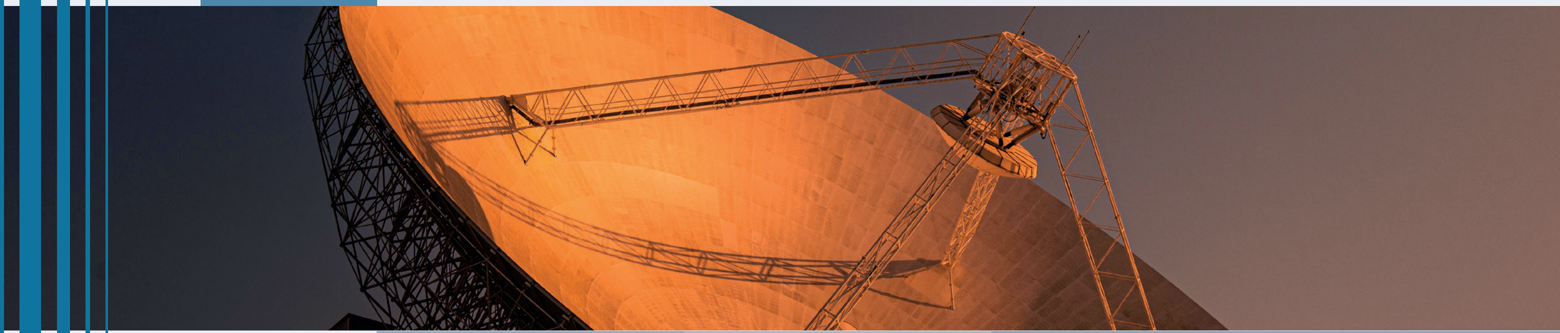

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An EDHEC Climate Institute Publication

Reducing Infrastructure Climate Risk Through Technology Measures: Data Infrastructure (IC50)

EDHEC Climate Institute
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Executive Summary

This report is part of a series of research papers that explore the broad strategies that infrastructure asset owners can take to reduce the transition and physical risks associated with climate change, with each paper covering a specific sub-sector of infrastructure.

This paper presents a literature review and assessment of key strategies to decarbonise data infrastructure assets and to increase their resilience to physical climate risks.

This information is designed to help organisations and investors evaluate, at a broad level, strategies that may safeguard their portfolios from future climate-related losses. While it is not a substitute for asset-specific analysis, it provides essential insights to support risk management and more informed decision-making.

Transition Risk

Transition risks represent the potential devaluation of assets as regulatory pressures to decarbonise increase. Without proactive decarbonisation, assets could lose up to 30% of their value in plausible scenarios (Blanc-Brude et al., 2023), prompting a need for clear, cost-effective strategies. Decarbonisation strategies represent tangible ways that asset owners or investors can reduce their exposure to transition risk (e.g. if assets emit less carbon, asset owners will have a reduced tax burden), however it does not fully insulate asset owners from the macroeconomic effects of a carbon tax (Blanc-Brude et al., 2023).

The global data sector currently accounts for approximately 1.5-4% of total global GHG emissions, however strong sectoral growth is expected to increase this proportion over the coming decades, thereby increasing the urgency with which decarbonisation efforts are pursued. The main emissions sources from data assets are from Scope 2 electricity demand and Scope 3 emissions from product manufacture and use, both upstream and downstream of the asset itself. Tackling these two major sources of emissions is vital if data asset owners are to substantially reduce their transition risk.

The largest difference in emissions profiles for data companies is determined by whether the company sells goods such as consumer electronics as this significantly increases their Scope 3 emissions. If a company does sell goods then Scope 3 emissions can be as high as 75% of total emissions, however if they do not then Scope 2 emissions are approximately 75% of the total. Tackling these two emissions sources will therefore have the greatest impact on reducing overall emissions.

The most effective strategies to decarbonise data assets are virtualising products and services, the use of renewable energy (either purchased or generated on-site), and reductions from efficiency and optimisation. Whilst none of these strategies individually has greater than a low effectiveness, between them they cover a large proportion of total emissions across all emission scopes. Additionally, given the high energy demands from cooling data centres, switching to natural cooling methods is also a very material strategy for those assets. Scope 3 emission reduction strategies often require liaising closely with other entities outside of the direct control of the company and therefore they are dependent on factors that a company can influence but not decide definitively making them more complex to implement than those to reduce Scope 1 and 2 emissions. The main barriers to data infrastructure sector decarbonisation are a local grid limitations on new additional renewable energy generation, the high CAPEX costs of installing on-site energy storage technology to enable reliable deployment of renewables, and high upstream and downstream supply chain emissions that companies have limited control over.

Physical Risk

Physical risk quantifies the potential value loss for transport assets due to physical damage and disruption caused by extreme weather events because of climate change. In a "hot house" scenario, this can rise to 54% of asset value lost and therefore requires mitigation. The majority of strategies analysed as part of this paper can achieve significant physical damage reductions for much lower costs than this to asset owners, and therefore represent good value for money.

This paper identifies the major strategies for increasing the resilience of data infrastructure assets to the primary risks arising from the effects of climate change, namely floods, wind, heat and wildfires. These risks all have the potential to curtail operations, damage assets rendering them temporarily or permanently inoperable, and in the worst cases, completely destroy them. As the severity of climate-related events increases, these risks are only likely to get more material for infrastructure assets and therefore asset owners need to consider strategies to proactively protect their assets.

Flood Risk

Flooding represents an ongoing risk to data infrastructure assets, although the strategies to protect them are well known and widely implemented to good effect.

Flood resilience is best achieved with a layered approach that utilises different strategies that complement each other, creating a system that is greater than the sum of its parts. The strategies here are presented individually and their effectiveness assessed in isolation, however in reality multiple strategies are likely to be combined at any particular site to provide this layered defence.

This layered approach combines hard engineered solutions with lower impact interventions. Hard engineered solutions such as flood barriers, elevated infrastructure, and sea walls are highly effective but high-cost measures, with effectiveness ranging from high to very high for a given design flood. To manage costs it is possible to protect critical areas of assets at this higher level, for example raising critical equipment onto higher floors of data centres as opposed to attempting to elevate the entire building.

This can then be combined with the lower impact, lower cost strategies such as blue-green infrastructure or pumps to provide a lower level of protection (medium damage reduction) but over a larger area. In the case of blue-green infrastructure there are also myriad additional benefits that increase the overall resilience of the site, with well-managed vegetation being able to also provide protection against the other physical risks assessed in this paper.

Wind Risk

Wind risk is equally relevant to data transmission and data storage companies, with extreme wind capable of damaging transmission towers or data centres, particularly if these assets are situated in exposed locations. Data infrastructure assets can be protected against wind damage in two main ways: making the structure more resilient to the effects of extreme wind, or blocking or disrupting the wind flow before it reaches the asset. Similarly to flood resilience strategies, layering these defences is most effective.

Structural improvements such as retrofitting existing structures or building new structures with wind-resistant design features can enhance wind protection. This may include reinforcing roof-wall connections, installing impact-resistant windows and doors, and anchoring equipment or structures to withstand strong winds. This can reduce damage by a medium amount.

Wind breaks are used to disrupt, stop or divert wind flow around and away from assets. By redirecting the wind around an asset the forces that cause damage are lessened. If data assets can be located within areas naturally protected by the terrain then they should be; however this can be enhanced by modifying the landscape to create terrain features that block wind, reducing damage by a medium amount. Structural wind breaks can be added to assets for a medium improvement. However, using vegetation to screen assets is a cost-effective method of increasing wind resilience with high damage reductions.

Heat Risk

Extreme heat represents the most material climate-related physical risk for data infrastructure with losses caused by cooling system overloading, cable sagging and tower foundation destabilisation. These losses are predicted to worsen with time as climate-related extreme heat events increase.

Whilst both data transmission and data storage companies are both highly affected by extreme heat, the strategies to mitigate this can differ widely in effectiveness between the two given the different ways in which extreme heat affects their operations.

Using natural and evaporative cooling systems can reduce damage to data storage assets by a high amount whereas it only reduces damage to transmission assets by a low amount. Heat-resistant construction materials also range from medium damage reduction for data storage assets but high for data transmission assets. Mechanical cooling systems have a more uniform high effectiveness between the asset classes.

Heat reflective coatings are a cheap method of reducing heat build up for a medium damage reduction, however they are more suitable for data transmission assets. Data storage assets can use process and layout optimisation to reduce heat gain by a low amount and both asset classes can use shading to reduce damage in particular locations.

One additional benefit for heat reduction strategies in general, but particularly for strategies such as switching to natural and evaporative cooling and optimising operational practices, is that they reduce the cooling demand on the asset. This in turn reduces both costs and emissions (and therefore transition risk) as less electricity is needed to power it.

Wildfire Risk

For data infrastructure assets in fire-prone areas, wildfires represent a significant threat. Strategies to protect assets focus on two main methods, preventing fires from starting or spreading, and protecting the asset itself if and when they do occur.

Stopping or slowing the spread of wildfires can be achieved through a number of different strategies that work in tandem to provide gaps between fire paths and assets, reduce the likelihood of ignition and remove fuel from areas prone to wildfires.

Strategies such as defensible space management and firebreaks add gaps that fires cannot spread across and can reduce damage by a medium to high amount. Fire retardants slow fires spreading with an effectiveness of medium to high. Removing fuel is often done as part of regular asset maintenance with strategies such as fuel reduction zones, prescribed burns, and vegetation management and landscaping all being effective (medium to high damage reduction).

Protecting data infrastructure assets can be achieved by using either fire suppression systems such as sprinklers, or by structurally hardening the asset itself and can reduce damage by a medium to high amount.

The total lifetime costs associated with both the decarbonisation and climate resiliency strategies are often a fraction of the total asset value and can provide significant improvements over the existing asset. This therefore represents good value for money to investors looking to reduce the transition and physical climate risks within their portfolios. Whilst this is not always the case, and there are outliers within the data, the general trend is that data infrastructure decarbonisation and physical climate risk reduction can be achieved for reasonable costs by targeted strategic investment.

Paper Structure

This paper is structured as follows:

- A brief introduction explaining the context and objectives of the study.
- A methodology section detailing the scope, assumptions, limitations, and processes used throughout the study.
- The results of the literature review are then presented, highlighting critical pathways for reducing the transition and climate-related physical risks of assets.
- A discussion of the risks and constraints to some of the strategies outlined in this study, as well as wider factors and influences.

1. Introduction

1.1 Objectives and Audience

This paper identifies the key strategies or actions that data infrastructure assets can take to decarbonise and build climate resilience. We give a high-level overview of influential approaches to achieve these aims that encompass a wide range of infrastructure assets. Our "top-down" approach focuses on the general properties of assets in major infrastructure sectors and explores which decarbonisation and climate resilience strategies may be effective in multiple sectors.

We aim to find the most material strategies for both decarbonisation and physical resilience and gauge their effectivity.

Our literature review identifies the most material strategies, and their associated key technologies, across Scope 1, 2 and 3 emissions and four climate-related physical risks - floods, extreme wind, extreme heat, and wildfires - and assess their effectiveness at reducing emissions or damage respectively. These four have been chosen as they have proven to be the most common climate-related physical risks over the 20year period from 2000-2019 (United Nations Office for Disaster Risk Reduction, 2020). We show how these strategies are relevant to the data infrastructure class, how they might differ between different types of data assets, and how they can best be employed by asset owners, filling a critical knowledge gap in the industry.

This paper forms part of a series of analytical studies by the EDHEC Climate Institute (ECI) into the measures that can be taken to mitigate the risks that climate change imposes in infrastructure investments. It is intended to help asset owners, prospective investors and risk managers assess at a high level which strategies might enable them to protect investments into infrastructure assets against climate-related losses in the future.

1.2 Classifying Data Infrastructure

Infrastructure types in this study are classified according to The Infrastructure Companies Classification Standard, or TICCS. TICCS is a class-based taxonomy developed by the EDHEC Infrastructure & Private Assets Research Institute (EIPA) that organises infrastructure asset-owning companies by business risk (a company's contractual and regulatory environment), industry type (what type of activity the infrastructure serves), geoeconomic influences and corporate structure.

TICCS differentiates all infrastructure types into eight industrial "superclasses":

- IC10 Non-renewable power generation.
- IC20 Environmental services (e.g., water treatment).
- IC30 Social infrastructure (e.g., health, education, defence, etc).
- IC40 Energy and water infrastructure (e.g., pipeline networks, fuels, etc).
- IC50 Data infrastructure (e.g., communications and datacentres).
- IC60 Transport (e.g. roads, rail, ports, aviation).
- IC70 Renewable power generation.
- IC80 Networked utilities (e.g., gas and power grids, sewage systems).

TICCS also contains subclassifications – for example, renewable power generation is divided by its fundamental primary energy source (wind, solar photovoltaic, geothermal, etc.) and transport by infrastructure modal type (rail, road, airports, etc.).

Within the TICCS classification system, data companies (IC50) are defined as "companies involved in the provision of telecommunication and data infrastructure" (Blanc-Brude and Whittaker, 2022). This is further broken down into the two classes and five subclasses shown in Table 1.

Table 1: IC50 Data Infrastructure TICCS Industrial Classification

Industrial Superclass	Industrial Class	Industrial Asset Subclass
IC50 Data Infrastructure	IC5010 Data Transmission	IC501010 Cell Towers
		IC501020 Long-Distance Cables
		IC501030 Communication Satellites
		IC501040 Radio and Media Towers
	IC5020 Data Storage	IC502010 Data Centres

1.3 Context

1.3.1 The Importance of Infrastructure Decarbonisation

As the infrastructure sector is a significant contributor to the global budget of GHG emissions, any transition to a low-carbon economy is inconceivable without decarbonising the operation of infrastructure assets. Thus, infrastructure decarbonisation is a fundamental cornerstone of meeting global legislative and financial GHG commitments.

These measures imply that infrastructure assets which cannot limit their GHG emissions to legislatively required levels may face penalties. This could result in limitations being placed, or fines levied, upon the operation of non-compliant assets, and may give rise to more emissions trading schemes such as the European Union's. It may also result in devaluation of infrastructure assets, due to perceived risks of curtailment or cessation of their operations, their lack of competitiveness or their premature decommissioning. In an extreme case, it could lead to an asset's operation becoming "stranded": devaluing the asset's value or profitability, possibly leading to it becoming commercially unfeasible, potentially leading to the organisation going out of business or forcing a sale of the asset at a dramatically reduced price. A study of the infrastructure asset-owning companies monitored by EIPA, which together hold assets valued at USD1.56 trillion, noted that up to USD10 billion worth of these assets are at risk of devaluation due to failure to meet the EU Taxonomy's sustainability criteria. Furthermore it is unclear whether a further USD245 billion worth of assets fall within these sustainability criteria (Manocha et al., 2024).

The risks of infrastructure failing to decarbonise thus include financial losses to investors from asset devaluation and stranding. They could also lead to a reduction in the economic and physical wellbeing of society through reduced service provision from the assets and in the potential of cost increases in services from constrained supply. These risks to current infrastructure assets can be mitigated by taking actions, such as the deployment of new technologies and the application of new operating practices, which upgrade and adapt the assets in a manner that reduces their GHG emissions.

1.3.2 The Importance of Infrastructure Climate Resiliency

The ability to decarbonise is not the only climate-related impact that presents risks to the value of infrastructure assets and their operation. Regardless of whether the climate objectives of the Paris agreement are met, climate change is already having an impact on physical assets. This can be seen in the growing frequency of extreme weather events, including heatwaves, unusually low temperatures, and extreme wind and precipitation events (Arias et al., 2021). All these can have a physical impact on infrastructure assets, leading to damage that can curtail or prevent their operation and which may entail significant repair costs to restore. In the most extreme case, they may cause asset destruction and loss.

An analysis of a large representative sample of the investible infrastructure assets that EIPA monitors, in its infraMetrics platform of financial and climate performance indices, suggests that 54% of combined assets' value is at risk from the impact of extreme weather events related to climate change, if remedial action to counter this risk and adapt to these impacts is not taken (Blanc-Brude et al., 2023).

The societal consequences of suddenly losing the services of critical infrastructure in an extreme weather event are all too apparent following the likes of a hurricane or major flood, and include the risks to life, health, and wellbeing from failure in electricity, water, and communications provision. These are compounded by their knock-on effects on social infrastructure providing healthcare, education, and shelter, as well as the co-ordination of government and administrative services involved in response and recovery actions.

The financial consequences of a lack of resilience to climate related extreme weather include the increased statistical risk of damage to infrastructure, which can lead to increased insurance premiums, and increased cost of capital as interest rates rise (Fantini et al., 2023). This increased risk may also disincentivise investment in these assets, decreasing valuations as investors become wary of the increased likelihood of damage to, or loss of, assets.

1.3.3 Relevance to Data Infrastructure

The global data sector currently accounts for approximately 1.5-4% of current global GHG emissions even whilst a third of the global population lack connection to the internet (The World Bank, 2024). Whilst these numbers represent the current best guess of experts monitoring these emissions they are considered a conservative estimate due to the lack of regulated reporting requirements across the sector. Critically this means that the emissions from global telecommunications infrastructure are not covered by national climate action plans.

One of the most striking patterns regarding the global data infrastructure sector is its rapid growth. For example data centre energy consumption in Ireland has grown from 5% of national consumption to nearly 20% in seven years, with projected consumption levels of 30% by 2030. Globally GHG emissions from colocation data centres and electricity consumption rose by 20% and 22% respectively in just two years, 2020-2022 (The World Bank, 2024). Whilst this growth may eventually level out as the market reaches saturation, in the short- to medium-term the growth forecasts predict a growing carbon footprint for the sector.

The number of internet users increased by 17% in the three years up to 2023, and connected data centres increased by 72% between 2018 and 2022 (The World Bank, 2024). Even though exact GHG emissions from the sector are cloaked in a degree of uncertainty, this rapid growth highlights an increasing imperative to tackle these emissions. It is worth noting that the growth in emissions is in spite of the sector accounting for 60% of all renewable power purchases in 2021 (The World Bank, 2024).

Despite these values being global figures, the geographic spread of these emissions are not evenly distributed across the globe, with 69% of all data infrastructure Scope 1 and 2 emissions being emitted in the Asia Pacific region, with 16% in EMEA countries and the remaining 15% in the Americas, with the three largest network operators in China accounting for nearly half of global data infrastructure emissions (The World Bank, 2024).

The widespread impacts from data networks ceasing to operate, or operating significantly sub-optimally as a result of physical damage, would have greater knock-on effects to the wider economy beyond simply the loss of revenue for the asset owner. It is significant that the risk to loss of network function is not dependent solely on the asset being physically damaged for extended periods of time but also on the asset being no longer financially viable and therefore being potentially shut down prematurely. As infrastructure provides critical public services and provides the physical services for almost all other economic activity, a failure to adequately transition infrastructure to support a green economy puts future economic stability at risk.

Similarly, the data sector is exposed to a higher risk of disruption and physical damage from increasingly frequent and intense weather events in the future than it is currently (UK Climate Risk, 2021). The specific risks differ by asset type and geographical location. However if climate change is allowed to continue on current trends, and measures are not taken to protect infrastructure assets, they could lose more than 50% of their value due to physical damage (Blanc-Brude et al., 2023).

Physical climate risks to infrastructure assets vary widely between geographical locations and asset types, much more so than transition risk. In this paper we make generalisations about these risks to aid cross-comparison. Whilst there are many different types of physical risks that infrastructure assets will be exposed to due to climate change, most physical risks to infrastructure assets from the resulting increase in extreme weather events are attributable to floods, storms, and extreme temperatures, including wildfires (Blanc-Brude et al., 2023). These risks are difficult for most infrastructure assets to avoid due to their fixed locations, which prevent relocation being used as a mitigation strategy. Therefore, asset owners should be cognisant of the steps they can take to reduce the risks of physical damage.

Data infrastructure has both point and linear assets that must be protected for networks to function as intended. Point assets in this context refer to assets in one fixed location such as data centres, cell towers, or radio towers, whereas linear assets such as long-distance cables go from one location to another.

2. Methodology

2.1 Identifying Strategies and Key Technologies

This paper assesses the effectiveness of strategies and key technologies that we have assessed to be the most material to the IC50 Data Infrastructure superclass for both decarbonisation and physical risk reduction.

In this context a strategy is considered material if it satisfies the following criteria:

- It contributes to significant emissions or physical damage reductions for that asset superclass.
- It applies to a significant number of assets, asset classes or asset subclasses within that superclass.
- The technologies are at a basic level of technical viability and could feasibly be employed by asset owners in the short to medium term. This does not necessarily imply current commercial availability or existing examples of functioning systems.
- It is considered a key strategy to reduce transition or physical risk by the industry or literature.

We describe here a joint methodology for all the TICCS® superclass papers. For both transition and physical risk, we have followed a general methodology to ensure consistency across superclasses, classes, and subclasses.

Within this paper, both transition and physical risk reduction pathways are examined at two levels of granularity:

- **Strategies** – a high-level set of actions that deliver the same set of outcomes for one or more TICCS® superclasses. These may be applicable to assets in individual or multiple classes and subclasses to achieve some degree of either decarbonisation or improved physical risk resilience. Strategies have the same outcome, but may depend on multiple, differing methods of delivery both between superclasses and within them. For example, different approaches to creating barriers to floods apply to different superclasses depending on how large and distributed their sites are. These may include many different engineering solutions and products (e.g., walls, earthworks, etc.), but they all achieve the same strategic outcome.
- **Key Technologies** – specific technologies and engineering solutions that asset owners can apply to assets to implement a strategy. These are the levels of decision-making that a design engineer would take. For example, flood walls will vary by architecture and materials which involve different technological solutions (e.g., concrete or masonry), but all deliver an effective flood wall.

These strategies and technologies have been collated via a literature review (see Results of Literature Review) and expert opinion based on the criteria above.

Using this framework of strategies and key technologies we have used the following methodology to quantify the effectiveness of decarbonisation and physical risk reduction for different TICCS® classes within the IC50 Data Infrastructure superclass.

2.2 Assessing Decarbonisation Potential and Damage Reduction

For both decarbonisation potential and damage reduction the following steps have been taken:

1. For each superclass, we have identified from literature the most material strategies to decarbonise or protect assets.
2. For each strategy, we have identified key technologies used within the sector to enable it, and identified if those technologies are differentiated by class or subclass.
3. From this, we have quantified the decarbonisation or resilience potential for relevant examples from literature and case studies.
4. In the case of decarbonisation specifically, to arrive at the decarbonisation potential, the following steps are followed

a) Quantifying technology effectiveness: For each decarbonisation strategy, we first quantify its effectiveness, which indicates the potential reduction in emissions when the technology is applied effectively to a specific facility type and relevant activity. For instance, switching to renewable energy has a 100% effectiveness because it completely offsets the emissions for that activity. This data is derived from a comprehensive review of academic studies, industry reports, and case studies. Effectiveness is typically expressed as a percentage improvement over a "no action" scenario, often presented as a range to account for variability in the technology's application.

b) Determination of Emission Profiles: The emission profile is drawn from a review of literature for the superclass being studied in this paper. The emission profile reflects the relative contributions of different emission sources. Given the diversity of assets within a category, there is some uncertainty in this estimation, though it relies on expert judgment to ensure accuracy. Scope 3 emissions, which include upstream and downstream activities like supply chain impacts and product end-of-life emissions, are often influenced by external factors beyond direct operational control, making them more variable and complex to assess. This limitation highlights a specific area for further research in the future.

c) Determination of the Share of Emissions each Decarbonisation Strategy Impacts: We then map each decarbonisation strategy to its relevant emission category within the emission profile. This step identifies the specific share of total emissions (Scopes 1, 2 and 3) that each strategy could potentially impact. For example, energy consumption might account for 30–40% of a facility's total emissions, meaning strategies aimed at reducing energy use would address this proportion. This mapping helps determine the scope of each strategy's influence on overall emissions.

d) Calculation of Strategy Decarbonisation Potential: The decarbonisation potential of each strategy is calculated by multiplying its reduction effectiveness by the proportion of emissions it impacts. For example, if a strategy has an effectiveness of 50% and targets an emission category that represents 30% of total emissions, its overall decarbonisation potential would be 15% of the facility's total emissions.

e) For Scope 1 and 2 strategies, this detailed approach allows for precise calculations based on technology effectiveness and emission share. However, for Scope 3 emissions, which encompass upstream and downstream activities outside the facility's direct control, we rely on literature and industry reports to understand the decarbonisation potential. This reliance is due to the complexity and variability in Scope 3 sources, which makes the same quantitative approach less feasible. Instead, data from previous studies and industry best practices guide the assessment of Scope 3 reduction potentials.

5. The values for strategy effectiveness, decarbonisation potential, and damage reduction have then been mapped to the qualitative categories below, to provide easy cross-comparison. Continuing the example above, the strategy effectiveness of 50% is considered Medium, however the decarbonisation potential of 15% is Low given the share of emissions that the strategy applies to:

a) Very High ≥95%
b) High 65-94%
c) Medium 35-64%
d) Low 5-34%
e) Very Low <5%

6. For the damage reductions for physical risks a qualitative assessment has been undertaken that defines what scale of hazard the strategy is effective up to.

a) Floods
  i. Very High > 1:1000 year event
  ii. High 1:100 < x ≤ 1:1000 year event
  iii. Medium 1:100 year event
  iv. Low < 1:100 year event

b) Wind
   i. Very High > 1:1000 year event
   ii. High 1:100 < x ≤ 1:1000 year event
   iii. Medium 1:100 year event
   iv. Low < 1:100 year event
c) Heat
   i. Very High ≥ 50 degrees centigrade
   ii. High 40 ≤ x < 50 degrees centigrade
   iii. Medium 35 ≤ x < 40 degrees centigrade
   iv. Low < 35 degrees centigrade
d) Wildfire
   i. Very High NA
   ii. High NA
   iii. Medium NA
   iv. Low NA

2.3 Accounting for Uncertainty

The uncertainty classification is determined by evaluating the level of confidence we can place in a data point, based on the following criteria:

- **Volume of supporting examples**: Data backed by a larger number of comparable, real-world examples is considered to have higher quality. Conversely, data derived from only one or two instances is rated as lower quality due to higher uncertainty.
- **Deployment track record**: Confidence in data increases when it is linked to strategies, technologies, or events that have been widely implemented or observed. Repeated deployment across infrastructure assets enhances reliability.
- **Maturity of source information**: Data that originates from well-established, commercially and technologically mature sources is rated higher. Data depending on novel, emerging, or experimental sources is treated with more caution due to its inherently higher uncertainty.

This classification framework allows us to systematically evaluate the reliability of data across use cases—from asset-level inputs and scenario modelling to strategy benchmarking—ensuring that outputs reflect varying levels of evidential robustness.

2.4 Assumptions

Given the uncertainty inherent in a case-study based literature review, we have made the following assumptions throughout the analysis:

- This study covers assets in all IC50 subclasses, including those without entries in the infraMetrics asset universe.
- We consider existing asset retrofit only (therefore exclude new build assets).
- Effectiveness values are presented as proportional percentage increases or decreases against a "no action" scenario.
- Risks are treated in isolation and the reductions are considered for individual risks only. For example, typhoons often cause both wind damage and flooding, however they are considered separately here to ensure consistency between asset classes.

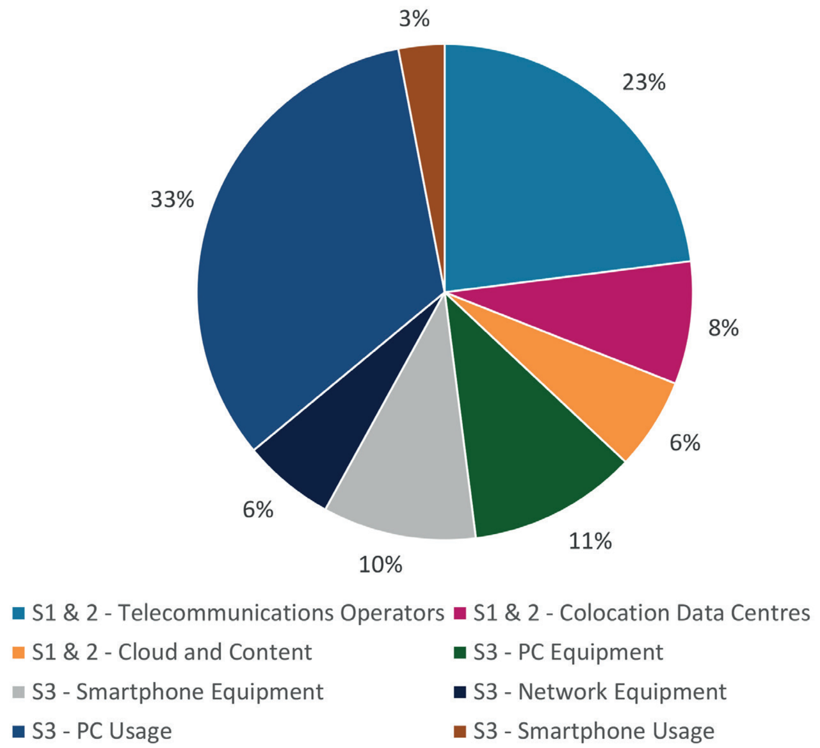
- Case study quantities are representative.
- Where strategies are dependent on actions in other superclasses, we have assumed these actions take place (e.g. transport electrification assumes that grid decarbonisation occurs).
- Wider costs or benefits are excluded – economic effects (such as carbon taxes), environmental pollution impacts and benefits, etc.

3. Results of Literature Review - Transition Risk

3.1 Decarbonisation Challenges

GHG emissions from the telecommunications sector account for a small percentage of global emissions currently, 1.7%, with nearly 2/3 of this coming from Scope 3 emissions (The World Bank, 2024). The full breakdown is shown in Figure 1.

Figure 1: Global Data Infrastructure CO2 Emissions Breakdown



Source: The World Bank (2024).

The global growth rate of emissions from data infrastructure is dominated by two opposing factors and how they interact with each other. Firstly, there is the growth in the construction and usage of data infrastructure, with the number of internet users doubling and internet traffic increasing by a factor of 25 since 2010 (International Energy Agency, 2024). This growth has largely been offset by energy efficiency measures, renewable energy usage and decarbonising electricity grids in regions with heavy data infrastructure usage such as Europe and the Americas, so that data sector emissions only rose by 5% in the years 2015-2020 (Malmodin et al., 2024).

The major source of data infrastructure emissions for companies that do not sell consumer electronics is the electricity use of the assets. With this one category of emissions accounting for approximately 75% of all Scope 1, 2 and 3 emissions for a telecommunications company, tackling this will have the greatest effect on overall emissions (Radonjic and Tompa, 2018).

For data companies that also sell electronic goods (servers, computers, smartphones etc.) these form the vast majority of their Scope 3 emissions, both in their manufacture and subsequent use by customers. Whilst Scope 1 and 2 emissions account for approximately 1/3 of all telecommunications sector emissions, the manufacture of devices accounts for just over another 1/4 and their usage a further 1/3 (The World Bank, 2024). These electronic goods are often manufactured with complex supply chains often involving several interlinked layers of vendors and outsourcing in geographically diverse locations across the globe. This makes tracking and reducing these emissions complicated, however the largest companies in this sector often account for the majority of the emissions due to their large market share and therefore their reported emissions can be used for making sector-wide estimations. For example the top six PC vendors are responsible for over 85% of all PC related manufacturing emissions (The World Bank, 2024).

For data companies that do not sell electronic goods the overwhelming majority of emissions are sourced from the purchase of electricity from the grid as shown in Table 2.

Table 2: Emission Profile of Representative Data Transmission Infrastructure Company

Category	Description	Contribution to Total Emissions (%)
Diesel, petrol and HVO fuels	Emissions burning diesel in on-site power generators and plant equipment.	2.2%
Transport (fleet)	Emissions from company vehicles.	0.4%
Refrigerant gases	Refrigerant leakage from mechanical and electrical plant.	0.3%
Natural gas and other fuels	Emissions from gas boilers.	0.1%
Electricity consumption (location-based)	Emissions from purchased electricity used to power the asset.	22.9%
Purchased goods and services	Transportation, extraction and production of purchased goods and services.	16.1%
Capital goods	Transportation, extraction and production of purchased capital goods.	7.4%
Fuel and energy-related activities	Transportation, extraction and production of purchased fuel and energy.	6.6%
Transportation and distribution (upstream and downstream)	Transportation and distribution of any products or services purchased or sold.	1.1%
Waste generation	Emissions from the disposal and treatment of waste generated.	0.1%
Business travel	Emissions from employee, company and publicly owned vehicles used for business trips. Includes planes and ships.	0.2%
Employee commuting	Emissions from employee, company and publicly owned vehicles used for commuting.	0.7%
Upstream leased assets	Emissions from the operation of leased assets.	4.2%
Processing of sold products	Intermediate products requiring processing.	0.0%
Use of sold products	Use of sold products by downstream customers.	9.1%
End-of-life treatment of sold products	Disposal and necessary treatment of sold goods and services.	0.0%
Downstream leased assets	Operation of assets owned by the asset owner.	0.1%
Franchises	Franchise operations.	1.1%
Joint ventures and associates	Investment operations.	27.8%

Source: Vodafone (2024).

3.2 Decarbonisation Strategies

We have identified 13 material strategies for decarbonising data infrastructure emissions:

1. Increasing energy efficiency of operations.
2. Leakage reduction.
3. Low-carbon fuels for power generation.
4. Low-carbon transport infrastructure (electrification).
5. Natural cooling.
6. On-site energy storage technology.
7. Optimise operational practices.
8. Renewable energy generation (off-site purchase agreements).
9. Renewable energy generation (on-site generation).
10. Decommission legacy systems.
11. Virtualisation.
12. Downstream recycling.
13. Sustainable procurement.

There is some crossover with strategies across the two different asset classes within the IC50 Data Infrastructure superclass, however given the unique requirements of data centres and their nature as buildings as opposed to predominantly towers means that more strategies are available for them to decarbonise. There is also significant crossover between emissions scopes as data companies often rent capacity to other vendors and share physical infrastructure, therefore emissions reduction strategies that are applicable to the company itself (Scopes 1 and 2 emissions) can often be extended to parts of their supply chain (Scope 3 emissions).

3.2.1 Increasing Energy Efficiency of Operations

One of the general approaches that telecommunications sector companies can use to reduce their transition risk is to improve the energy efficiency of their operations. This is a very broad approach and can be implemented by a wide range of technological and logistical solutions with differing impacts across the three emissions scopes.

Scope 1 Decarbonisation

For data transmission companies upgrading equipment to more efficient versions reduces the fossil fuel load on generators, particularly in remote locations with less reliance on connections to the local power grid. In this context, energy efficiency measures can reduce Scope 1 emissions by a low amount (Juraeva et al., 2020). Data storage companies such as data centres can reduce their Scope 1 emissions by a medium amount by upgrading to newer, more efficient servers (Song et al., 2015).

It is worth noting that this saving in Scope 1 emissions only applies where fossil fuel-powered generators are used to avoid double counting emissions reductions for purchased electricity, which fall under Scope 2 (see below).

Scope 2 Decarbonisation

For both data transmission and data storage companies the efficiency gains and associated emissions reductions are proportionally the same for Scope 2 as Scope 1 (low and medium respectively), however the total amount of emissions reduced is likely to be much larger for Scope 2 as purchased electricity accounts for the vast majority of operational run time, whereas back up generators are used during power failures and maintenance.

The total emissions reductions available to each company will be dependent on the relative carbon intensity of the local electricity grid.

Scope 3 Decarbonisation

The Scope 3 effects of energy efficiency measures are largely dependent on the specific business models of data infrastructure companies and whether they lease out their assets to third parties, as is common practice for both data transmission and data storage companies. Decreasing energy use by increasing the efficiency of equipment such as cell towers or servers in data centres reduced the emissions for downstream customers. The reductions are the same as for Scopes 1 and 2 with a low reduction for data transmission companies and a medium reduction for data storage companies.

3.2.2 Leakage reduction

The coolants used to regulate temperatures in data infrastructure have differing global warming potentials (GWP) but most of them have a significantly higher GWP than carbon dioxide and as such even small amounts of coolant gas leaked into the atmosphere has a disproportionately large effect on the global climate.

Scope 1 Decarbonisation

Two interlinked strategies exist to deal with this. Firstly, reducing leakage in coolant systems can reduce leaks by a high amount (Bostock, 2008) and secondly, replacing refrigerants with lower GWP alternatives can reduce emissions by between a medium (Yana Motta, 2023) and high amount (ACHR News, 2024) depending on the refrigerant used for data centres and by a low amount for transmission assets (Beshr et al., 2017). The values for low GWP refrigerants used here represent options that are currently commercially available and it is likely that in the near future refrigerants will come to market with even greater emissions reduction potential. This has a greater impact on Scope 1 emissions for data storage companies as cooling loads make up larger proportion of emissions the for transmission networks.

3.2.3 Low-carbon fuels for power generation

Replacing diesel or petrol used on-site with lower carbon alternatives is a simple way to reduce emissions in generators and other equipment that uses fossil fuels. Whilst this strategy is intended to be applicable to non-vehicle related emissions it is also valid for that as the current fuel mixes used are similar between the two end uses. However it has been excluded as a specific strategy here as the vast majority of vehicle fleets can be electrified instead, which has a much better emissions reduction potential for vehicles.

Scope 1 Decarbonisation

For a representative blend of 20% biodiesel and 80% diesel mix that is currently used as a lower-carbon fuel the reduction in emissions compared to 100% diesel is low (Ogunkunle and Ahmed, 2020). This strategy is relevant for both data transmission and data storage companies.

3.2.4 Low-Carbon Transport Infrastructure - Electrification

For companies in the Data Infrastructure sector, switching to electric vehicle fleets for company vehicles and providing any required charging infrastructure to support them is a simple and widely available method of reducing Scope 1 emissions. Whilst vehicle fleet emissions do not account for the majority of Scope 1 emissions for telecommunications companies they are easy to reduce using widely commercially available electric vehicles, with most companies in Europe and the Americas currently partway through, or about to start the process of converting their fleets at the time of writing. One of the major barriers with electric vehicles is the availability of adequate charging infrastructure and therefore companies should both purchase or rent the vehicles themselves but also install vehicle charging points at their premises to improve the usage of these vehicles. Other charging technologies are available such as inductive charging, which works by wirelessly charging vehicles via electromagnetic fields and have the potential to allow on-the-go charging if integrated into road construction, however the likelihood of this technology being widely available in the short- to medium-term is low.

It should be noted that the majority of electric vehicle types currently available on the market are for motorbikes, cars and light goods vehicles. Whilst electric vehicle prototypes are being developed for heavy goods vehicles they are not widely available currently so in these instances companies can explore using low-carbon fuels instead as these are more developed technologically, or adjust their logistics to require only light goods vehicles where possible.

Scope 1 Decarbonisation

Electric vehicles produce no emissions when they run and therefore can potentially reduce the Scope 1 impact by a very high amount, however in practice this benefit is tempered by the relative decarbonisation of local electricity grids. One of the common misconceptions about electric vehicles is that the embodied carbon emissions from the battery production are higher than for internal combustion engine equivalents and therefore the environmental benefits are overstated. Whilst this argument partially holds true it grossly misrepresents a more rounded picture of the lifetime emissions of comparative vehicles. On average the carbon payback period of a new battery electric vehicle is two years when compared to buying a new internal combustion engine car, or four years when compared against continuing to drive an existing petrol or diesel car, both less than the average 12 year car lifespan (Hausfather, 2019).

3.2.5 Natural Cooling

Another method to reduce emissions associated with both refrigerant leakage and the electricity required to power mechanical cooling is to replace it entirely with natural methods of cooling such as ventilation and evaporative cooling.

Scope 1 Decarbonisation

For Scope 1 emissions reduction this takes the form of replacing refrigerant emissions and reducing energy demands on fossil fuelled back up generators for a medium reduction (Jahangir et al., 2021).

Scope 2 Decarbonisation

Natural cooling measures reduce the electrical demand from data centres in particular and lower overall Scope 2 emissions by a medium amount (Jahangir et al., 2021). This is one reason why significant numbers of data centres are being constructed in locations such as Iceland, to take advantage of the naturally low ambient temperatures to reduce cooling loads.

Scope 3 Decarbonisation

Similarly, electrical energy use by data centre tenants can be reduced by natural cooling by the same medium amount (Jahangir et al., 2021).

3.2.6 On-site Energy Storage Technology

The premise behind using on-site energy storage to reduce GHG emissions is that it replaces any fossil fuel use from backup generators, or allows reliance on locally produced renewable energy that is stored when supply exceeds demand as opposed to being sold to the grid and is used when necessary.

Scope 1 Decarbonisation

Scope 1 emissions are reduced by replacing fossil fuel powered backup generation with stored renewable energy with an effectiveness range of between medium and high (Yin et al., 2019).

3.2.7 Optimise Operational Practices

Operational optimisation covers a range of measures that can be employed by the operators of data infrastructure to reduce emissions across all three scopes.

Scope 1 Decarbonisation

The reduction of Scope 1 emissions is predominantly down to reducing fuel use by generators used mainly as back-up power. Using different data transmission practices and integrating systems across the transmission network can reduce energy use by a low amount (Kuthadi et al., 2022). Data storage assets can reduce energy use by a low amount by optimising layouts and increasing the temperatures at which data centres operate (Kaur et al., 2019).

Scope 2 Decarbonisation

The emissions reductions for Scope 2 will be the same as for Scope 1 for both data transmission and data storage companies (see above) but will have a larger overall impact on emissions reductions given the greater proportion of Scope 2 emissions as a percentage of overall emissions.

Scope 3 Decarbonisation

For data storage companies the emission reductions for Scope 3 are the same as for Scopes 1 and 2, namely a low amount (Kaur et al., 2019), however there is a much larger range of reductions available to network operators and data transmission companies, between a medium and high amount (Antonopoulos et al., 2015). This is due to the ability to increase network interoperability between third party customers and the sharing of equipment between providers, thereby reducing the physical hardware requirements of tenants and customers.

3.2.8 Renewable Energy Generation - Off-site Purchase Agreement

One common strategy for reducing the emissions of a data infrastructure asset is to purchase renewable energy from an external third party, often in the form of Renewable Energy Certificates (REC). These are certificates issued to electricity producers that demonstrate the company has produced an equivalent amount of electricity from low carbon sources. Data infrastructure companies can then purchase electricity from these generators and theoretically their emissions from purchased electricity will be zero.

Scope 2 Decarbonisation

This strategy is very material for reducing Scope 2 emissions and given the maximum possible reduction of very high (ESA Solar, 2023). In practice this is somewhat more complex as the low carbon electricity is mixed in with electricity generated from fossil fuels in the electricity grid and there is no way to tell exactly what the generation mix is when the power is delivered to an asset. However, as more renewable energy comes into the system the average grid carbon intensity will reduce and the purchase of RECs increases investment in renewable energy generation.

3.2.9 Renewable Energy Generation - On-site Generation

In contrast to off-site renewable energy generation, generating renewable energy on-site is an easy and cost-effective way for data infrastructure companies to reduce their emissions. As the low carbon electricity is generated on-site the companies can be sure that their emissions have actually reduced their emissions. This can be achieved using a variety of technologies but solar panels, wind turbines and small hydroelectric plants are common. In reality, renewable energy has associated lifecycle carbon emissions from the manufacture, supply, decommissioning and non-CO2 environmental impacts of its use that result in it producing low, but positive, carbon emissions. These vary from around 8g/kWh CO2e to 50g/kWh CO2e (NREL, NREL), however to avoid double counting with Scope 3 emissions, this has been ignored in this analysis.

Scope 1 Decarbonisation

Using renewable energy that has been generated on-site to displace fuel usage from generators will reduce those Scope 1 emissions by a very high amount (ESA Solar, 2023).

Scope 2 Decarbonisation

Producing renewable electricity on-site reduces Scope 2 emissions by a very high amount (ESA Solar, 2023).

3.2.10 Decommission Legacy Systems

Many data transmission companies still operate old 2G and 3G networks that have very low usage and are largely superseded by the newer 4G and 5G networks but still consume significant amounts of electricity to run.

Scope 2 Decarbonisation

By decommissioning these legacy systems, data transmission companies can reduce their electricity demand by a medium amount (Langham, 2022).

3.2.11 Virtualisation

Virtualisation describes the process of both concentrating processes in a smaller number of locations to benefit from economies of scale of physical hardware, or making processes entirely virtual as a way to further reduce the number of physical devices required.

Scope 2 Decarbonisation

For Scope 2 emissions reductions this largely refers to transferring physical data centres in multiple locations into cloud-based solutions that reduce the quantity of hardware required and enjoy energy efficiencies gained from the larger, more concentrated centralised locations. This can reduce electricity demand by a low amount (Ma et al., 2023).

Scope 3 Decarbonisation

Emissions reductions for downstream customers in the supply chains of data transmission companies come largely in the form of digitalising products and services so that fewer physical devices have to be made and sold. Given the range of consumer electronic devices and the range of services offered by telecommunication companies, the effectiveness of virtualisation can range anywhere between a low and high amount (Seidel et al., 2021).

Centralising data centres can reduce the emissions of data storage companies by a low amount as for Scope 2, as those benefits also apply to any downstream vendors who rent capacity from the company (Ma et al., 2023).

3.2.12 Downstream Recycling

Given the large quantities of IT equipment required in both data transmission networks and their supply chains, and their relatively short lifespan compared to the lifespan of the network as a whole, recycling as much IT equipment as possible can have a large impact on Scope 3 emissions.

This is also relevant for data storage companies, especially given the short useful lifespan of servers, although the different make up of server equipment over consumer electronics means that there is a smaller benefit in terms of emissions reductions.

Scope 3 Decarbonisation

Consumer electronics and outdated transmission equipment are both widely recyclable goods with high material recovery rates that can reduce the embodied emissions of new IT equipment by a high amount (Ngoma, 2017). The material recovery rates for server equipment used in data centres is generally lower than for consumer electronics and therefore the potential emissions reduction benefits are also lower at a medium reduction (Menikpura et al., 2014).

3.2.13 Sustainable Procurement

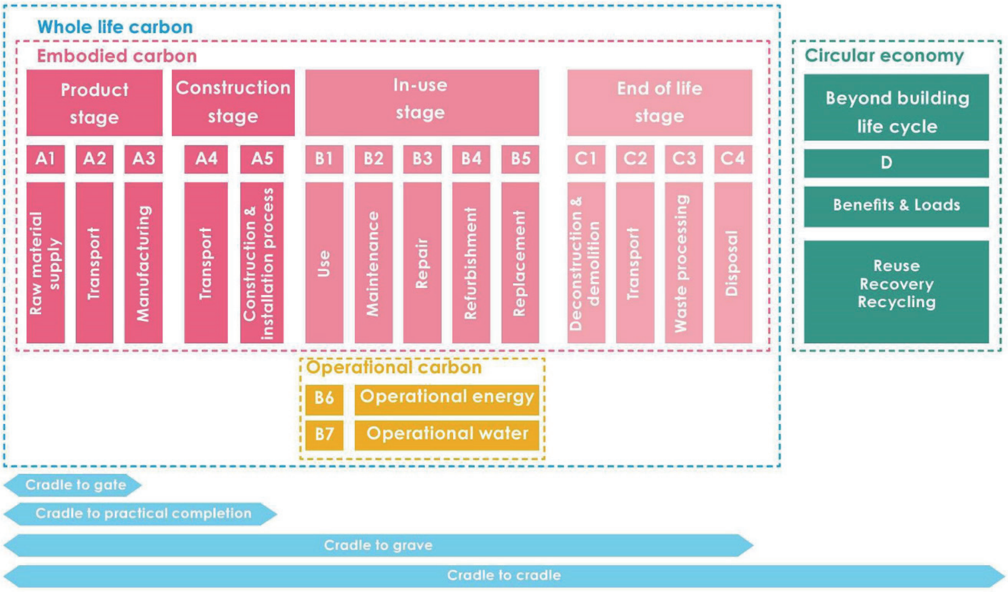
Whilst several strategies above deal with decarbonising the downstream supply chain, it is equally important for data infrastructure companies to look at strategies that reduce the emissions of their upstream supply chain. This strategy can significantly contribute to reducing the embodied carbon of assets and products made or constructed by data infrastructure companies (see Figure 2 for a definition of embodied carbon).

Scope 3 Decarbonisation

As this strategy covers a significant number of different options for individual assets the effectiveness value of low (The World Bank, 2023) is deliberately broad-based.

Example measures for reducing the GHG emissions from procurement include sourcing materials, equipment services from suppliers with lower carbon footprints, prioritising products with recycled content, and selecting local suppliers to reduce transportation emissions.

Figure 2: Lifecycle Carbon Boundaries in the Built Environment



Source: London Energy Transformation Initiative (2020).

3.3 Summary

The data infrastructure sector accounts for a small percentage of global emissions, roughly 2-4%, however the sector is undergoing rapid growth and with approximately a third of the global population currently lacking internet access there is significant scope for further growth in the future. Given that large impacts can be made on the emissions on this sector using widely commercially available technology such as on-site renewables for moderate costs, asset owners should make attempts to reduce these emissions as low hanging fruit. More complex supply chain engagement should then follow to reduce Scope 3 emissions.

The data infrastructure sector's decarbonisation potential has a wide range between different strategies and subclasses, ranging from very low, for reducing refrigerant leakage, to low for virtualising products and services, installing renewable energy on-site or purchasing renewable energy from external sources. These show that a multi-pronged approach must be taken by data asset owners across predominantly Scopes 2 and 3 to achieve meaningful emissions reductions.

The main obstacles to data infrastructure sector decarbonisation are insufficient grid capacity restricting the availability of renewable energy for assets to either purchase externally or connect their own renewable generation into, the high costs of energy storage technology that enables the use of renewable energy and the large proportion of total emissions that come from the upstream and downstream supply chains that data infrastructure companies have limited influence over.

A summary of the strategies and key enabling technologies is provided in Tables 3.

Table 3: Decarbonisation Potential of Scope 1, 2 and 3 Emission Reduction Strategies

Strategy	Impacted Emission Category	Scope	Key Technologies	Applicable Subclasses	Technology Decarbonisation Effectiveness (Range)	Strategy Decarbonisation Potential (Scope 1 and 2)	Strategy Decarbonisation Potential (Scope 1, 2 and 3)
Increasing Energy Efficiency of Operations	Diesel, petrol and HVO fuels, electricity consumption, upstream and downstream leased assets.	1, 2, 3	Monitoring integrated systems.	All.	Low-Medium	Low	Low
Leakage Reduction	Refrigerant gases.	1	Leakage detection and monitoring systems, replacement mechanical equipment.	All.	Low-High	Very Low	Very Low
Low Carbon Fuels for Power Generation	Diesel, petrol and HVO fuels.	1	Blends of biofuels.	All.	Low	Very Low	Very Low
Low-Carbon Transport Infrastructure - Electrification	Transport (fleet).	1	Charging infrastructure, electric cars and light goods vehicles.	All.	Very High	Very Low	Very Low
Natural Cooling	Refrigerant gases, electricity consumption, downstream leased assets.	1, 2, 3	Ventilation, evaporative cooling, planting to enhance evapotranspiration.	Data centres.	Medium	Medium	Low
On-Site Energy Storage Technology	Diesel, petrol and HVO fuels.	1	Chemical, thermal or gravitational energy storage systems.	All.	Medium-High	Very Low-Low	Very Low
Optimise Operational Practices	Diesel, petrol and HVO fuels, electricity consumption, upstream and downstream leased assets.	1, 2, 3	AI-driven workload management, smart energy management systems.	All.	Low-High	Low-High	Low
Renewable Energy Generation - Off-Site Purchase Agreement	Electricity consumption.	2	Power purchase agreements, renewable energy certificates.	All.	Very High	High	Low
Renewable Energy Generation - On-Site Generation	Diesel, petrol and HVO fuels, electricity consumption.	1, 2	Solar panels, wind turbines, small scale hydropower.	All.	Very High	Very High	Low
Decommission Legacy Systems	n Electricity consumption.	2	Automated network migration tools, AI-driven power management systems.	Cell towers, long distance cables, communication satellites, radio and media towers.	Medium	Medium	Low
Virtualisation	Electricity consumption, use of sold products.	2, 3	Websites and apps, cloud-based data centres.	All.	Low-High	Low-High	Very Low-Low
Downstream Recycling	Capital goods, end-of-life treatment of sold products.	3	Recycling facilities, streamlined waste disposal and collection systems.	All.	Medium-High	NA	Very Low-Low
Sustainable Procurement	Purchased goods and services, capital goods, fuel and energy-related activities, transportation and distribution.	3	Supply chain tracking, AI-driven procurement analytics, integrated enterprise resource planning (ERP) systems.	All.	Low	NA	Low

Note: Classification for Uncertainty - Red =High, Amber = Medium, Green = Low.

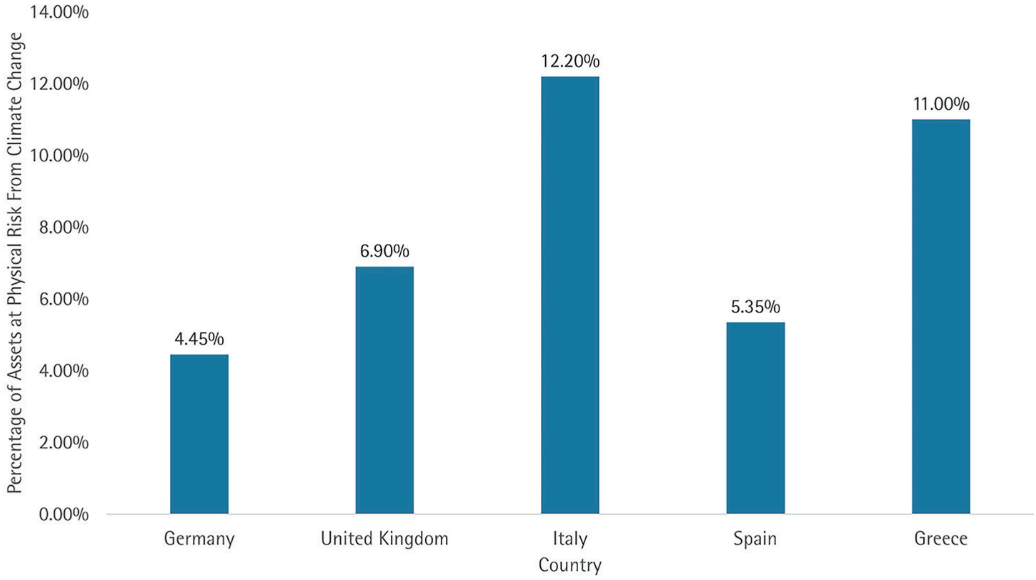
4. Results of Literature Review - Physical Risk

4.1 Improving Climate Resilience of Assets

Data infrastructure provides a backbone for modern services that other infrastructure types are dependent on and therefore the consequences of outages have cascading societal effects beyond simply the value loss to asset owners. Whilst data infrastructure itself is currently at less risk from the physical effects of climate change than other infrastructure types, this is predicted to change in the near future as extreme weather events become more frequent and of greater magnitude (UK Climate Risk, 2021). The average impact on the net asset value of data infrastructure assets within the Current Policies NGFS Scenario is a loss of 3.7% (Blanc-Brude et al., 2023), with losses rising as climate scenarios worsen.

Physical risks from climate change are highly geographically dependent (see Figure 3), with small differences in location accounting for an outsized variation in risk (for example flood risk at the top and bottom of a hill). Some physical risks also have secondary effects that cause damage after the initial weather event has passed, such as flood-driven landslides. For data infrastructure the most material risks are from high temperatures (including wildfires), flooding and storms (Blair Chalmers, 2020).

Figure 3: Percentage of Vodafone Assets at Physical Risk from Climate Change



Source: Vodafone (2023).

Damage to data infrastructure assets from weather events can come in different forms ranging on a scale from degrading performance, to temporary loss of function through to partial or total asset destruction. Some resilience is built into these assets already on the basis of design codes and standards and at a network level there is usually some capacity to absorb lower levels of disruption without noticeable impacts to users. These standards and design codes provide a level of protection against weather-related physical damage, however this is only effective up to a certain severity level. This is usually expressed as the probability of an event to occur in a given year, called a return period: a 1 in 100-year return period is an event which as a probability of 1% to occur in a given year. These return periods correspond to the intensity of an event. The 1 in 100-year is usually taken as a standard (Susdrain, 2024) although there are cases where different thresholds are applied, for example when designing resilience to earthquakes.

It is worth noting that drainage networks are designed to flood in 1 in 100-year events. However the floodwater is only allowed to pond in non-critical areas of assets to preserve asset function. These events limit damage to performance degradation but still enable the asset to function.

Whilst the design standards vary country-by-country, and asset-class-by-asset-class, there is some inherent resilience to weather events included in the design of these assets without additional retrofitting.

Assets are usually not designed to be completely resilient beyond this (or a similar threshold) return period and events larger than this will likely start to cause loss of asset function. For example, extreme flooding can partially or fully flood data centres and extreme winds can tear components off telecommunications towers. The most material climate related physical risks to data infrastructure assets are those related to extreme heat, both in the form of raised temperatures, and to a lesser extent wildfires. Extreme temperatures can overload data centre cooling systems, cause cable failures, and destabilise tower foundations if the surrounding soil dries excessively, and wildfires ravage assets caught in their path.

Asset owners can reduce the physical risk to their assets from the effects of climate change in a number of ways set out below for the different risk types. There is a significant incentive for asset owners to proactively adapt their assets as they can reduce total adaptation costs by approximately 30% when compared to predicted future operating conditions (Gil Olmos, 2020), and adaptation costs to prevent issues in the future are cheaper than repairing damage after the fact.

4.2 Flood Resilience

4.2.1 Blue-Green Infrastructure

Blue-green infrastructure is an innovative approach to managing flood risk that utilises networks of natural and semi-natural environments to mitigate the impact of flooding on critical data infrastructure. This strategy focuses on features such as swales, rain gardens, and storage ponds, which are designed to slow down, collect, and redirect excess stormwater away from vulnerable data centres, server farms, and communication networks. These green solutions are often more cost-effective compared to traditional flood defences like barriers and levees, making them an attractive option for organisations looking to enhance their resilience against flooding. However, it is important to note that the effectiveness of blue-green infrastructure decreases as flood intensity increases, meaning that during extreme weather events, these systems may not provide sufficient protection on their own.

Moreover, the integration of interlinked natural environments and sustainable urban drainage systems not only helps alleviate flood risk but also brings additional benefits, such as improved air quality, enhanced biodiversity, and increased recreational spaces. These features can significantly enhance the surrounding environment and contribute to the overall well-being of communities.

Given their limitations in extreme flooding scenarios, it is essential for data infrastructure owners to combine blue-green solutions with other flood management strategies. This might include elevating critical assets, installing flood barriers, or implementing advanced monitoring systems to create a comprehensive approach to flood resilience. By leveraging both green and traditional methods, organisations can better safeguard their data infrastructure against the increasing threats posed by climate change and severe weather events. Blue-green infrastructure installation is common practice for construction projects, particularly in urban settings in Europe with small scale examples such as Priory Common and Derbyshire Street Pocket Park in London and larger scale examples such as Rue Garibaldi in Lyon and Västra Hamnen in Malmö (Transport for London, 2016). Blue-green infrastructure methods have an average medium effectiveness for low intensity flood events (Alves et al., 2020).

4.2.2 Drainage System Upgrades

Traditional drainage infrastructure primarily consists of networks of pipes, often referred to as grey infrastructure, which rely on technical manufactured solutions. These systems are typically buried underground and operate on a gravity-driven basis. In many developed countries, including the UK, some of these networks are several decades old—London's sewer system, for example, dates back to the 1860s (Museum of London, 2019). This ageing infrastructure often lacks the capacity to handle modern flood events and the anticipated increases in flooding due to climate change.

Upgrading these drainage systems is essential for enhancing the resilience of assets against flooding. By ensuring that floodwaters are efficiently removed from sites before they can accumulate and cause damage, upgraded networks play a crucial role in flood management. However, because these systems are buried, any upgrades necessitate significant excavation work. Additionally, since the drainage operates on gravity, modifications to one section of the network can have cascading effects on long stretches of drainage systems both upstream and downstream of the affected area.

For example, in the 1990s, Tokyo undertook a substantial overhaul of its drainage infrastructure to address flooding caused by heavy rainfall. This upgrade included the construction of five large underground caverns and interconnecting tunnels beneath the city streets, significantly improving the city's ability to manage stormwater and reducing flood risks (Poon and Oda, 2023). Such ambitious projects highlight the importance of modernising drainage systems to cope with contemporary challenges and future climate impacts.

Upgrading drainage systems is an expensive flood measure compared to blue-green infrastructure but has a low effectiveness (Sohn et al., 2020).

4.2.3 Elevation

Elevating telecommunications infrastructure is a critical strategy for safeguarding it against potential flood damage. This process involves raising assets above expected flood levels, ensuring they remain operational during extreme weather events. Common methods for elevation include constructing platforms on embankments, raising foundations, or installing equipment on columns or stilts. In data centres this can mean moving server rooms up to higher floors in the building so any flooding at ground level does not affect the main equipment. While these approaches are effective, they are generally best suited for new developments, as integrating them into existing infrastructure often incurs significant retrofitting costs. For instance, retrofitting a network of communication towers or data centres can involve extensive modifications, making it less feasible financially. Additionally, flood depth predictions are highly location-specific, often varying even on a meter-by-meter basis. This granularity means that for linear telecommunications assets, such as fibre optic cables or transmission lines, the most economical solution may be to elevate only those segments that face the highest risk of flooding. By prioritising vulnerable sections, telecom operators can maximise resource efficiency while ensuring service continuity during adverse weather conditions. This targeted approach allows for a balance between cost-effectiveness and resilience in telecommunications infrastructure. The greatest flood risk to data infrastructure assets is often power failures from power network asset flooding, not flooding of data assets directly.

Provided the asset, or critical section of that asset, is elevated above the predicted flood levels in that location, the effectiveness of elevating assets is very high (de Moel et al., 2014).

4.2.4 Flood Barriers

Flood barriers are large structures designed to mitigate exposure to floodwaters by being situated within or alongside water bodies. These barriers can take various forms, including locks, weirs, and gates in rivers, as well as embankments and flood walls in riverine and coastal areas. Societies have utilised these defences for centuries due to their effectiveness.

The scale and costs associated with constructing flood barriers make them significant investments. Typically, they are built, owned, and operated by local authorities rather than individual asset owners. Therefore, it is highly advisable for asset owners to collaborate with local authorities when planning new flood defence measures. However, many flood barrier assets are privately owned and managed, demonstrating that this model can vary. For instance, in the UK, up to 50% of levees are owned by private entities. This highlights the importance of both public and private cooperation in flood management strategies, ensuring comprehensive protection for vulnerable areas and infrastructure (EUCOLD Working Group on Levees and Flood Defences, 2018).

These defences are particularly effective at reducing damage from flooding but damage can be catastrophic if overtopped. This is a risk if the climate change assumptions incorporated into the design are too optimistic. It has also been posited that building flood barriers may increase flood risk due to the reduced perception of risk inherent in constructing assets in flood prone areas and the increased false sense of security from physical protection being in place, even if inadequate (Gross, 2023).
There are various different types of flood barriers that can be installed by asset owners with different associated costs and appropriateness for different situations, however with similar high effectiveness (Adnan et al., 2019).

4.2.5 Pumps

Pumps are large mechanical pieces of equipment that can move significant volumes of water away from critical assets, or zones within assets, in a short time period to avoid or reduce damage from floodwaters. These can be employed at both the asset level in sumps at low points in the asset footprint or upstream of the asset to divert floodwaters away to a different area.

Pumps are largely used as a last resort protection measure as their use often signifies that other protective measures have failed, in which case the volume of water inundating the asset is likely to be large and the avenues for discharging this water less effective than during smaller flood events. Due to the dispersed nature of linear telecommunications assets such as cables, and the fact that most critical equipment in telecommunications towers is above ground level, using pumps as a flood protection measure is more material for data centres where a centralised location is both more at risk than a dispersed network but also easier to protect efficiently (Carter, 2018).

Heavy duty pumps in data infrastructure assets can reduce flood damage by a medium amount (Song et al., 2014).

4.2.6 Sea Walls

Sea walls are large, hard engineered structures used in coastal locations to reduce the impact of flooding in the local area. They are typically constructed from materials such as concrete, masonry or rock baskets known as gabions, with different designs having specific advantages and disadvantages.

Walls are often large-scale pieces of infrastructure themselves and are designed to provide protection to large at-risk areas, for example urban areas, and as such are frequently built, owned and maintained by local authorities, in a similar manner to flood barriers. They are favoured in some locations (e.g. the UK) due to the high protection they offer immediately to vulnerable areas as soon as they are constructed (as opposed to, for example, habitat restoration) and can expand the area of land suitable for development in the protected area. They are also useful for preventing cliff erosion and wave damage to the base of slopes.

The maintenance of sea walls is of particular interest to asset owners as they are both expensive to construct but additionally require significant ongoing maintenance to continue to provide the same level of protection. Frequently designed to last for 30 to 50 years they may well have shorter design lives than the infrastructure they are protecting with significant associated ongoing costs. There is also evidence that sea walls can have significant negative externalities for the local area by accelerating beach loss and increasing insurance premiums for properties nearby (Brucal and Lynham, 2021).

Using sea walls to protect assets from coastal flooding can reduce damage by a high amount (Adnan et al., 2019).

The key technologies, costs and predicted damage reductions of the main flood resilience strategies are shown in Table 4.

Table 4: Flood Resilience Strategies

Flood Resilience Strategy	Key Technologies	Applicable Subclasses	Damage Reduction (% of Total Damage)	Design Hazard Level
Blue-Green Infrastructure	Swales, storage ponds, rain gardens.	All.	Medium	Low
Drainage System Upgrades	Pipes, underground storage, hydrobrakes.	All.	Low	Medium
Elevation	Raised foundations, stilts, embankments.	All.	Very High	High
Flood Barriers	Embankments, flood walls, locks, weirs.	All.	High	High
Pumps	Heavy-duty pumps.	Data Centres.	Medium	Medium
Sea Walls	Vertical, curved, stepped, floating, natural sea walls.	All.	High	High

Note: Classification for Uncertainty - Red =High, Amber = Medium, Green = Low.

4.3 Wind Resilience

4.3.1 Structural Improvements - Building Strengthening

One effective strategy to enhance the wind resilience of data infrastructure is to increase the structural strength of critical components. This can involve measures such as reinforcing connections, upgrading building envelopes, and enhancing support systems, which are particularly relevant for facilities like data centres. The technologies needed for these upgrades are widely available in the market and have been in use for decades.

High wind speeds exert significant forces on the structural components of buildings, creating pressure differentials that can lead to severe damage, such as the complete detachment of roofs and other elements. By retrofitting vulnerable parts of the structure, organisations can bolster the resistance of their facilities to these wind forces. However, it is important to note that while this approach improves the overall structural integrity, it does not diminish the wind forces acting on the building itself. As a result, the reduction in potential damage is increased significantly when combined with other resilience measures, such as site selection or advanced wind-resistant design features, with an average medium reduction (Sutter et al., 2009). Combining structural enhancements with a comprehensive risk management strategy can provide a more robust solution for protecting data infrastructure from extreme weather events.

4.3.2 Wind Breaks

Wind breaks are an effective strategy to reduce wind damage to data infrastructure by blocking, diverting or breaking up wind flows, thereby reducing the forces that act on structures. Whilst all assets have some level of wind resilience as part of their design to certain standards, some assets are inherently more resilient to high wind speeds due to the physical form of the structure. For example cell towers with their lattice structure allow wind to pass through and around them more effectively than a box-shaped data centre with solid facades.
Structural

There are various overarching methods that can be employed by asset owners, the first of which being constructing structural barriers that predominantly either divert or disrupt wind flow and the forces acting on assets. For example, perforated walls are useful for breaking up wind flow on exposed sections of assets such as long facades on buildings by diverting wind up and over the asset and reducing pressure differentials on either side of the barrier. This enables data infrastructure assets to remain operational at higher wind speeds and in severe conditions reduce damage to the structure. Structural wind breaks can reduce damage to assets by a medium amount (Kozmar et al., 2012).

Terrain and Landscaping

The second common method of utilising wind breaks is by using terrain and the landscape around asset to protect them. This can be in the form of either natural or artificial solutions, with berms or dips in the landscaping sheltering assets from the worst of severe winds. This can reduce wind damage by a medium amount (Paek et al., 2016).

Vegetation

Vegetation can also be used by asset owners to protect assets, with multiple additional benefits to biodiversity. Vegetation works in a different manner to terrain and landscape features, which block wind from reaching an asset, by breaking up wind flows as they pass through the vegetation and by slowing down and disrupting the wind it reduces the forces that can act on a structure. However, care needs to be taken when designing and planting dense vegetation around assets as a major source of damage to linear assets in particular can come from wind-blown debris from nearby trees and bushes, so a maintenance regime is required to preventatively remove potentially damaged branches in advance of storms. This is a highly effective strategy (Stathopoulos et al., 1994).

The key technologies, costs and predicted damage reductions of the main wind resilience strategies are shown in Table 5.

Table 5: Wind Resilience Strategies

Wind Resilience Strategy	Key Technologies	Applicable Subclasses	Damage Reduction (% of Total Damage)	Design Hazard Level
Structural Improvements - Building Strengthening	Reinforced connections, upgraded envelopes, enhanced bracing systems.	All.	Medium	High
Wind Breaks - Structural	Perforated walls, solid walls.	All.	Medium	High
Wind Breaks - Terrain and Landscaping	Embankments.	All.	Medium	Medium
Wind Breaks - Vegetation	Trees and bushes.	All.	High	Medium

Note: Classification for Uncertainty - Red =High, Amber = Medium, Green = Low.

4.4 Heat Resilience

4.4.1 Cooling Systems - Mechanical

Retrofitting data infrastructure assets with mechanical cooling systems, or upgrading existing ones, reduces the temperature of spaces within buildings by use of mechanical systems such as heat pumps, mechanical ventilation and the use of refrigerants. It can be split into two main categories, space cooling and equipment cooling. Space cooling is mainly a building or room scale measure aimed at providing a steady ambient environment for data equipment to operate in, whereas equipment cooling refers to technologies that cool individual components of the equipment itself, such as servers. These categories have a dual purpose, both to reduce thermal wear on internal parts of the structure but also to provide an optimal environment for data assets to operate, which is particularly relevant to data centres that require specific temperature ranges to function fully with decreasing capacity as internal temperatures increase. Equipment cooling is relevant to both data transmission and data storage assets. It is worth noting that the electrical power required to run these systems is often significant, approximately 40% of all data centre electricity demand (Whiting, 2021), and therefore depending on the carbon intensity of the energy supply to an asset it can be responsible for large quantities of GHG emissions, therefore reducing the physical risk to the asset but increasing the transition risk.

Mechanical cooling systems have a high effectiveness for both data transmission assets (Samba et al., 2013) and for data storage assets (Gomes et al., 2020).

4.4.2 Cooling Systems - Natural and Evaporative

In contrast to mechanical (or active) cooling, an alternative method of cooling data infrastructure revolves around different passive methods that require no electrical power input such as planting grass around assets to aid with evapotranspiration or evaporating stored rainwater near assets. For buildings it can also include options such as designing buildings to ventilate properly utilising the thermal properties of air movement to ensure a constant flow of cooler air moving heat away from equipment and changing the building fabric or form to reduce heat exposure. These strategies are of particular relevance in hot climates where mechanical cooling loads can prove costly under current climate conditions and natural cooling strategies can reduce or eliminate that burden. Despite this design ethos being relatively new compared to mechanical cooling, it is often based on traditional designs and principles that have been used in buildings in different climate zones for centuries.

The effectiveness of natural cooling techniques for data transmission asset is low (Samba et al., 2013) but high for data storage assets (Gomes et al., 2020) highlighting different use cases and the requirements for some assets to use this in conjunction with other strategies.

4.4.3 Heat Reflective Coatings

The material properties of data infrastructure assets plays a large role in how much heat a particular asset absorbs, particularly industrial finishes for assets such as cell towers. Materials which are dark in colour absorb more heat energy and therefore increase the thermal stresses on the material, eventually leading to damage, whereas lighter surfaces reflect a greater proportion of this heat away from the structure. Increasing the albedo of surfaces can help reflect more heat away to reduce damage further. This can be a very cost-efficient retrofit as it is cheap to do and reduces heat damage by a significant amount. One downside to these methods is reflecting the heat away from the ground can increase heat damage to assets above ground level and make the air temperature too high for human comfort, which is relevant for staff health and wellbeing, particularly during outdoor maintenance in extreme temperatures.

Heat reflective coatings can reduce heat related damage to assets by a medium amount (Cheela et al., 2021) for data transmission assets.

4.4.4 Heat-Resistant Construction Materials

New materials are being designed that have been optimised to function well in extreme heat and existing assets can be upgraded with these to increase resilience to high-temperature events. A lot of these measures are commercially available currently and include technologies such as phase change materials, heat resistant steel for telecommunication towers, and aluminium alloys for overhead cables. Whilst these materials are roughly equivalent in cost to their non-heat-resistant equivalents, they can require substantial retrofit to existing assets to achieve the benefits and therefore can prove costly. This is also an area of ongoing research and development so new materials will likely become available in the near future.

For data transmission assets such as telecommunication towers, heat-resistant materials can reduce thermal damage by a high amount (Qiao et al., 2020), and a medium amount for data storage companies (Skach et al., 2017).

4.4.5 Optimise Operational Practices

Throughout the lifetime of data centres it has been widely assumed that it could only operate successfully within very strict temperature ranges that had to be maintained constantly despite external ambient temperature fluctuations. Recent research is questioning this assumption and showing that data centres can operate effectively at higher temperatures than previously thought without significant reductions in performance, although this strategy is not effective above approximate temperature thresholds of 35 degrees centigrade and should be used alongside other measures. One effective operational change that asset owners can make at the project inception stage is locating a data centre in a cold environment to take advantage of the cooler ambient temperatures to reduce cooling needs (Stacey, 2023). Iceland, Ireland and Scotland have all become prime locations for data centre construction in part because of their cold climates.

There are limits to the effectiveness of this strategy, however, and the effectiveness is low for data centres (Islam et al., 2015).

4.4.6 Shading - Shade Structures

Data infrastructure assets are most exposed to physical risk from extreme temperatures, especially high temperatures, with both reductions in operational capacity and reduced lifespans associated with extended or repeated periods of extreme high temperatures. Shade structures reduce the heat transfer to these asset components and therefore reduce the heat-related damage incurred. Shade structures also have additional benefits to human health when placed in areas frequented by staff members such as entrances to buildings and key areas that require frequent maintenance.

Shade structures are highly effective at reducing localised heat related damage with a high effectiveness (Almusaed and Almusaed, 2011).

The key technologies, costs and predicted damage reductions of the main heat resilience strategies are shown in Table 6

Table 6: Heat Resilience Strategies

Heat Resilience Strategy	Key Technologies	Applicable Subclasses	Damage Reduction (% of Total Damage)	Design Hazard Level
Cooling Systems Mechanical	Chillers, cooling towers, air conditioning units.	Cell towers, long distance cables, communication satellites, radio and media towers.	High	High
Cooling Systems Mechanical	Chillers, cooling towers, air conditioning units.	Data centres.	High	High
Cooling Systems Natural and Evaporative	Evaporative cooling, insulation, natural ventilation.	Cell towers, long distance cables, communication satellites, radio and media towers.	Low	Medium
Cooling Systems Natural and Evaporative	Evaporative cooling, insulation, natural ventilation.	Data centres.	High	Medium
Heat Reflective Coatings	High albedo coatings, reflective pigment additives.	Cell towers, long distance cables, communication satellites, radio and media towers.	Medium	High
Heat-Resistant Construction Materials	Heat-resistant metals, ceramics, composites.	Cell towers, long distance cables, communication satellites, radio and media towers.	High	Very High
Heat-Resistant Construction Materials	Heat-resistant metals, ceramics, composites.	Data centres.	Medium	Very High
Optimising Operational Practices	Higher operating temperatures, cold external climates, internal layouts.	Data centres.	Low	Medium
Shading - Shade Structures	Architectural features, built structures.	All.	High	Medium

Note: Classification for Uncertainty - Red =High, Amber = Medium, Green = Low.

4.5 Wildfire Resilience

4.5.1 Defensible Space Management

Defensible space management includes creating a buffer strip immediately around assets filled with non-flammable materials and surfacing that removes the ability of wildfires to reach the asset itself. It will slow or stop the spread of a wildfire as it approaches the building and gives firefighters more space to safely tackle the blaze if required. Different levels of protection can be used in a concentric pattern around the asset footprint that offer different levels of protection and require different levels of management to maintain. The furthest zone is a fuel reduction zone, involving the removal of major fuel sources. Closer to the asset is a middle zone with a greater focus on reducing potential fuel sources, and finally an internal ring that encloses the asset and uses fire retardant materials and a rigorous clearing of any ignition and fuel sources.

Defensible space management has an effectiveness range of between medium and high (California Wildfire and Forest Resilience Taskforce, 2024).

4.5.2 Fire Retardants

It is common for flame retardant chemicals to be sprayed on areas prone to wildfires in the build up to wildfire season, particularly aerial spraying, as a method to slow down the spread of wildfires when they do occur and reduce the likelihood of them occurring in the first place by reducing the chances of ignition in sprayed areas. Fire retardants are intended to be used to provide working space for firefighters to operate safely behind. Whilst they can be liberally applied quickly from the air and prior to wildfires commencing, the guidance on their use is generally several decades old and there are environmental and health concerns about their use now. Newer formulae are likely to become available if the risks to wildlife and local inhabitants is considered too great.

Fire retardants have an effectiveness range of between medium and high (Ai et al., 2024).

4.5.3 Fire Suppression Systems

Fire suppression systems comprise systems of water sprinklers and fire suppression tools, such as foam or gas systems, that automatically detect and extinguish fires before they spread. For asset owners trying to protect their assets from wildfires this could include storing and piping water to vulnerable areas around critical buildings or components and spraying on these areas to either prevent or stop fires from damaging it. These systems are widely commercially available and are included as standard building design for the purposes of fighting internal or external fires, but they may need upgrading to accommodate the increased risk from wildfires.

Fire suppression systems can range in effectiveness from medium to high (Reimer et al., 2019).

4.5.4 Firebreaks

Firebreaks are zones that are systematically cleared of vegetation and can be covered with non-combustible materials such as gravel or sand, to create a defensive line between an approaching wildfire and an asset over which the fire cannot spread. There are three main types of firebreaks that can be employed by asset owners to protect their assets: natural, existing, and constructed firebreaks. Natural firebreaks are often formed by natural water bodies such as streams, rivers and lakes where the body of water is wide enough for the fire to be unable to spread across. Other natural firebreaks consist of areas of wet or damp vegetation that is unable to burn other than smouldering that will eventually burn out and not feed the conflagration. Existing firebreaks can be things like cultivated fields that do not have flammable vegetation, or roads through areas at risk of wildfires. Constructed firebreaks are specifically designed and built firebreaks through wildfire-prone areas where a gap is created between vegetation that is too wide for the fire to cross.

Firebreaks have a high effectiveness (Suffling et al., 2008).

4.5.5 Fireproof Building Materials

Assets can be made more structurally resistant to wildfire damage if they are constructed of certain fireproof materials. Steel, for example, does not burn and also keeps its strength and form up to much higher temperatures and therefore is less likely to collapse or require complete reconstruction post-fire. Wood can be treated with fire retardant chemicals that reduce its combustibility, however it is vulnerable to repeated exposure to wildfires and suffers degradation under environmental conditions. Concrete is also a good fireproof material that provides a strong barrier to wildfire with the added benefit of slowing heat transfer to interior spaces due to its high thermal mass. One downside to all the above materials is that they are high-carbon alternatives to construction materials such as untreated timber and therefore decrease physical risk at the expense of increasing transition risk.

Utilising fireproof building materials have a range of effectiveness depending on the materials used, from low (Askaripoor et al., 2020) to medium (Hull et al., 2023).

4.5.6 Fuel Reduction Zones

Creating fuel reduction zones is a broad strategy aimed at reducing the amount of fuel available for a fire to reduce the spread as much as possible. It can be achieved through a number of measures but generally involves the removal of dry brush dead trees and any flammable debris near an asset, as well as thinning out dense tree stands and is usually done by hand or with machinery. A traditional method for reducing the amount of fuel available for wildfires was the use of grazing animals such as sheep and goats to eat underbrush and remove ignition sources.

Creating fuel reduction zones around assets can reduce wildfire damage by a high amount (Ager et al., 2010).

4.5.7 Prescribed Burns

Like most of the strategies examined in this report, prescribed burns are primarily used as a method to safely reduce the fuel available for wildfires by proactively burning it during low risk conditions ahead of wildfire season. Utilising prescribed burns can clear areas around an asset of fuels that would feed a wildfire as it approaches and therefore slow down and reduce the intensity of the fire. Prescribed burns also have several additional benefits to the local ecosystem, such as recycling nutrients into the soil, promoting vegetation growth and removing pests, particularly in areas where historically wildfires have been part of the ecosystem cycle. Prescribed burns can reduce wildfire damage by a medium amount (Walker et al., 2018).

4.5.8 Structural Hardening

Reinforcing buildings and storage areas with fire-resistant materials, which can withstand higher temperatures and prevent the spread of flames. Individual aspects of assets can be specifically hardened to improve their resilience to the effects of wildfires, both in the high intensity but short duration period when the fire front passes around an asset, and in the lower intensity, longer duration stage where the fire has passed but the danger of hot embers causing secondary fires remains. Measures such as installing fireproof screens over ventilation intakes, cavities, doors and windows will help reduce ember ingress, and replacing windows with fireproof glass and adding shutters to doors and windows reduces potential damage in both phases of the wildfire. This allows vulnerable parts of the asset to be able to withstand higher temperatures and prevent the spread of flames. It is also significantly cheaper than reconstructing the entire asset with fire-resistant materials if it was not originally.

Structural hardening can reduce wildfire damage to assets by between a medium and high amount (Penman et al., 2015).

4.5.9 Vegetation Management and Landscaping

Planting and maintaining fire-resistant vegetation around assets reduces the fuel available to wildfires and can slow down its spread. Plants with high moisture content in the leaves, that leave little in the way of dead vegetation in the surrounding area and low levels of natural oils and resins such as those present in evergreens, can all help to reduce fuel build up. Easily ignitable vegetation such as tall grasses and other plants that die back in winter leaving significant quantities of dead material on the ground should be avoided if the wildfire risk to an asset is high.

Managing vegetation and landscaping around and beneath assets has an effectiveness of between a medium and high amount (Penman et al., 2015).

The key technologies, costs and predicted damage reductions of the main wildfire resilience strategies are shown in Table 7.

Table 7: Wildfire Resilience Strategies

Wildfire Resilience Strategy	Key Technologies	Applicable Subclasses	Damage Reduction (% of Total Damage)
Defensible Space Management	Hand clearing, machine clearing, chemical spraying.	All.	Medium-High
Fire Retardants	Foams and gels, aerial spraying.	All.	Medium-High
Fire Suppression Systems	Water sprinklers, foam or gas dispensers.	All.	Medium-High
Firebreaks	Rivers, roads, man-made breaks.	All.	High
Fireproof Building Materials	Steel, concrete, chemically treated timber.	All.	Low-Medium
Fuel Reduction Zones	Hand clearing, machine clearing, chemical spraying.	All.	High
Prescribed Burns	Hand burning.	All.	Medium
Structural Hardening	Flame-retardant screens, fireproof glass, door shutters.	All.	Medium-High
Vegetation Management and Landscaping	Hand clearing, machine clearing, chemical spraying.	All.	Medium-High

Note: Classification for Uncertainty - Red =High, Amber = Medium, Green = Low.

4.5.10 Summary

Flood barriers offer high protection levels but are high-cost investments and are often constructed at larger-than-asset scales to protect large areas. If flood barriers are being considered by investors or asset owners, then coordination with local authorities is advisable. Elevation provides very high protection but is very expensive and should be considered for critical areas of assets to prevent prohibitive costs. Blue-green infrastructure represents a low-cost method of reducing flood related damage whilst providing additional benefits not quantified here and should be employed by asset owners wherever practicable as part of good design.

Wind risk can be effectively mitigated up to a point for data infrastructure assets but is more dependent on asset type than flood resilience. For example cell towers are naturally wind resistant due to the lattice nature of their construction that allows wind to freely pass through the structure. Cables are more easily downed and buildings such as data centres are vulnerable due to the strong forces that act on large roofs during intense storms.

Current technologies for reducing heat-related damages are widely available and can reduce heat damage by significant amounts, albeit with widely divergent costs. Whilst asset owners should expect damage to occur, primarily from operational losses due to downtime as opposed to asset destruction, these strategies will reduce costs in the long-term. Moreover, strategies such as shading have significant additional benefits to human health and well-being that, whilst outside the scope of this assessment, may render more favourable cost/benefit ratios.

Wildfire-related damages can be effectively reduced for most data infrastructure asset classes for reasonable costs to asset owners. A number of the strategies display significant similarity and are based on similar principles of reducing fuel, slowing down the spread of wildfires and leaving gaps between assets and their surroundings.

5. Discussion

5.1 Risks and Constraints to Strategies

The strategies presented here are perceived to be actions that an asset owner could take using mostly currently commercially available technologies, or technologies likely to be available in the near future. However, given uncertainties both in reporting Scope 3 emissions globally and in an asset owner's ability to shape and manage supply chain behaviour this represents a significant risk to the success of data infrastructure companies attempts to decarbonise their operations. This includes both upstream supply chain actors, predominantly in the production of electronic goods used and sold by data infrastructure companies, and downstream consumers, often of these same electronic goods.

A second major risk is that both the electricity usage for data infrastructure companies is a significant proportion of overall emissions, and the energy usage of sold products, counted under Scope 2 and Scope 3 emissions categories respectively, are reliant on external factors such as wider electrical grid decarbonisation. Whilst this is accelerating in some nations other regions around the globe are not decarbonising their grid, or are doing so at a very slow pace and therefore the emissions for data infrastructure companies from these sources is likely to continue to be large for some time into the future.

Electricity grids in most areas with large growth in data infrastructure are suffering from a lack of grid capacity that restricts the amount of renewable energy capacity that can be added. Compounding this problem, the high cost of on-site energy storage technology is also a barrier to the effective rollout of greater renewable capacity as it is a critical enabling technology to increase the reliability of renewable generation.

The physical risks to data infrastructure assets have two major risks, one unavoidable due to the nature of network utilities, the other due to the choices of asset owners in locating their assets. The former refers to the need for network utilities such as data networks to cover large distances with failures along any part of the length of the asset resulting in the entire length being unusable, for example a cable breaking halfway along its length renders the entire cable unusable. This risk is and can be reduced by network redundancies and whilst these aspects of resilience are not looked at in this paper they may be more effective methods of ensuring resilient networks. The latter risk is specific to data centres and refers to data centres being located in warm climates that are predicted to get significantly warmer in the coming decades. This is particularly relevant for data centres constructed in areas like the southern United States and southern Europe, where demand and commercial incentives are driving data centre construction in climate zones that are already unsuitable for the temperature ranges required for the assets to function effectively, and the risk will only increase in the future.

For some of the resilience strategies, there are trade-offs that must be taken into consideration. The most obvious contradiction in objectives is that the majority of the resiliency measures will increase the carbon emissions associated with a particular asset. For example, all the flood resilience measures barring the use of blue-green infrastructure involve significant increases in carbon emissions from materials used in the construction of the measures. The use of concrete and steel are particularly impactful in this regard. Where resiliency measures are considered the use of low-carbon materials and construction methodologies will be paramount to reduce this impact. Also for data centres in particular, low-carbon energy solutions to reduce energy usage needed for cooling will be critical as global temperatures rise.

5.2 Wider Factors and Influences

The data infrastructure sector is less at risk from the physical effects of climate change than other infrastructure sectors, however given the interdependence of these sectors, failures in a different, higher risk sector may have knock-on effects for data assets. For example, if power networks fail during a storm, then power to parts of the data network may not be available, or only for a limited time as back-up generators are used. Or if road networks are washed away during a flood then data cables buried underneath may be broken and connectivity lost.

The reverse is also true in that data infrastructure now reinforces all other infrastructure types and disruption to data infrastructure will have very wide societal effects, from monitoring systems in water networks, to IT systems in healthcare, to personal device usage. This increasing interlinkage between data infrastructure and every aspect of modern life means that even though the risk to these assets is low, the wider potential damage at a system scale is large.

Reducing transition risk for data infrastructure assets for their controllable emissions (Scopes 1 and 2) is relatively straightforward in most locations as it predominantly requires reducing emissions from electricity usage and can be achieved by installing renewable energy capacity on site. However, in locations where renewable energy generation is unsuitable the asset owner is very dependent on grid decarbonisation, which is out of their control and subject to a very broad set of local, regional, national and supranational factors that are outside the scope of this paper to analyse.

Similarly, as discussed in the previous section, the market and regulatory forces that govern third party supply chains dominate the Scope 3 emissions for data infrastructure companies and therefore it is critical to ensure concerted effort at widespread emissions reductions in the key manufacturing sectors.

5.3 Strategy Subclass Alignment

5.3.1 Transition Risk

All of the transition risk reduction strategies assessed in this paper are applicable to both classes of data infrastructure assets, apart from natural cooling which is more applicable to data centres and decommissioning legacy systems which can be used on data transmission assets. All of the high impact strategies such as virtualisation, efficiency and optimisation gains, and renewable energy usage are applicable across all asset types. Any strategies that involve electrifying something, for example electrifying company vehicles or virtualising products and services, will increase Scope 2 emissions and therefore need to be accompanied by a simultaneous increase in the use of renewable energy. To highlight how different strategies apply across the data asset types, the distribution of class applicability for each strategy is shown in Table 8.

Table 8: Data Decarbonisation Strategy Applicability

Strategy	Data Transmission	Data Storage
Virtualisation	Y	Y
Renewable energy generation - on-site generation	Y	Y
Renewable energy generation - off-site purchase agreement	Y	Y
Optimise operational practices	Y	Y
Natural cooling	N	Y
Increasing energy efficiency of operations	Y	Y
Decommission legacy systems	Y	N
Downstream recycling	Y	Y
Sustainable procurement	Y	Y
On-Site energy storage technology	Y	Y
Low-carbon fuels for power generation	Y	Y
Leakage reduction	Y	Y
Low-carbon transport infrastructure electrification	Y	Y

5.3.2 Physical Risk

The physical risk exposure of different asset classes is largely the same across both classes of data infrastructure assets with minor differences in flood and heat resilience strategy applicability.

Floods

Flooding is a material risk to data infrastructure assets, although damage and downtime can often occur from upstream flood disruption as opposed to purely from the asset itself. For example, a common cause of data infrastructure outages is power outages caused by flooding of power network assets such as transformers. This highlights the interconnectedness of different infrastructure types and how resilience is often dependent on defence measures taken by other organisations outside of an asset owner's direct control. All flood strategies are applicable to both data asset classes, barring the use of pumps which is more suitable for data centres. The distribution of flood strategy applicability across subclasses is shown in Table 9.

Table 9: Flood Resilience Strategy Applicability

Strategy	Data Transmission	Data Storage
Elevation	Y	Y
Flood barriers	Y	Y
Sea walls	Y	Y
Blue-green infrastructure	Y	Y
Pumps	N	Y
Drainage system upgrades	Y	Y

Wind

Extreme wind also poses a significant risk to data transport assets, particularly those in exposed, remote locations such as rural data centres or data transmission cables. The vulnerability of cables that cover long distances is high but as such the designs that are utilised have some level of inherent resilience incorporated in already. The strategies for protecting data assets against wind damage are applicable to both classes of data infrastructure and the distribution of wind strategy applicability across subclasses is shown in Table 10.

Table 10: Wind Resilience Strategy Applicability.

Strategy	Data Transmission	Data Storage
Wind breaks - vegetation	Y	Y
Structural improvements - building strengthening	Y	Y
Wind breaks - terrain and landscaping	Y	Y
Wind breaks - structural	Y	Y

Heat

Extreme heat is very material to data infrastructure assets. For example, it can cause transmission cables to sag and eventually break, and overload data centre cooling systems leading to system downtime and damage. This can be mitigated by various strategies outlined above, with shading, heat-resistant materials and different types of cooling system being applicable across both classes of data infrastructure. However, heat reflective coatings are more applicable to transmission assets and optimising operational practices is more relevant to data storage assets. The distribution of heat strategy applicability across subclasses is shown in Table 11.

Table 11: Heat Resilience Strategy Applicability

Strategy	Data Transmission	Data Storage
Shading - shade structures	Y	Y
Heat-resistant construction materials	Y	Y
Cooling systems - mechanical	Y	Y
Cooling systems - natural and evaporative	Y	Y
Heat reflective coatings	Y	N
Optimising operational practices	N	Y

Wildfire

Data infrastructure assets in wildfire prone areas are both exposed to fires but also can indirectly contribute to reduced firefighting effectiveness in the event of a fire. This is because data centres can be clustered in certain locations and if those locations are in areas with high water stress then the additional water demand from a rapidly expanding data centre sector can lead to supply issues in the event on a wildfire as posited happened in the recent Los Angeles wildfires (Snider, 2025). Despite this, the strategies to improve the wildfire resilience of data assets are applicable to both classes of assets. The distribution of wildfire strategy applicability across subclasses is shown in Table 12.

Table 12: Wildfire Resilience Strategy Applicability.

Strategy	Data Transmission	Data Storage
Firebreaks	Y	Y
Fire suppression systems	Y	Y
Defensible space management	Y	Y
Fire retardants	Y	Y
Structural hardening	Y	Y
Fuel reduction zones	Y	Y
Vegetation management and landscaping	Y	Y
Prescribed burns	Y	Y
Fireproof building materials	Y	Y

5.4 Use Cases

The use cases for the information presented in this paper fall into two main categories: firstly, uses by infrastructure asset owners and investors to guide decision making; and secondly, to further research aims within this field.

Regarding the former, this information is useful to asset owners and investors when discussing options for reducing both transition risk and physical climate risk to their portfolios. Whilst not intended to replace asset specific engineering expertise it highlights to investors the range of options, as well as giving an indication of effectiveness that is useful in making early-stage decisions. It also demonstrates to investors that the costs associated with readying their portfolios against the effects of climate change makes sound economic sense given the costs of transitioning, increasing resilience and unprotected damages brought about in a "no action" scenario.

In terms of being used for additional research, one example use case could be the effects of physical climate risk of infrastructure assets under different transition scenarios and the effectiveness of strategies to prevent damages. Additional avenues of research include could include comparisons against costs for new build assets or as the basis for regional or country-specific analyses to discern any quantifiable differences between markets.

5.5 Recommendations for Further Research

To improve the accuracy and applicability of the conclusions reached in this paper there are several steps that could be undertaken as next steps.

The major focus of any follow up research will be on quantifying the costs associated with the various strategies to provide more robust indications to investors of any likely cost-benefit ratios, and finding representative emissions profiles for each superclass that will decrease the uncertainty in some of the emissions reduction values provided here.

Following this the next step it to conduct a sensitivity analysis using average asset sizes based on data held in the infraMetrics universe to refine assumptions about the costs and benefits of each proposed strategy for both transition and physical risks. This will help align the costs with the scale of private infrastructure assets commonly held by asset owners.

Developing a database of granular representative industry data will enable a comparison of the example projects included in this paper and real-world project values on parameters such as costs, carbon emissions and reduction amounts. This would enable a more statistical approach to be taken in determining these values. This work will require industrial partners, particularly within the engineering field, as they are likely to own large quantities of project-scale data that could be used to provide generalised baselines. Additional partners across the policy, research and financial spectra will also be necessary to refine and streamline the process, as well as ensuring as broad a reach as possible. There is potential to tie into existing, disparate initiatives and bring them together into a centralised repository of data.

To further refine the transition risk values, indices of carbon reduction cost efficiencies could be developed for different TICCS® classes and levels to help inform asset owners of strategies that they can employ.

For both transition and physical risk, a similar analysis as conducted here could be extended to explicitly cover new-build assets as opposed to the costs of retrofit for existing assets presented in this paper. Whilst the decarbonisation potentials and risk reductions are likely to be broadly similar as shown here, the costs associated with implementing certain strategies on new-build as opposed to existing assets is likely to be significantly different.

Additionally, this research is being broadened out to encompass different economic sectors with a particular initial focus on the corporate sector.

5.5.1 Conclusion

Both the anticipated transition and climate-related physical risks to data assets are substantial but can be reduced through timely and effective implementation of the strategies set out in this paper. With GHG emissions from the sector currently accounting for a modest proportion of global emissions but potentially with explosive demand growth in the coming decades, if existing trends continue, then without mitigation the data sector will become a major contributor to climate change. For asset owners this impact can be effectively reduced through a combination of using renewable energy, making efficiency and optimisation improvements and working with their supply chain to reduce the emissions from the equipment used in data infrastructure assets, or sold by data companies.

Additionally, with predicted losses from climate-related physical risks in the region of 50% of asset value, increasing the resilience of data infrastructure is increasingly becoming fundamental to safeguarding future operations. By investing in asset decarbonisation and resilience, owners can reduce potential future losses and equip themselves to weather the effects of climate change now and in the coming decades.

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About EDHEC Climate Institute

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Institutional Context

Operating from campuses in Lille, Nice, Paris, London and Singapore, EDHEC Business School is ranked in the top ten European business schools. With more than 110 nationalities represented in its student body, some 50,000 alumni in 130 countries, and learning partnerships with 290 institutions worldwide, it is truly international.

EDHEC Business School has been recognised for over 20 years for its expertise in finance. Its approach to climate finance is founded on a commitment to equipping finance professionals and decision-makers with the insights, tools, and solutions necessary to navigate the challenges and opportunities presented by climate change. EDHEC has developed a significant research capacity on the financial measurement of climate risk, which relies on the best researchers in climate finance, and brings together experts in climate risks as well as in quantitative analysis.

The DNA of EDHEC's work has also resided, since its origin, in the ability to generate business ventures, by encouraging spin-offs based on the research work of its teams. EDHEC is currently involved in three ventures: Scientific Portfolio, Scientific Infra and Private Assets, and the soon-to-launch Scientific Climate Ratings.

Mission and Ambitions

The EDHEC Climate Institute (ECI) focuses on helping private and public decision-makers manage climate-related financial risks and make the most of financial tools to support the transition to a low-emission economy that is more resilient to climate change.

It has a long track record as an independent and critical reference centre in helping long-term investors to understand and manage the financial implications of climate change on asset prices and the management of investments and climate action policies.

The institute has also developed an expertise in physical risks, developing proprietary research frameworks and innovative approaches. ECI is also conducting advanced research on climate transition risks, with a focus on supply chain emissions (Scope 3), consumer choices, and emerging technologies.

As part of its mission, ECI collaborates with academic partners, businesses, and financial players to establish targeted research partnerships. This includes making research outputs, publications, and data available in open source to maximise impact and accessibility.

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