossible. Design features can also be added for those scenarios, for example, adding a way to manually operate vessels, or hand pumps in case pipes need to be drained without electricity and power. Line blinds are also recommended to make mothballing easier. Beyond that, the components in industry can also be designed to have thicker walls for more corrosion allowance [3]. With thicker steel walls, a carbon steel vessel is able to be in operation for longer periods of time.

From the literature review, the rate of corrosion can be slowed down by about 35.7% if the material is changed from carbon steel to stainless steel [101]. In Table 4 below a bridge is used as an example. The costs of using stainless steel instead of carbon steel and the costs of simply thickening the carbon steel structures to achieve the same lifetime as stainless steel was compared with status quo. The total lifetime of the equipment is estimated to be at 75 years, which is typical for bridges [102]. Stainless steel is also 3.29 times the price of steel [103]. If C represents the initial materials cost required to build a certain structure, then the materials cost spread out yearly for carbon steel and stainless steel is 0.0133C and 0.0439C respectively.

According to the literature, the initial upfront cost of 3.29 C for stainless steel will be offset by the maintenance cost of carbon steel in about 65 years [103]. Therefore,

$$65M_{CS} = 2.29C + 65M_{SS}$$

Where M_{CS} and M_{SS} is the maintenance cost of carbon steel and stainless steel per year respectively. Thus,

$$M_{CS} = 0.035C + M_{SS}$$

As for the relationship between M_{CS} and M_{SS}, assuming that the corrosion rate is correlated to the maintenance cost:

$$M_{SS} = (1 - 0.357)M_{CS}$$

Thus,

$$0.357\, M_{CS} = 0.035C$$
$$M_{CS} = 0.0980C$$
$$M_{SS} = 0.0630C$$

Table 4: Cost of different ways to avoid corrosion at the design considerations stage.

Across: Solution type (material used) **Down: Costs, per year**	**Status quo (S355 steel)**	**Replace with stainless steel (EN1.4162)**	**Thicken carbon steel walls (S355)**
Materials cost	0.0133C	0.0439C	0.0181C
Maintenance cost	0.0980C	0.0630C	0.0980C
Total cost per year	0.111C	0.1069C	0.116C

Given the parameters stated above, the replacement of carbon steel with stainless steel was the most economical due to reduced maintenance costs, followed by status quo and then thickening carbon steel walls. As such, an overall estimated savings of US$10 billion per year can be achieved from reducing the maintenance cost of structures. If structures were replaced with thicker carbon steel walls, the cost would roughly be about US$108 billion.

The reduced maintenance required by replacing carbon steel with stainless steel can make it more suitable in a power outage. Maintenance - such as repainting coatings - may not be possible in a power outage, and can thus reduce the effectiveness of thickness increases of carbon steel walls in extending the lifespan of equipment and structures. However, the supply of stainless steel is about 2.7% that of carbon steel [104], [105], making replacement impractical except for the most crucial industries.

4.4.2. Environment control

Controlling the humidity and the pollutants present in environments is one of the best ways to slow down corrosion.

There are a few ways this can be done. The first way is to physically move important machinery (where possible) into desert climates with proper covering of vulnerable parts (as done with planes for up to 2 years) [106]. Deserts have a very low humidity ranging between 17-55% and temperatures ranging between 10-40°C (taking the case of Sabha, a city in Libya [107]), making them ideal for storing machinery. A second way to do this would be to seal smaller rooms within buildings or other structures and fill them with appropriate amounts of desiccants. These desiccants, once used up, can be reused by sunning the material outside every few months, or by briefly heating them up to evaporate the water absorbed. Instead of using rooms, refrigerators that are unused can be re-utilised to store fragile and small equipment, since they already come with insulation and door seals by design. One last solution is to implement a PV system (or some other renewable energy system) to power an air-drying system along with temperature control. This solution has been tested for a small, normal office-type room (~20 m^2) [108]; better insulation can make the system more efficient.

The cost of environment control per metre cube (m^3) was calculated, and the total cost per method to preserve all of industry was also calculated. For the latter, a large hypothetical container that is able to encompass all of industry was the model for the volume needed. The total built up area in the world is about 1.5 million km^2, and it was assumed about half of the area is used for industry. The value is around 7.5×10^{11} m^2. Since critical infrastructure makes up about 41% of the value of industry, it was assumed that 41% of the land for industrial use is used by the critical infrastructure sectors. A total height of 3 metres was also assumed, bringing the total volume needing environment control to be 9.23×10^{11} m^3. For the desiccant and dehumidifier methods, the scenario used for the cost assumes that a relative humidity (RH) of 75% is reduced to 20% at 25 °C or 298 Kelvin (K). For the air conditioning scenario, the cost to change the temperature by 10 K was calculated. Some of the capacity of equipment - such as foam insulation, air conditioning and the dehumidifier - are reported in m^2, and volume information is difficult to find; as such, for air conditioning and dehumidification, it is assumed that the space to be dehumidified has a ceiling height of 3 metres. For foam insulation, the cost to insulate a 3m x 6m x 3m container was used to calculate cost per m^3. The results are summarised in table X below and how the numbers were obtained are further elaborated on in tables 5, 6, 7, 8 and 9.

Table 5: A comparison of the costs of environment control across multiple different methods.

Method	**Transportation to the desert**	**Desiccants (simple packs with no special equipment involved)**	**Foam Insulation**	**Air conditioning**	**Dehumidifier (using machine and with solar-powered electricity)**
Cost per m^3	$0.0231	$0.0109	$0.802	$55.56	$0.24
Cost for CI (multiply by 9.23×10^{11} m^3)	$21.3 billion	$10.1 billion	$739 billion	$51.3 trillion	$21.3 billion

The costs estimated here in Table 5 are a combination of material and operating costs. It should be noted that for transportation to the desert, operating costs make up a bulk of the costs involved, unlike the other methods. As such, it will become one of the most expensive methods long-term, unless the monthly cost of parking equipment in the desert decreases due to recessions caused by the global catastrophe. The breakdown of the calculation is shown in Table 6. For transportation to the desert, existing examples of such arrangements for old aircraft were studied and costs were estimated from those figures.

Table 6: The breakdown of how the cost for transportation to the desert is calculated.

Calculations for transportation to the desert	**Value**
Cost in USD to place a Boeing 727 in the Mojave desert (monthly, 2002) [109]	250
Monthly cost in USD, adjusted for inflation from 2012 to 2021 [65]	368
Coverage area (m^3), as estimated by the volume taken up by a cuboid with the dimensions of a Boeing 727. Boeing 727s were previously stored in the Mojave desert. [109], [110]	15924
Cost per m^3, in US$	0.0231

In Table 7, the calculations for desiccant use is shown. Since desiccants are normally specified according to the mass of water they can remove from the atmosphere, this value was first calculated before it was converted to cubic metres. For desiccants, the ability of it to absorb moisture would depend on the chemical composition. In this case silica gel was used for the modelling since it was the least expensive desiccant found on the market.

Table 7: The breakdown of how the cost for using desiccants is calculated.

Calculations for desiccant use	**Value**
Average cost in USD for 1 tonne of silica gel desiccant [111]	185
Amount of water absorbed (as % of weight at 25 °C)	35 (in 75% RH), 11 (in 11.3% RH)
Assuming a roughly linear relationship [112], average drop in percentage points of amount of water absorbed with reduction in %RH	0.377
Average amount of water absorbed from 75%RH to 20%RH, as % of weight at 25 °C	24.2
Moisture holding capacity per kg of air at 25 °C (kg) [113]	0.02
Amount of water to remove per kg of air to reduce humidity from 75%RH to 20%RH at 25 °C (kg) [113]	0.011
Weight of air in one cubic metre (kg)	1.29
Amount of water to remove per m^3 (kg)	0.0143
Desiccant needed per m^3 (kg)	0.0591
Cost per m^3, in USD	0.0109

In Table 8 the calculation for foam insulation is shown. Spray-on foam sealant was the least expensive option found among a few different kinds of similar insulators. In this case, the sealant is assumed to be used for all insulation purposes covering the entire surface, instead of simply filling in cracks or window gaps in typical applications. Insulation needs to be used in conjunction with a cooling or drying source, and can reduce infiltration of moist air from outside the controlled environment.

Table 8: The breakdown of how the cost for foam insulation is calculated.

Calculations for foam insulation	**Value**
Cost in US$ per bottle of spray-on foam sealant [114]	1.01
Coverage area per bottle of sealant (70 metres long, with assumption that sealant is 0.03 metres tall) [114]	2.1
Cost per m^2, in US$	0.481
Cost per m^3, in US$, assuming the sealant insulates a container with dimensions 3m x 6m x 3m	0.802

In Table 9 the calculation for air conditioning is shown. It is assumed that a 10 °C difference between the outside and the controlled inside environment is able to reduce the humidity in the controlled environment sufficiently.

Table 9: The breakdown of cost calculations for air conditioning is shown here.

Calculations for air conditioning	**Value**
Average cost in US$ per cooler [115]	3000
Coverage volume assuming a container size of 3m x 6m x 3m, in m^3	54
Material cost per m^3, in US$	55.56
Power of cooler, in W [115]	7000
Heat capacity of air at atmospheric pressure and 25 °C, kJ/kgK	1.006
Time required to cool down 1 m^3 of air by 10 °C, given mass of air to be 1.29 kg per m^3 and power to be 7 kW, in seconds	1.85
Operation cost per m^3, assuming electricity prices of $0.20 per kWh, in US$	0.000719
Cost per m^3, in US$	55.56

In Table 10, the breakdown of costs for a dehumidifier is shown. One main assumption is that the ceiling height of the space covered by the dehumidifier is 3 metres. The cost may change under different assumptions.

Table 10: The breakdown of cost calculations for dehumidifiers powered by machines and solar power is shown here.

Calculations for dehumidifiers	**Value**
Average cost in US$ per dehumidifier [116]	275
Rate of water removed, in litres per day [116]	268
Power of dehumidifier, in W [116]	5200
m^2 covered [116]	399
Assuming the m^2 covered is a room with a ceiling height of 3m, cost of dehumidifier per m^3, in US$	0.23
Operation cost of dehumidifier, given 0.0143 kg of water to be removed per m^3 and electricity price of US$0.20 per kWh	0.0013
Total cost per m^3, in US$	0.23

4.4.3. Cathodic/anodic protection with PV

In the event of a power outage, renewable sources of energy will still be in operation if they are disconnected from the grid in the case of EMP. In such a scenario, cathodic protection systems should be modified to draw energy from photovoltaic systems so that they are not reliant on the grid.

Thus, the cost of the protection system includes the cost of setting up a PV (photovoltaic) system along with battery storage capabilities. Initial cost estimates range from US$600 million to US$680 billion annually, which is still about 3 orders of magnitude smaller than the cost of corrosion currently.

Table 11 below shows the calculation of this cost, with lower-bound values on one end and the upper-bound value on the other. The cost includes the price of a PV system together with battery storage.

Table 11: Basis of calculation for costs of cathodically protecting all metal in industry in 2020. Values are rounded off to 3 significant figures.

Variable	Value			Units	Source
	low	median	high		
Current needed to protect 1m x 1m carbon steel	0.05	0.1	10	mA/m^2	[117]
Voltage supplied by PV system		12		V	[118]
Power to protect 1 m^2 of steel, using P = IV	0.0006	0.0012	0.12	watt	
Crude steel production per year		1808		million tonnes	[119]
Assume 50% of steel goes into industry (using CO_2 emissions as proxy for resources)		904		million tonnes	[120]
Steel density (median)		7900		kg/m^3	[121]
Volume of steel in industry ($V = \frac{m}{\rho}$)		114		million m^3	
Total surface area to be protected[10]		34.3		billion m^2	[122]
Total energy needed per second (total surface area x power)	20.6	41.2	4120	million watts	
Total energy needed annually for protection	6.50×10^{14}	1.30×10^{14}	1.30×10^{17}	Joules	
Conversion into kWh	1.81×10^{8}	3.61×10^{8}	3.61×10^{10}	kWh	
Cost per kWh	0.081	0.2	0.45	USD	[123]
Total cost per year to protect new machinery created from steel	14.6	72.2	16300	million USD	
Machinery lifetime	50	50	50	years	[124]
Discount factor[11]	0.833	0.833	0.833		[125]
Total cost per year to protect all equipment globally	**0.609**	**3.01**	**677**	**billion USD**	

[10] This assumes that half of all the volume of steel in industry is in one long single rod of 20mm diameter. The other half is assumed to be in one large single square plate of 5mm thickness. Numbers are from the source in this row.

[11] Steel production was generally lower in the past (1500 million tonnes, ~83% of current 2020 levels). As such, fewer new pieces of equipment were created in the past. The discount factor multiplies the result obtained by 0.83 to account for that change across the years.

Another way to calculate costs would be to take the total value of the 5 industries shortlisted against global GDP to estimate steel use. This turns out to be about 41.0% of global GDP (36 trillion of 87.75 trillion [50]), which results in about 0.499 billion USD for the lower-bound estimate.

However, one of the drawbacks of this system is that it will not work as smoothly if the cause of the power outage will also cause the sun to be blocked. A larger PV system will need to be set up for the same protection, which would increase the costs of the protection. If used in conjunction with other passive solutions that existed before the power outage such as paint coatings that can provide some protection in the first ten years [3], the cost of the system may be reduced. In conclusion, cathodic protection is a promising solution, if budget allows and PV systems were set up before the power failure.

It is worth noting that the galvanic anode method is also a viable solution, however it will not last as long as impressed current systems.

4.4.4. Removal of corrosive components

In some sectors, corrosive chemicals that were necessary when in operation can be removed to reduce corrosion. For example, jet fuel can be replaced by preservative oil in airplane engines [106], or the corrosive chemicals in the energy and chemical sector can be drained into titanium storage vats instead of letting them remain in the original steel vessels and pipes. Titanium will reduce corrosion rates by about 125 times [3], with only a 7.8-fold increase in price [126], [127]. However, given that the production of titanium is about 3.93×10^{-5} times of carbon steel [119], [128], it is unlikely that most industrial chemicals can be stored in this manner. Simply draining the pipes and allowing the chemicals to be stored in the original vessels would cause lowered corrosion in the pipes - localised corrosion will be eliminated, and corrosion can be reduced by at least 40% [129]. This would also be a low- or even no-cost way of preventing corrosion, creating savings of around US$206 billion for the energy and chemical sectors due to the amount of corrosion averted. However, this method would mostly be applicable to the energy, chemical and transportation systems industries only. This is because many corrosive chemicals such as sulfur-related compounds are used in the energy and chemical industries.

As for transportation systems, fuel can be removed from vehicles so that it can be repurposed for other uses in an emergency. Other industries do not come into as much contact with such corrosive components.

4.4.5. Inhibitors

In the event that corrosive chemicals cannot be removed, inhibitors can be added into those components. These inhibitors prevent corrosion by protecting the metal, forming films on the metal, or by reacting with the offending ions in the solution. This solution is also mainly tailored to the Energy and Chemicals sector. Adding more inhibitors to fuel in the Transportation Systems sector may cause the fuel to be unusable in the future when the inhibitors react with the fuel. Additionally, vehicles may also still be used during a power outage and will become a valuable source of power. Thus, there will be no need to add inhibitors.

Generally, inhibitors as a whole are able to reduce the corrosion rate to about 0.1mm/year, which is about 8% of original corrosion rates of 1.25mm/year [3], [130]. Table 12 breaks down the cost.

Table 12: The breakdown of cost calculations for corrosion inhibitors.

Breakdown of cost of inhibitors	**Value**
Amount of inhibitor to add as wt% [131]	0.186
Average cost of inhibitor in USD per kg [132]	50
Global production capacity of petroleum and chemicals, in tonnes [133]–[135]	6.27 billion
Inhibitor needed, in tonnes	11.7 million
Cost of inhibitor, in USD	583 billion

The two more common ways to apply the inhibitors are continuous injection or squeeze treatment. Continuous injection - where inhibitors are constantly added - can be the most economical. However, continuous monitoring is needed and manpower may not be available to operate the pumps. On the other hand, inhibitor management may also create jobs during the disaster, if unemployment rates become an issue. The alternative is batch treatment, where all the inhibitor is first added and then slowly released on its own due to existing chemical processes in the equipment. However, higher upfront costs are needed, since all the chemicals are added at once.

4.4.6. Coatings and Packaging

Metal plating is often applied to prevent corrosion of the underlying steel. A coating of zinc (80-100 μm) can last about 10-22 years. [3] Re-applying these coatings past their lifespan may prove to be difficult, since electroplating is commonly used and that may not be available during the power outage.

Another way that industry can be protected is using paint. Protective paint is usually expected to last at least 20 years, with a full repaint in 37 years. [136] Between 20-37 years, spot painting is expected to repair the coat and maintain its performance.

Packaging is another way to physically protect the items in question. For example, engine parts can be stored in specially-designed gusset bags filled with volatile corrosion inhibitors to provide protection against moisture. [3]

For Table 13 below, the total surface area to protect is assumed to be about 34.3 billion m^2, as calculated from section 4.4.3. on cathodic/anodic protection.

Table 13: Cost estimations of different coatings and packaging available to prevent corrosion.

Method	**Price per unit**	**Unit description**	**Surface area covered per unit, in m^2**	**Total cost (USD)**	**Source**
Packaging	3	1 roll of 27 m2	27.1	3.80E+09	[137]
Asphalt coating	1	per kg Density: 2.243 tonnes/m^3 Coating thickness: 87.5 microns	5.10	6.73E+09	[138], [139]
Paint	35.55	per barrel of 20kg, which covers 7.5 m2 per kg	150	8.13E+09	[140]
Electroplating zinc	2.08	per kg (adjusted from 2007 prices to 2021 prices). Density: 7.1 tonnes/m^3 Coating thickness: 90 microns	1.56	4.56E+10	[141]

For electroplating zinc and asphalt coating, the volume per kilogram is found. Subsequently, that value is divided by the required thickness of the coating to find the surface area covered per kilogram of material.

4.4.7. Corrosion impact mitigation

In cases where it may be too costly to prevent corrosion, the impacts of corrosion could be mitigated instead. For example, if a dam were to collapse due to structural degradation, it may be better if measures were taken to prevent damage downstream, or to keep spillways open in the event of a flood, instead of reducing the corrosion caused to the dam.

It was found that impact mitigation would cost at least four times more than proper storage, which typically includes inhibitors, coatings and packaging, and some form of environment control [142]. As such, the cost of this strategy would likely be much higher than the costs of the solutions detailed above. As such, more in-depth calculations were not done for this strategy.

4.4.8. Summary

A summary of the costs for each type of mitigation method is listed below in Table 14. For methods with separate cost calculations for sub-methods, the average was taken to obtain an overall comparison.

Table 14: Comparison between different mitigation methods.

Method	**Average cost (USD)**
Design considerations	$54 billion
Environment control	$10,418 billion
Cathodic/anodic protection	$227 billion
Removal of corrosive components	-$206 billion (savings possible)
Inhibitors	$583 billion
Coatings and packaging	$16.1 billion
Corrosion impact mitigation	$44,070 billion (four times the total of inhibitors, coatings and packaging, and environment control)

4.4.9. Comparing the different strategies

A brief estimate of the resources required for each kind of prevention method is listed in Table 15 below. “Catastrophe” refers to any scenario that caused the power outage. “Preparation time required” refers to how early the method needs to be planned for before the power outage. “Maintenance required” shows the amount of effort required to keep the method working during the power outage. “Time to implement” refers to the time needed to get the method up and running if it were to be implemented after the catastrophe. A ‘-’ in this field refers to methods that cannot be applied once the outage occurs. “Restoration past catastrophe” refers to how long it will take industry to be restored after the catastrophe if the method were applied during the catastrophe.after applying the methods during the catastrophe. “Cost” refers to the estimated supplies needed to implement the solutions.

While it is best to prepare beforehand how corrosion will be mitigated, some of the solutions can be implemented even without much preparation time. The measures also vary in the amount of time and resources required.

Design considerations require the most preparation time, since large structures such as the Three Gorges Dam take up to 16 years to build [143], and even the process of designing a new car takes about 6 years [144].

Table 15: Comparison between resources required for each kind of corrosion method.

Method	**Preparation time required before catastrophe (years)**	**Maintenance required during catastrophe (once every X years)**	**Time to implement during catastrophe (years)**	**Cost**
Design considerations	6-16	0	-	Medium
Environment control	2	0.5	4	High
Cathodic protection with PV	1	10	5	High
Removal of corrosive components	0.083	0	1	Low
Inhibitors	0.083	0	2	High
Coatings and packaging	0.5	10	2	Medium
Corrosion impact mitigation	3	0	5	High

4.5. Suitability of strategies for each sector

For the information technology sector, design and environment control may be the best way to mitigate corrosion, since most equipment is indoors. In the special case of batteries, they should be kept at their various recommended charging states to ensure they last as long as possible, even during use. In storage, they should be kept in dry conditions separate from one another and not in closed circuits.

For the energy and chemical sector, a variety of options exist. Plant operators should take stock of their existing options and consider which ones to reinforce in the event of an outage, and what steps can be taken then.

For the transportation systems sector, some of the infrastructure (roads, railways) cannot be moved indoors or protected, while some can be moved (buses, planes, rolling stock (trains), ships). Additionally, removing corrosive oil or fuel from oil tanks would mostly refer to the engines of the buses, planes, trains and ships.

For dams, it is suggested that spillways be kept open such that any floods that may occur during the power outage can be dissipated easily. Mechanisms should be put in place such that the gates are still operable if there was no electricity supply from the grid. In this case, design considerations become important, and because of the sheer size of the infrastructure, many of the other methods become impractical.

Table 16 below summarises the mitigation measures and how much of each industry they can protect. The estimated amount of industry that can potentially be protected by each method is listed below as ‘full’, ‘none’, or ‘partial’, for full protection, no protection or partial protection respectively. As can be seen, there are more options for the Energy and Chemical sector, and fewer options for the other sectors. This may be because the Energy and Chemical sector has harsher environments during operation, which require more protection. However, this will change during a power outage.

Table 16: Industries compared against suitable mitigation methods.

Sector	**Design considerat-ions**	**Environ-ment control**	**Cathodic protectio n with PV**	**Removal of corrosive components**	**Inhibitors**	**Coatings and packaging**	**Corrosion impact mitigation**
Information Technology	Full	Partial	None	None	Partial	Partial	Full
Energy and Chemical	Full	Partial	Partial	Partial	Partial	Partial	Full
Transportatio n Systems	Full	Partial	Partial	Partial	Partial	Partial	Full
Dams	Full	None	None	None	Partial	None	Full

5. Future Work

This report focused largely on preventing corrosion of steel. However, more work can be done to look at preventing corrosion in electronics, semiconductors and degradation in polymers. Crucially, semiconductors are important to the information technology and communications sectors, on which the lifeline functions depend.

Much of the calculations in this report were simply predictions based on existing data and hypotheses generated from them. These suggestions and recommendations have yet to be tested in the real world; the logical next step would be to create realistic setups in accelerated weathering systems to refine these suggestions. Actual PV backup systems can also be built to test out the cathodic protection system and its effectiveness.

Beyond that, we can also look into different adaptation and mitigation strategies for different countries, since each country will have different environmental factors that will affect the rate of corrosion drastically. The availability of renewable resources will also affect which solutions are viable, such as the setting up of a PV-based cathodic protection system. Further, ancient structures and materials with good corrosion resistance and lasting ability - such as Roman concrete, which can last more than 2000 years [145] - can also be studied to find applications to modern structures. Additionally, this type of analysis can be performed on all Critical Infrastructure sectors, instead of only the shortlisted ones, and thus backup plans can be created for more industries than the ones explored here.

Finally, how best industry can be restored can also be explored. Once electricity and the power grid has resumed, industry will also resume. Starting up systems again can create unforeseen problems, since they will likely behave differently from new systems and may need special procedures before use resumes.

6. Conclusion

In this report, the possibility of a long-term power outage along with corrosion risks from such an outage were explored. The costs to prevent such corrosion was also outlined. Removal of corrosive components, coatings and packaging, and design considerations were the cheapest ways to reduce corrosion risks.

Moving forward, the industries highlighted and governments can be more aware of the risks they face in long-term power outages. They can also initiate more conversations about how best to prepare for such scenarios to improve recovery times and reduce losses. This report illustrates possible ways to do so.

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