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Improving climate risk preparedness - Railroads in Norway

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HIGHLIGHTS

- Railroad tracks are vulnerable to physical impacts of climate change.
- Flooding events and heat stress are most of concern in Norway.
- Railroad companies must interpret climate science according to their situation.
- The preparedness framework introduced is a useful tool to reduce vulnerability.

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ABSTRACT

Climate change affects all sectors of society due to changes in temperature and precipitation patterns and will continue to do so in the foreseeable future. Extreme weather events are already more frequent and intense, generating additional costs for businesses nationally and globally. Climate risk disclosure and management can be challenging due to the complexity of climate impacts and unpredictability of extreme events' occurrence and location. To address the need for a systematic approach to manage physical climate change, this paper presents a 'preparedness framework' for a comprehensive physical climate risk assessment, which is inspired by the Task Force on Climate-related Financial Disclosures' (TCFD) framework and based on interviews with representatives from the financial sector in Norway and Sweden on their management of climate risks. We analyze railroads in Norway as a case study due to the sector's sensitivity to flooding events and heat stress. After assessing Bane NOR's management of risk associated with flooding and heat stress, we discuss potential improvements regarding knowledge, strategy, management, and tools and metrics at a general level, emphasizing the benefits of improving capacity to handle climate change and the importance of contingency plans. The preparedness framework has helped identify strategies and actions that can reduce vulnerability to climate change impacts. We suggest that this checklist is sufficiently general to be applicable for other sectors and countries.

Practical Implications: Transportation is one of the sectors that may be significantly affected by climate change, and this includes railroads and train travel. Heavy rain events, dry spells, extreme temperatures, and freeze–thaw events can cause problems for railroad operations. We have therefore chosen railroads in Norway, with Bane NOR as the state-owned organization responsible for the administration of the network, as an insightful case for examining the climate risk and vulnerability to climate change. We introduce a 'preparedness framework' as a tool for identifying and handling climate risk. The preparedness framework aims to combine science-based information with the user context and their needs according to their activity and vulnerability to climate change impacts. The framework can highlight Bane NOR's general potential to reduce vulnerability and improve resilience to withstand negative impacts caused by climate change. Building resilience is paramount to business continuity, and involves climate stress-testing, precautionary action, better information carrying less uncertainty, capacity building, and contingency plans in the case of climate-related disturbances affecting train operations. This requires efficient monitoring, closer attention to weather forecasts, good maintenance, as well as implementing measures such as lowering the speed limit for trains in high-risk situations. Contingency plans include provision of alternative transportation when tracks are blocked. We envisage that the preparedness framework' checklist can be applied to other sectors than railroads and other countries than Norway.

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Introduction

Anthropogenic climate change has substantial impacts on nature and society. All economic sectors are exposed to the impacts associated with climate change. The physical effects are already globally apparent, manifesting through extreme weather events and climate patterns, such as flooding, heat waves and droughts. These events are expected to increase in frequency and intensity in the future. Most countries have adopted the Paris Agreement, stating that global warming should be limited to well below 2 °C compared to the preindustrial level, and pursuing 1.5 °C (Paris Agreement, Article 2.1.a; UN, 2015). Pathways consistent with the continuation of currently implemented climate policies indicate continued increase of greenhouse gas (GHG) emissions, leading to global warming of around 3 °C by 2100 (IPCC, 2022). Both the physical impacts of climate change and transitional risk stemming from policies to reduce emissions of GHGs, already affect all sectors of society. The value of assets at risk from climate change is expected to range from 4.2 to 43 trillion USD globally between now and 2100, dependent on which climate change scenario materializes (EIU, 2015). Shifts in temperature and precipitation patterns can affect crop yields and consequently, food security (FAO, 2023). Extreme weather events can cause substantial physical damage to buildings and critical infrastructure along with economic damage, leading to reduced economic growth. Increases in heat-related mortality and latitudinal and altitudinal expansion of vector borne disease contribute to the global burden of disease (O'Neill et al., 2022).

Meeting the Paris Agreement's goal will require much stricter climate policies and substantial reduction of GHG emissions, implying higher prices on emissions of carbon dioxide and other GHGs to move away from fossil fuels and related assets.[1] Energy generation, transportation, industry, and land-use changes are the highest greenhouse gas (GHG) emitting sectors globally, requiring swift decarbonization. Emissions from power production represent around 40 percent of the global CO_2 emissions. Transitioning to power systems dominated by renewable energy sources and carbon capture and storage (CCS) technology for the remaining fossil based energy resources is needed. Decarbonization of the transport sector, responsible for about 25 percent of global GHG emissions, is closely interlinked with power generation. CCS is not a feasible option for transportation as the consumption of petroleum-based fuels generates dispersed CO_2 emissions that are difficult to capture. Therefore, policies supporting vehicle electrification and biofuels are expected to drive the transition in this sector. Industrial emissions, accounting for around 20 percent of GHG emissions globally, are mostly related to fossil fuel combustion for energy. Steel and cement production are the largest emitting subsectors. Cement production could achieve deep decarbonization given a substantial reduction in CCS cost, whereas CO_2 emission reduction for steel and iron production would depend on CCS as well as enough renewable power and bioenergy (Kaya et al., 2019).

Physical risks are related to changes in the climate system, which lead to increased frequency and intensity of extreme weather events, sea level rise and other types of acute or chronic hazards, causing various degrees of disruptions to human activities across multiple sectors. This includes changes in agricultural productivity, and damage to buildings, infrastructure, and production facilities (Cepni et al., 2022). The Intergovernmental Panel on Climate Change (IPCC) defines physical risk as a function of hazards, exposure, and vulnerability (IPCC, 2014). Hazards refer to the physical effects of climate change, such as floods, sea level rise, heat waves, and droughts. Exposure refers to the presence of people, livelihoods, infrastructure, or economic, social, and cultural assets in places that could be adversely affected by hazards. Vulnerability refers to the aspects of natural and human systems, infrastructure and assets that are affected by the hazards. Vulnerability can be understood as a function of sensitivity and adaptive capacity. Sensitivity determines how an exposed system may be afflicted by a hazard. Sensitivity to physical climate risks depends on land use, demographic characteristics, and economic structure, such as dependency on agriculture and the extent of industrial diversification. Adaptive capacity refers to a system's ability to adjust and cope with hazards. This depends on factors like knowledge, available resources, and tools (IPCC, 2014).

Regional and global institutions have begun to develop strategies for addressing climate risks and managing their financial implications. The European Commission (EC) has examined how sustainability considerations can be integrated into its financial policy framework to mobilize finance for sustainable growth (EU, 2019), leading to the launch of a taxonomy on sustainable investment in 2020 (EU, 2020). In 2015, the Financial Stability Board (FSB), at the request of the G20, launched an industry-led Task Force on Climate-related Financial Disclosures (TCFD) to address and develop consistent and coherent principles and guidelines for institutions to disclose their climate-related risks. The TCFD issued its final report in 2017, on recommendations to develop voluntary and consistent climate-related financial disclosures (TCFD, 2017).[2] The primary advice is for an institution to prioritize disclosure of climate risks and management, to improve transparency of financial markets, which will make more information available to investors and improve efficiency of these markets. Climate risk assessment and adoption of the TCFD recommendations pose a set of challenges related to conducting scenario analyses, risk management processes, and implementing governance procedures. Climate risks are complex, long-term in nature, and difficult to quantify, and they are seldom easy to align with traditional corporate planning and risk management. The TCFD recommendations highlight the need for conducting scenario-based assessments for climate related risks and incorporate these assessments into strategic decision-making processes. Scenarios are coherent narratives that describe plausible future outcomes and are used to identify and assess climate implications based on a range of assumptions regarding future GHG emissions, demography, and socio-economic development. The inclusion of high-warming and low-warming climate change scenarios allows for consideration of different levels of climate change impacts. One challenge is the lack of tailored expertise within companies who wish to follow the TCFD recommendations as well as for potential investors, lenders, insurance underwriters and other users of climate-related financial disclosures. Furthermore, the multitude of scenarios from scientific communities makes it difficult to select and analyze the most appropriate data for a specific context. Second, available scenarios are based on climate and economic models, so the output must be translated into meaningful and quantifiable terms in the specific context of an organization conducting a climate risk assessment. Thus, there is a disconnect between the macro-level information available in scenarios and the requirements for micro-level analysis.

Conducting a physical climate risk assessment is not trivial for a business, particularly when the assets cover a large geographic area with heterogeneous topography. Historical and scenario-based climate data, while openly available from platforms like the Copernicus Data Store (CDS, 2023), require specific skills for processing and analysis, have a coarse resolution and seldom allow for detailed spatial analysis. Furthermore, assessing physical risks at a granular level, considering the specific geographic locations of assets and operations, can be resource-intensive and may require detailed climate modeling and mapping with the associated computational resources, as well as capacity to evaluate model and scenario uncertainties. Few organizations possess the internal expertise, or the resources needed for investments in data analytics capabilities, and continuous monitoring and reporting.

[1] An asset is any resource owned by an economic entity that has economic value.

[2] We use institution, organization, and company interchangeably, where in our context the important feature is that these are public or private entities facing some type of climate risk.

To address the need for a systematic approach to manage physical climate risks and disclosure of respective implications, this paper presents a 'preparedness framework' that is designed to be a helpful 'checklist' for overcoming the challenges of conducting physical climate risk assessments at a general level for an individual organization. This framework helps businesses navigate the wide range of climate data available, bypassing the requirement for specialized internal expertise, rendering it useful for a wider range of public and private companies and institutions that are exposed to the physical consequences of climate change but do not necessarily possess the skills or resources to invest in such assessments, thus making them more attractive to potential investors. The preparedness framework is based on interviews with representatives from financial institutions and a review of studies on climate risk management (Torvanger et al., 2019), and is inspired by the TCFD recommendations. The framework aims to provide a tool for risk screening and management and emphasizes accessibility and usefulness for companies, institutions, and organizations.

We showcase the application of the preparedness framework in the context of railroads in Norway. This application also constitutes a test of the usefulness of the preparedness framework. We chose railroads in Norway due to their sensitivity to main climate risk factors such as flooding, heat stress and drought, and due to the varied conditions for railroads given topographical and meteorological differences. Some reports on climate risk for railroads have been produced and some processes are ongoing, predominately through the Norwegian Environmental Agency (Miljødirektoratet) (Norwegian Environmental Agency, 2020) and Norconsult (2020), and the collaboration within 'Naturfareforum' and the 'Klima2020′ process. The railroad network is capital-intensive infrastructure, involving extensive land management around the tracks. Many stakeholders are involved, as it employs thousands of people and transports many passengers and a large volume of goods. Following a broad assessment of climate scenarios and climate risks for railroads in Norway we focus on Bane NOR, the state-owned Norwegian company that is responsible for development and maintenance of railroad tracks across Norway. We interviewed representatives for Bane NOR and assessed the organization's climate risk management according to our framework. While every organization operates within different contexts, the preparedness framework is designed to be useful at a broad level across different sectors and countries.

On this background the aim of this study is to:

Improve the understanding of climate risk management for railroads in Norway and identify measures to augment preparedness.

The associated research questions are:

- What are the main physical climate impacts and risks facing railroads in Norway?
- How is Bane NOR handling climate risk?
- Given the preparedness framework introduced, what are suggestions for improved management of physical climate risks for Bane NOR?
- Is the preparedness framework a useful tool for management of climate risk for railroads?

In the next section we present the methodology, followed by an analysis of climate risks for railroads in Norway based on anticipated climate change impacts. Section 4 describes Bane NOR's management of climate risks, followed by an assessment of the organization's climate risk management, and suggestions for improved management. Section 5 presents concluding findings.

Methodology

The research questions and architecture of the study are depicted in Fig. 1. The methodology consists of six steps:

1. Introduce the preparedness framework and the embedded checklist
2. Assess climate change risks for railroads in Norway
3. Select climate change scenarios and associated indicators most relevant for railroads in Norway
4. Interview representatives from Bane NOR on management of physical climate risks
5. Use the climate change scenarios and the preparedness framework to assess Bane NOR's management of climate change and vulnerability
6. Identify areas of improvement for Bane NOR's climate risk management and test the usefulness of the preparedness framework.

The framework for improved climate risk preparedness for

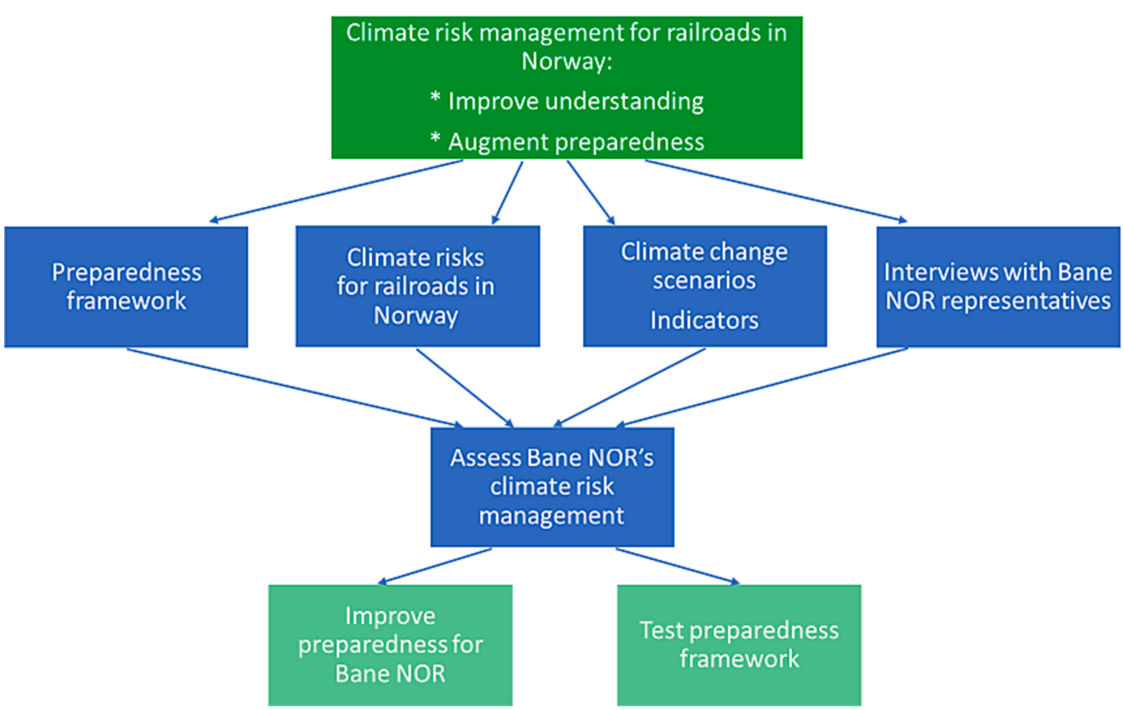

Fig. 1. Research questions and architecture of the study.

companies, institutions, and organizations presented has evolved over time. Initially it was based on interviews from 20 financial institutions, as documented in Torvanger et al. (2019). This report provides an overview of physical climate risk and transition risks for Scandinavia and presents findings from interviews among representatives from major institutions in the financial sectors in Norway and Sweden. The interviewees were asked about their views on climate risks, current management of climate risks in their institution, and suggested measures to improve management. The major challenges identified were lack of transparent and easily accessible information, lacking overview of expected climate change and impacts of relevance for an organization, insufficient standardization of data and tools, and the need for a more systematic management of climate risk.

Based on the interviews on climate risk and management in Torvanger et al. (2019), this article further develops the concept of 'climate risk preparedness' visualized through the preparedness framework, adding more items and measures from the climate risk management literature as well as generalizing the measures to fit a broader set of industries than the finance sector. The main categories partly overlap with the recommendations from the Task Force on Climate-related Financial Disclosures on information disclosure, but are not identical (TCFD, 2017). We test the usefulness of the preparedness framework and its checklist of measures for the case of railroads in Norway, to assess whether there are unused or underused measures Bane NOR could use to improve management of physical climate risk. The interviews with Bane NOR representatives are used to learn about the organization's climate risk management, before using the preparedness framework to assess this management. However, with the objective of only testing Bane NOR's climate risk management, the findings from these interviews are not used to update the preparedness framework. While the TCFD recommendations are aimed to facilitate disclosure of climate risk relevant information among financial institutions, to better inform investors and other stakeholders in the financial market, this preparedness framework takes a step further aiming at management of climate risks. This encompasses general strategies and actions in companies to better identify, report, and manage climate risks. On this background, our preparedness framework is divided into the categories 'Knowledge', 'Strategy', 'Management' and 'Tools and metrics'. Fig. 2 presents the framework on improved climate risk preparedness, including a checklist of measures under each of the four categories.

The preparedness framework provides a generalized structure for companies to check their progress towards preparing for physical risks related to climate change. The list of measures is not exhaustive but should be used as a guide to check the status of climate risk preparedness within a company and assess improvements over time. New and amended measures to improve preparedness can be categorized and fitted into this framework to a suitable level. The measures in the checklist have been developed to fit a general level that is less dependent on the specific country, sector, industry, and company context. Here, we test the framework for the management of railroads infrastructure. We expect that this framework is sufficiently general to be broadly applicable in other companies, sectors, and countries.

Railroads in Norway

Physical climate risk for railroads in Norway

Attention to climate risk has increased in Norway over the past few years. The government has been active in raising awareness on climate change and related risks. Physical climate risk is high on the agenda of the Norwegian financial sector, with heavy precipitation and flooding raising the most immediate concerns (Finance Norway, 2020). In their 2018 report, the Expert Commission on Climate Risk, appointed by the Norwegian government, stresses the need for further analysis on physical climate risk in Norway (Norges offentlige utredninger (NOU), 2018; Norwegian government, 2018). The commission discusses how climate risks can affect markets and cause instability, and the need for regulation by authorities to reduce these risks.

The climate in Norway is varied, stretching from the temperate south to the arctic north and from the Atlantic west to the humid continental climate in the center of the Fennoscandian Peninsula. Railroads in Norway present an interesting case study due to railroad infrastructure's wide geographic range, and its resulting exposure to climate change impacts across different climatic zones. This allows a detailed and quantified climate risk analysis at high geographical resolution, as railroads are facing various challenges related to climate change.[3] The physical impacts of climate change may cause more disruptions to railroad than road transportation since there are fewer alternative railroads than roads, making railroads more vulnerable. Bane NOR is a state-owned company that owns all railroads in Norway. The company builds and maintains railroad tracks across Norway, managing over 4,000 km of track. Even though Bane NOR may face some transition risks, e. g. those associated with a change in the price of power compared to other energy prices, these are deemed relatively small compared to physical risks. Increasing carbon taxes due to green transition and stricter climate policies will likely make railroad transportation more competitive compared to fossil-based transportation.

The Norwegian landscape is dominated by a high altitude, mountainous terrain with a very long coastline of more than 25 000 km, broken up by large fjords. Although Norway is well-connected through the railroad network, traffic is concentrated in more populated regions in Southern Norway, and where most lines are operated, as seen in Fig. 3. In 2018, more than 80 million passengers and almost 35 million tons of goods were transported by railroads in Norway (SSB, 2020).

The frequency and intensity of extreme weather events are expected to increase with climate change in all future scenarios in Norway, as will the likelihood of other long-lasting hazards such as sea level rise. Increased temperatures will bring hotter summers, as well as increasing risk of wildfires. Changing precipitation patterns are likely to increase the frequency and intensity of flash floods, landslides, and overflowed drainage systems in summers, as well as heavier snowstorms and avalanches in winter (Torvanger et al., 2019). The potential implications for the railroad network include buckling of tracks due to heat, cracking of the tracks' foundation, and reduction in the ability to support rail traffic (Chinowsky et al., 2019). According to the 2010 national assessment report on climate change adaptation, Norway is "less vulnerable and better equipped to meet climate change" than most other countries (Ministry of the Environment, 2010). Nevertheless, extreme events and long-lasting hazards are expected to create significant disruptions and delays in railroad transportation, and even in the scenarios with lower warming.

The four major hazards related to climate change are extreme precipitation leading to flooding, extreme heat and heat waves, drought, and sea-level rise. To determine the most relevant hazards for railroads in Norway, we must first assess exposure, based on the location of the tracks. Most of the railroad network is located inland (see Fig. 3), meaning that exposure to sea level rise is negligible. Therefore, the hazards most likely to impact the Norwegian railroad transportation are flooding, drought, and extreme heat.

Many indicators have been developed to measure the associated impacts of different hazards. These indicators are chosen rather arbitrarily in existing literature. One review paper identified over 170 indicators commonly used to assess heat related hazards (de Freitas and Grigorieva, 2017). A joint effort between the World Meteorological Organization Commission for Climatology (WMO CCl) and World

[3] The focus on railroads is also motivated by synergies with the study of railroads in the ClimINVEST project, which one of the authors participated in. This project examined how companies and institutions in European countries manage increased physical risks associated with climate change and is funded by EU's JPI program: https://www.cicero.oslo.no/en/climinvest.

Fig. 2. A framework and checklist of measures to improve climate risk preparedness.

Fig. 3. Railroads in Norway. Data obtained from Bane NOR (Bane NOR, 2023). The base map was developed by OpenStreetMap.

Climate Research Programme (WCRP) project on Climate Variability and Predictability (CLIVAR) established the Expert Team on Climate Change Detection and Indices (ETCCDI). One of the ETCCDI mandates was to develop a suite of climate change indices based on temperature and precipitation variables and coordinate international efforts to enable global analysis of extreme events. These efforts resulted in 27 ETCCDI indices defining global temperature and precipitation extremes (Alexander et al., 2006). Aiming to increase transferability of the preparedness framework in other sectors and geographical regions in Europe, our analysis of physical climate risks for railroads relies on user-friendly tools and metrics that are openly available and easily accessible for railroad operators. Thus, we employ the data available from the Climate Indicators Database on the ClimINVEST platform (van Eupen et al., 2023). The Climate Indicators Database provides a series of climate extremes indices, computed from high-resolution (EURO-CORDEX) climate data, using the ETCCDI definitions. The only ETCCDI indicator specific for drought is the Consecutive Dry Days (CDD) indicator. CDD refers to the maximum length of a dry spell, or the maximum number of consecutive days when daily precipitation is less than 1 mm. In this paper we use an indicator that mirrors CDD, namely Consecutive Wet Days (CWD) to assess the risk of flooding. However, several other indices are available in the Climate Indicators Database, which can be employed for further analysis. CWD refers to the maximum length of a wet spell, or the maximum number of consecutive days when daily precipitation is at least 1 mm. Finally, for extreme heat, we use the monthly maximum value of daily maximum temperature (TX_x).

Increased climate risks under a high emission scenario

To determine the possible extent of current and future climate hazards and their associated risks, multiple climate models are used to simulate different possible futures and their impacts on society, economy, and the environment. These models employ different scenarios of radiative forcing from increased concentration of GHGs in the atmosphere. The latest generation of global development scenarios focuses on uncertainty in future societal conditions and how this can be combined with climate change projections, economic growth, and population development assumptions. The Shared Socioeconomic Pathways (SSP) describe plausible alternative changes in demographic, economic, technological, social, governance and environmental aspects of societal development. They include qualitative descriptions or narratives of broad development trends as well as quantification of key variables (O'Neill et al., 2017). The Representative Concentration Pathways (RCP) are older scenarios used by the IPCC to describe different pathways of GHG emissions and atmospheric concentrations, and air pollution emissions and land use. The RCP have been combined with SSP. The combined scenarios include a stringent mitigation scenario (SSP1 – 2.6) leading to global warming of approximately 2 °C by the end of the century, three intermediate scenarios, and one scenario with high concentration levels (SSP5 – 8.5) leading to 4 – 5 °C warming by 2100

(IPCC, 2014). SSP include societal choices that will affect GHG emissions as well as different alternatives to meet the Paris Agreement's goal. Like RCP, SSP are based on five narratives which describe broad socioeconomic trends of the future, ranging from SSP1, which describes a future of sustainable growth and equality, to SSP5, which represents a fossil fueled development, in a world of rapid and unconstrained growth in economic output and energy use (IPCC, 2021). The high emission scenario (SSP5 − 8.5) is representative of a future with no climate mitigation policies and rapidly increasing emissions of carbon dioxide (CO_2) and other GHGs (van Vuuren et al., 2011).

We conduct a multi-hazard physical climate risk assessment and compare outcomes across two different scenarios, namely a low emission and a high emission scenario. The low emission scenario combines the radiative forcing of RCP2.6, which is the low emission scenario among the RCP corresponding to the below 2 °C goal, with SSP1, which is the sustainable growth narrative among the SSP. The high emission scenario combines the radiative forcing of RCP8.5, the high emission scenario, with SSP5, which is the fossil fuel development scenario. The inter-scenario analysis is performed using eighteen Coupled Model Intercomparison Project Phase 6 (CMIP6) models (O'Neill et al., 2016). We recognize that climate change impacts are expected to increase towards the end of the century, but it is outside the scope of this analysis to include long-term global warming, given that most railroad infrastructure has a shorter lifetime than this. Here, we focus on near- and mid-term changes in the next few decades, which means until 2040. In this section we explore potential outcomes of the high emission scenario for the three hazards: drought, flooding, and extreme heat.

Drought is defined as a period of abnormally dry weather that is long enough to cause hydrological imbalance. In the case of railroads, we assess the increased risk of drought. Thus, we are primarily interested in meteorological droughts, also defined as periods of abnormal precipitation deficit. The number of maximum consecutive days per year when daily precipitation is under 1 mm per day was selected for this analysis. Fig. 4 and Fig. 5 below show the multi-model mean of the indicator Consecutive Dry Days (CDD) under the high emission scenario. The data in Fig. 4 and Fig. 5 have been calculated as part of the ClimINVEST project. Fig. 4 shows values from 2020. The maximum number of CDD in Norway currently varies between less than or equal to 15 and less than or equal to 20 days, which is similar to most regions in Western and Central-Western Europe. Fig. 5 shows the difference between modelled CDD in 1990 and 2040 under the high emission scenario. As the data in Fig. 4 indicate, maximum CDD is projected to decrease by 2040 in southeast and most of Northern Norway. Only a half-day increase is projected in some other regions. This main result is that precipitation is expected to increase in Norway (Hanssen-Bauer et al., 2017). This leads us to conclude that drought and the related risk for wildfires in these modelling studies will remain at the same level as today, even under the high emission scenario.

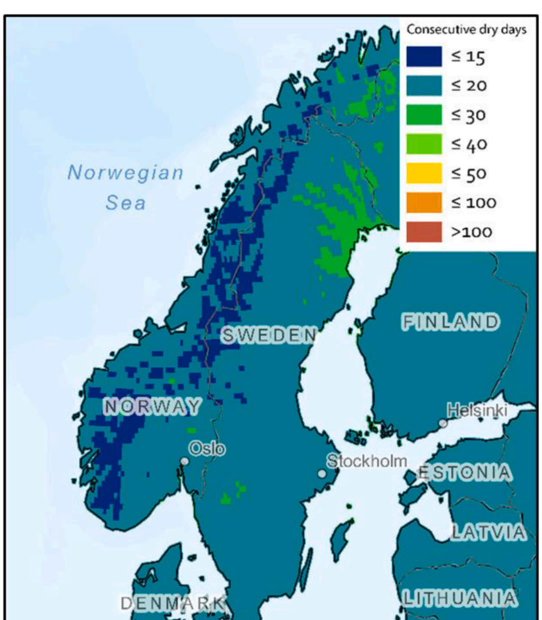

Fig. 4. Consecutive dry days 2020.

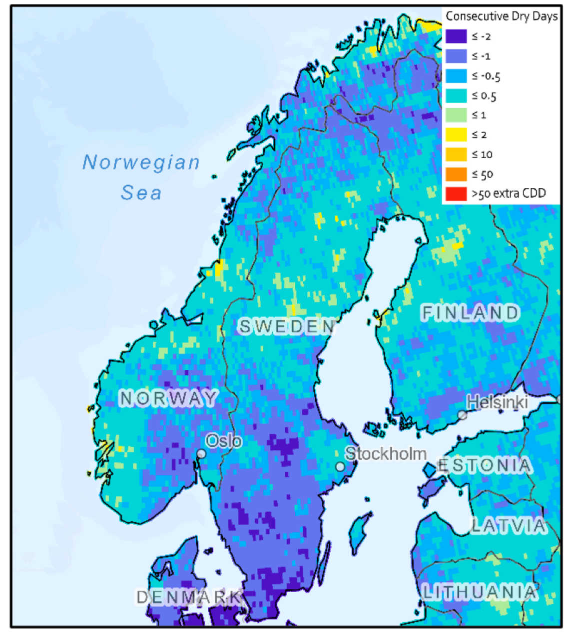

Fig. 5. Projected change in consecutive dry days 1990–2040 under the high emission scenario.

Flooding is defined as the overflowing of the normal confines of a stream or other bodies of water, or the accumulation of water over areas that are not normally submerged. Depending on how they are generated, floods can be *fluvial* (overflowing of water courses), *pluvial* (accumulation of water from rainfall), flash floods, urban floods (accumulation of water in urban settings), sewer floods (mostly referring to overflowing of sewage systems during intense rainfall), coastal floods, or glacial lake outburst floods (IPCC, 2014). The occurrence of floods depends heavily on local conditions and prediction typically requires hydrological modelling. Here, we focus on rainfall-generated floods as opposed to coastal flooding because, as seen in Fig. 3, most of the railroad tracks are located inland. The number of maximum consecutive days per year with intense rainfall is represented by the CWD indicator. Like CDD, CWD describes a specific event rather than a general trend. Increased CWD means that multi-day precipitation spells are getting longer. High CWD in low-lying areas may significantly increase the risk of flooding.

Fig. 6 and Fig. 7 below show the multi-model's mean of the indicator CWD under the high emission scenario. Fig. 6 shows values from 2020 with extreme precipitation along the coast of Norway. Fig. 7 shows increase in CWD from half-day and up to 2 days or longer in many regions in Norway. Moreover, while coastal flooding is not included in this indicator, it is fair to assume that any additional coastal flooding related to sea level rise would further increase the overall risk of flooding in coastal areas. This leads us to conclude that the risk of flooding from accumulated rainwater will be significant in multiple regions in Norway.

Extreme heat events, also referred to as heat waves, are defined as periods of abnormally hot weather. A heat wave is often defined as a period of at least three days with high maximum temperature. Several heat wave indicators have been computed and published on the Climate Indicators Database on the ClimINVEST platform. The risk of buckling railroads increases under extreme heat conditions. However, hot

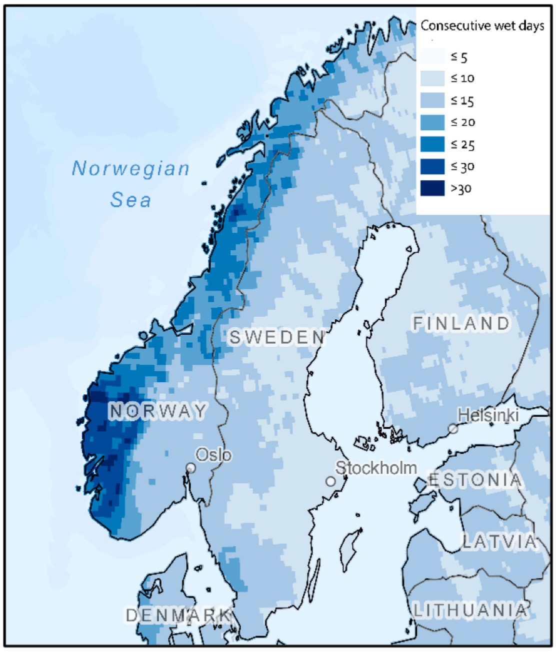

Fig. 6. Consecutive wet days (CWD) 2020.

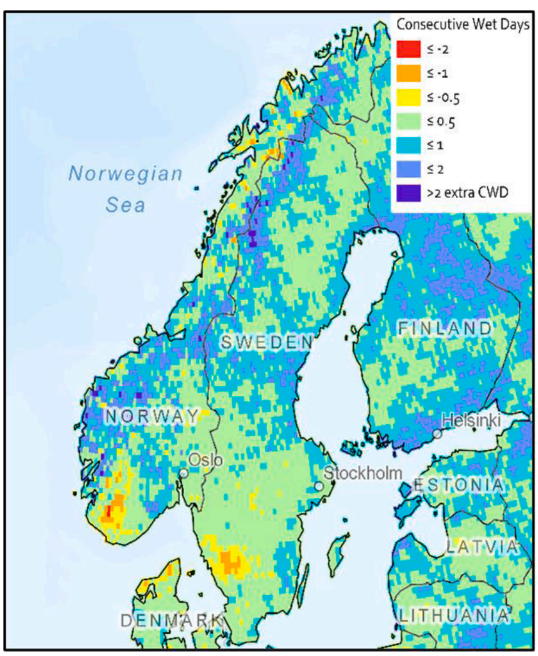

Fig. 7. Projected change in consecutive wet days 1990 – 2040 in the high emission scenario.

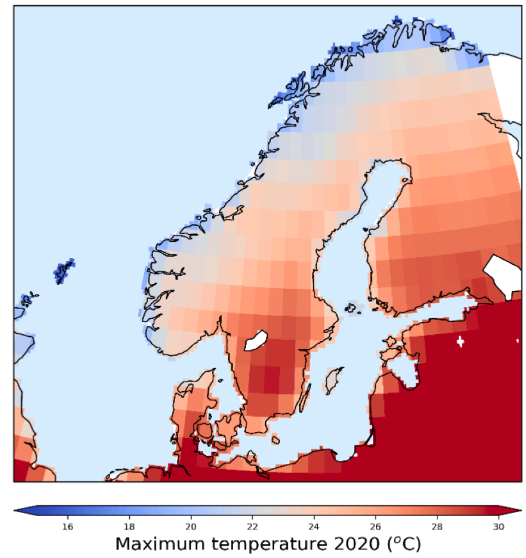

Fig. 8. Maximum temperatures 2020.

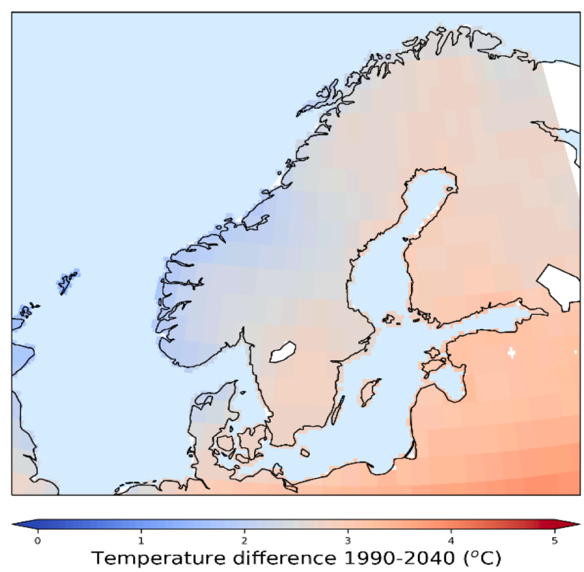

Fig. 9. Projected temperature change 1990 – 2040 in the high emission scenario.

conditions can also occur outside periods that are scientifically defined as heat waves. Therefore, we use the maximum temperature indicator to assess the risk of extreme heat. The daily maximum temperature is often used due to its simplicity, which shows the maximum temperature near the surface. Figs. 8 and 9 show the multi-model mean of the daily maximum temperature indicator. This indicator was calculated based on the average of eighteen CMIP6 models under SSP585 scenario, which combines RCP8.5 and SSP5. Fig. 8 shows high maximum temperatures between 24 °C and 26 °C across Norway and up to 28 °C in some regions in the south of the country. Comparing Fig. 3 with Fig. 8, we see that the regions with highest temperature are also those with highest concentration of railroads. Fig. 9 shows a temperature increase of 2–3 °C over the entire Fennoscandian Peninsula between 1990 and 2040, which could lead to temperatures of up to 30 °C in the south-eastern regions of Norway. The risk of railroad buckling due to heat is highly dependent on the temperature that the tracks have been stress-tested for.

The difference in temperature outcomes between a high emission, fossil-fuel development scenario, and a low emission, sustainable development scenario, provides an insight into the full range of expected temperature increases in Norway. Fig. 10 shows the difference in daily maximum temperature as a multi-model mean between the 2040 outcomes of the two scenarios in Scandinavia. TX_x was calculated based on the average of eighteen CMIP6 models under SSP585 scenario, which combines RCP8.5 and SSP5. The plot is shown at one-degree resolution. Values between 0.5 and 1 °C can be seen across Norway, and the inland areas exhibit the greatest temperature difference. Again, it is important to find what temperatures the tracks were stress-tested at to determine how exposed the tracks are to this physical climate risk. Railroad tracks are built to last around 45 years (Hofgaard, 2016), whereas higher

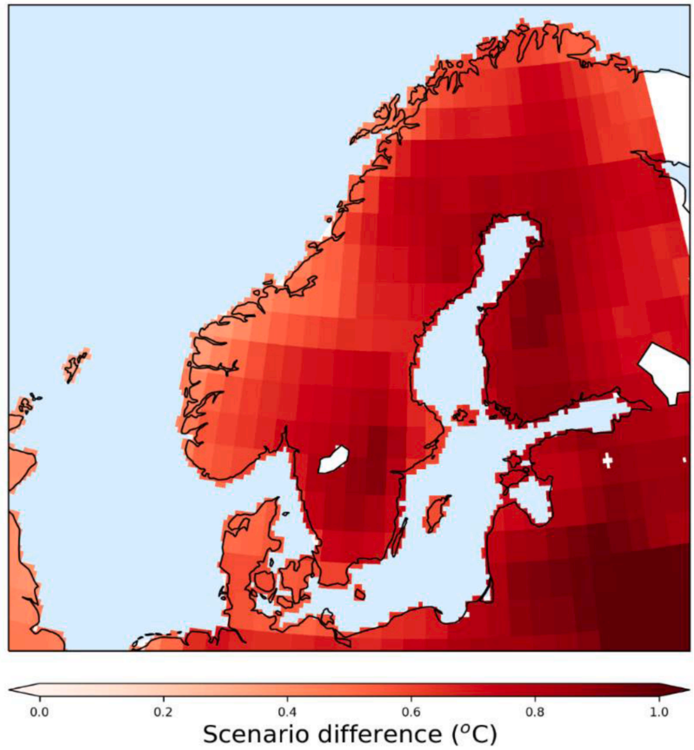

Fig. 10. Projected difference between the high emission and low emission scenarios in 2040.

temperature differences between the two scenarios are expected by the end of the century.

Discussion of multi-risk assessment and sources of climate vulnerability for Norwegian railroads

The risk analysis indicates that there is little risk of drought-related problems for railroads in Norway. However, railroads can expect to face an increased risk of flooding and impacts of heat waves, and railroads therefore need to prepare accordingly to reduce their vulnerability. We have identified important factors to consider when determining the extent of potential impacts to railroads due to climate-related vulnerabilities. This includes factors related to infrastructure, land characteristics around railroads, age and lifespan of railroads, the volume of traffic, and connectivity to other parts of the transport system, and the related ability to substitute trains for other transportation modes. Below, we discuss the main sources of sensitivity and potential solutions to increase adaptive capacity.

Regarding **infrastructure,** there are 4,087 km of railroad tracks across Norway, with 696 tunnels and 2,760 bridges. 64 % of the tracks are electrified with overhead wires, exposing them to environmental hazards, such as ice, storms, strong winds or heat stress. We have not received information about the temperatures that the tracks were stress-tested against in Norway. From similar cases in other countries (e. g. the UK) tracks are commonly stress-tested at 27 °C. As our analysis shows, maximum temperatures in Norway are likely to exceed 27 °C, for prolonged periods of time in high emission scenarios. Therefore, new tracks should be stress-tested for the heat levels expected in the future, as well as assessing if the tracks are designed to withstand extreme weather for long periods of time, considering that the frequency of railroad maintenance and replacement is low. Some railroad sections in low-lying areas and areas close to waterways and on aqueducts may not be elevated enough to avoid being submerged during flooding events. A more detailed analysis, using higher resolution climate data is needed to identify the specific areas that are highly exposed to flooding.

In high-risk areas, the **land characteristics** around the railroad are important to determine permeability and water absorption capacity. Forestry activities around railroads should be taken into consideration, as fewer trees increase the risk of landslides under heavy rainfall. Less tree cover also reduces vegetation interception and the permeability of the land, which will lead to a reduction in the lag time between peak rainfall and peak discharge, leading to more intense flooding.

Railroad infrastructure has a long lifespan, so decisions regarding tracks and the materials used for building new railroads are long-term and later refurbishments could be expensive. New tracks should therefore be built with consideration for future heat stress and flooding risks, while old tracks should be stress-tested against the most likely hazards in the exposed areas and refurbished if required.

The traffic volume is high, particularly in urban areas and between urban centers (Oslo-Bergen, Oslo-Trondheim) in the south of the country. About 70 % of the railroad traffic is located around the low-lying area of the Oslo Fjord. These are the areas with high exposure to heat stress and flooding. This increases the potential impact of the hazard, as more people and goods will be affected by the disruptions.

Connectivity is relevant in situations when disruptions occur, and it influences the scale of disruption. Delays and cancellations of services may have severe implications for transportation of goods and passengers. In the case of extreme events and disruption to the rail network, it is unclear whether buses or ferries can be made readily available to provide alternative transportation.

Bane NOR’s management of climate risk

Interviews with Bane NOR

Bane NOR manages construction and maintenance of railroad tracks across diverse landscapes in Norway. Our information on Bane NOR and its vulnerability against the relevant hazards is mainly based on interview and email communication with representatives from Bane NOR, autumn 2020.[4] The interview template consists of 14 questions, as seen in Text box 1.

Text box 1. Interview template for Bane NOR

a. Explain the mapping of locations and risk elements related to climate change.
b. Where are the major concerns regarding climate change impacts?
c. Does Bane NOR have sufficient data and tools?
d. What is Bane NOR's assessment of extreme rain events and flooding: flooding of tracks; earth, stone, and mud slides, etc.
e. What is Bane NOR's assessment of heat stress and buckling of tracks (in UK tracks must be able to handle up to 27 °C)?
f. What is Bane NOR's assessment of risks related to sea level rise?
g. Are there more issues of concern related to climate change impacts?
h. What precautions and actions to increase robustness and preparedness has Bane NOR taken?
i. Do you have sufficient diches and pipes capacity to funnel off heavy rainwater?
j. How do you handle the risk of buckling of railroads?
k. What warning and precautionary systems and routines do you have?
l. Have you increased the organization's capacity to handle climate change related risks?
m. How has climate change risks affected management and procedures within Bane NOR?
n. Where is the biggest room for improvements in terms of building resilience and risk management in Bane NOR?

Information from the interviews

In general terms, Bane NOR consider their risk management as sufficient. Preparedness towards climate risks and management of these risks are prioritized at Bane NOR (Bane NOR, 2020). Bane NOR has always handled various types of risks related to railroad infrastructure. In this sense physical impacts from climate change are not a new challenge, but such risks are expected to increase. Some planning frameworks are available, e. g. 'Plan- og bygningsloven'.[5] Bane NOR has comprehensive preparedness systems for monitoring and handling disruptions of operations, e. g. related to weather events, but has some challenges to integrate a broader climate risk perspective into its existing risk portfolio. There is good potential for further digitalization of preparedness systems, and for inclusion of climate-related elements.

Norway has an elaborate system for assessing rainfall and landslide risk that is operated by the Norwegian Water Resources and Energy Directorate (NVE).[6] Still, the representatives from Bane NOR express that Norway would benefit from coordinating climate risk mapping and cost-benefit studies across all affected sectors, instead of only mapping e. g. risk for railroads. One example is that extreme rain events can cause soil slides affecting railroads, but also impact roads, buildings, and agriculture. Thus, there will be overlapping effects and interdependencies between sectors. The company experiences challenges with coordination, since investments, maintenance, etc., in more sectors are ongoing simultaneously and involve different institutions, and there may be conflicting interests. Another challenge for Bane NOR is lack of resources, since new investments, e. g. to increase resilience towards landslides, must compete with lagging maintenance of railroads.

Flooding

Bane NOR has a major concern related to extreme rain events and flooding, namely erosion of the railroad embankment, and stone, soil or snow avalanches blocking the railroad. Not all traditional embankments for the rail tracks are designed for increased rainfall and potential associated landslides. Bane NOR has a comprehensive preparedness system for monitoring and handling disruptions of operations caused by flooding events and avalanches associated with extreme rainfall.

Heat stress and buckling of tracks

Railroads are sensitive to heat stress and buckled tracks can derail trains (Chinowsky et al., 2019). Steel tracks are designed to operate in a range that is based on the temperature in which they are originally laid, known as the 'design neutral temperature', and have been tested only for forecasted weather trends. The risk of buckling of train tracks is included in Bane NOR's attention list and the company undertakes precautionary measures such as extensive monitoring and measurements of track quality as well as including such activities in routine maintenance of railroads. High emission scenarios are often used for climate impacts and risk assessments against multiple hazards.

Drought

Bane NOR has some sensitivity to drought due to slower infiltration of water in embankment masses and soil if drought is followed by an extreme precipitation event. In addition, drought periods increase the risk of wildfires, but this risk is low if vegetation along the tracks is well maintained. Brush maintenance is routine for Bane NOR and is low cost.

Adaptive capacity

Among the three hazards examined, Bane NOR's exposure to flooding is highest. The company has learned from previous flooding incidences and undertakes precautionary actions, by closely monitoring weather forecasts and implementing measures such as lowering the speed limit for trains. In addition, Bane NOR has contingency plans if flooding should occur. These include bus transport made available to provide alternative transportation when tracks are submerged or otherwise blocked. New lines are built in compliance with the 'Planning and Building Act' ('Plan- og bygningsloven') in Norway, and regulation sets standards for flooding considerations. For existing lines, cost-benefit analyses are conducted for measures related to flooding risk, using 200-year floods for stress-testing.

Assessment of Bane NOR's climate risk preparedness

Railroads in Norway are facing specific challenges associated with climate change that must be addressed, dependent on the climate change scenario and time horizon. We assess Bane NOR's robustness to hazards and its adaptive capacity against flooding, heat waves, and drought. To assess Bane NOR's adaptive capacity, we consider factors such as mitigation of risks, existence of contingency plans, and maintenance of railroads.

The risk of flooding will be significant in multiple regions in Norway under a high emission scenario. Bane NOR already addresses these risks through strategies and adaptation mechanisms. The Norwegian Environmental Agency has provided guidelines for planning and construction of railroads (and roads), recommending that the design should be based on a 40 % increase in intense rain events lasting less than three hours (Norwegian Environmental Agency, 2020). The most important measures to handle the risk of extreme rain events and flooding are preserving the natural drainage paths, prioritizing open drainage (avoiding drainpipes if possible), and including flooding calculations when planning dimensions of trenches and bridges. For the most important infrastructure, the recommendation is to add 40 % more water volume to 200 years flooding events due to climate change. In addition, railroad managers should assess safe paths for flood water and planning should encompass the full watershed (i. e. the area of land that

[4] The views expressed may therefore not be representative for Bane NOR. The authors are alone responsible for the interpretation of the information received from Bane NOR, and therefore also for the text formulations in this section.

[5] 'Plan og bygningsloven' (The Planning and Building Act) is an act for planning, building and land-use in Norway, intended to coordinate the responsibilities and tasks of government, regions and municipalities, where different interests are balanced.

[6] NVE collaborates with Jernbanedirektoratet (Norwegian Railway Directorate), Statens Vegvesen (Norwegian Public Roads Administration), Meteorologisk Institutt (Norwegian Meteorological Institute), Norges Geotekniske Institutt (NGI) (Norwegian Geotechnical Institute) and Norges Geologiske Undersøkelser (NGU) (Geological Survey of Norway).

drains water into a specific water body).

Our analysis reveals that heat stress increases the risk of buckling of railroads. Bane NOR, however, considers the risk of erosion of the track bed or blocking of railroads associated with heavy rainfall and flooding events as more important than track buckling. Bane NOR has not considered heat stress testing of the tracks for high emission scenarios and is less concerned about the risk of increasing temperatures, leading us to conclude that Bane NOR has a low preparedness for railroad buckling events. Even though heatwaves can cause operational problems the company considers that few technical measures are available to directly reduce vulnerability to railroad buckling, except reduced speed of trains in periods with increased buckling risk. The best preparedness option is to implement efficient monitoring and maintenance systems and sufficient plans for handling the problems when they arise. In our risk assessment, we find that there is some exposure and sensitivity of railroads to stress during heat waves, which calls for a more detailed analysis in the most exposed areas. Bane NOR, however, is not responsible for air conditioning inside train cars in case of high temperatures, since this responsibility falls upon the train owner Norske tog AS, and train operators such as Vy and Flytoget.

We find that Bane NOR is prepared for other climate related hazards, such as snowstorms and ice on tracks. The company hires winter preparedness surge capacity staff in mid-November to run ploughs and snow clearing equipment, clear ice build-up on tracks, maintain point heating and snow brushes to reduce ice build-up, steam ditches and culverts, and install and check embankment structures intended to resist several meters of snow.

Sea level rise is a fourth challenge, but we consider this as a small problem in central-east Norway due to continued land level rise, which started after the end of the last ice age. The risk of sea level rise will be higher in Western Norway, but there are few stretches of railroad in this region.

We have also highlighted some shortcomings in the adaptive capacity of Bane NOR. One of the challenges for Bane NOR is that resources are limited, so strict priorities are needed for allocating the budget across investments in improved adaptive capacity on some railroad stretches, maintenance, and reduced vulnerability to operational problems caused by heavy rainfall damaging the track embankment, and avalanches and flooding blocking the railroad.

Assessment of Bane NOR's climate risk management according to the categories of the preparedness framework

Combining the identified climate risks associated with physical impacts with the checklist provided by the climate risk preparedness framework can identify possible strategies and measures that could assist Bane NOR in improving handling of climate risks. On this background we examine the railroad case for each of the preparedness framework categories: knowledge, strategy, management, and tools and metrics.

Knowledge

Even though the fields of weather and climate science are making significant advances, predictions for extreme rain, flooding events, and heatwaves remain uncertain, and particularly in terms of local consequences for railroads and track embankments. Scenarios provide a useful tool for comparing different possible future outcomes and assessing the implications of these trajectories in the near- as well as long-term future. Our assessment reveals that heat stress can lead to buckling of railroad tracks, particularly in the high-emission scenario. Bane NOR has mostly focused on the risk of flooding, this being deemed the most important and visible physical climate risk in Norway. With new knowledge from this risk screening Bane NOR can calculate the temperature tolerance level for its railroads and do a stress-test on how the probability for track buckling increases in different regions dependent on the climate scenario.

Strategy

Bane NOR is aware of its climate risks and has access to data and tools from e. g. the Norwegian Water Resources and Energy Directorate (NVE), but improving resilience is challenging due to uncertainties related to timing, events, and localization of climate change related impacts. Some disclosure of Bane NOR's strategy to handle climate risks is found at its website, but only at a general level. Precautionary actions and investments require resources to increase resilience to impacts from flooding and rain events that could trigger damage to track embankments and avalanches blocking tracks. There is a budgetary issue here, however, since a large backlog on maintenance of railroad tracks exists. Bane NOR already has in place monitoring systems for buckling tracks and buses that can replace trains in case of flooding. Since Bane NOR considers climate risk as only one amongst other risks, the company has made few organizational or personnel changes. Building awareness about the risk of impacts, especially due to heat waves, can improve contingency plans. It is important for Bane NOR to strengthen its capacity to handle climate risk within the company as well as developing robust strategies accounting for uncertainties associated with climate change impacts.

Management

Railroads are always exposed to weather-related risks. Bane NOR considers that climate risks are similar to risks related to weather and flooding events that cause operational problems for railroads. Bane NOR has a warning system that operates continuously, including contingency plans for repairs and alternative transportation modes if the problem requires more than minimal time to correct. Climate change will likely increase the frequency and magnitude of problems but does not require new responses and management. Thus, climate risks will be systematically handled together with other risks. For these reasons Bane NOR has made a few changes in its organization or operations to improve the management of climate risks. Bane NOR could, however, benefit from more scenario-based stress-testing of the organization and procedures and improve its capacity to handle climate change related operational problems, especially regarding the risk of buckling tracks. The company provides limited specific reporting of climate risks and management of these. For this reason and due to uncertainties associated with impacts of climate change, an assessment of Bane NOR's performance regarding climate risk management is not straightforward.

Tools and metrics

NVE provides good tools, such as the webpage 'https://www.varsom.no', showing projections on risks related to rainfall, flooding, snow, avalanches, wind conditions and wildfires, whereas more comprehensive and detailed mapping of risks is expensive. Bane NOR considers that availability of climate scenarios and risk elements is sufficient, where the data from NVE is an important resource. However, methods and tools to compare costs and benefits of different actions and investments could be improved. More economic research, analyses, methods, and tools to perform cost-benefit analyses with explicit treatment of risks are needed to inform prioritization between different projects and investments. New analytical methods and tools may be needed, e. g. to evaluate climate risks for the track embankment for railroads. Stress-testing of railroad operations based on climate change scenarios and associated physical impacts in different regions in Norway, as conducted in this paper, is a useful approach to identify risks that might have been understated in the past. We encourage Bane NOR to complement the stress-testing with explicit emphasis on the uncertainties.

Conclusions

In this paper, we have combined an analysis of climate-related hazards with the exposure of railroads in Norway and vulnerability assessment of railroads in Norway as a case. Reducing vulnerability to climate change impacts reduces the overall climate risk for railroads. The preparedness framework we have introduced in this paper contributes to a comprehensive assessment of the management of physical climate risks for railroads in Norway. This framework and its associated checklist helped identify strategies and actions that can reduce vulnerability. The differing perspectives from climate science compared to a company responsible for an operational railroad infrastructure illustrate the importance of utilizing science that is available to and useful for the users. The priority list of climate risks can and should be amended by users as more aspects and detailed knowledge of the affected institutions and operations are layered on top of the more general scientific assessment of physical impacts and risk management. The preparedness framework is expected to be sufficiently general to be relevant for other sectors and companies than Bane NOR, as well as for other countries.

In terms of future research, more detailed and less uncertainty-prone data on climate change impacts for each specific institution/company will improve the prospect of good climate risk management. Reducing vulnerability and building resilience to handle climate risk requires a thorough understanding of the activity and operations of an institution/company, as well as comprehensive knowledge of the organization and its operational processes. Therefore, further research on the most promising approaches to combine the three individual elements of climate change scenarios, frameworks for building capacity and robustness, and the specific context of an institution, company, or sector in terms of business area, activities, and geography, is called for.

CRediT authorship contribution statement

Asbjørn Torvanger: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Project administration, Funding acquisition. **Charlotte Dyvik Henke:** Writing – original draft, Writing – review & editing, Visualization, Supervision. **Iulia Marginean:** Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

Alexander, L.V., Zhang, X., Peterson, T.C., Caesar, J., Gleason, B., Klein Tank, A.M.G., Haylock, M., Collins, D., Trewin, B., Rahimzadeh, F., Tagipour, A., Rupa Kumar, K., Revadekar, J., Griffiths, G., Vincent, L., Stephenson, D.B., Burn, J., Aguilar, E., Brunet, M., Taylor, M., New, M., Zhai, P., Rusticucci, M., Vazquez-Aguirre, J.L., 2006. Global observed changes in daily climate extremes of temperature and precipitation. J. Geophys. Res. Atmos. 111 (D5). https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2005JD006290.

Bane NOR, 2020. Klimatilpasning. https://www.banenor.no/Om-oss/Miljo/Klimatilpasning/.

Bane NOR, 2023. Banekart. https://banekart.banenor.no/kart/.

Cepni, O., Demirer, R., Rognone, L., 2022. Hedging climate risks with green assets. Econ. Lett. 212. https://www.sciencedirect.com/science/article/abs/pii/S0165176522000222?casa_token=edPnotWI1KkAAAAA:CHYyWatKPguURZeT4FiDrqqQE8xeEd7Qj0TR4Mlo5X_97trq5MwAsMNohPxiv10MfDZMYmX38w.

Chinowsky, P., Helman, J., Gulatic, S., Neumann, J., Martinich, J., 2019. Impacts of climate change on operation of the US rail network. Transp. Policy 75, 183–191. https://doi.org/10.1016/j.tranpol.2017.05.007.

de Freitas, C.R., Grigorieva, E.A., 2017. A comparison and appraisal of a comprehensive range of human thermal climate indices. Int. J. Biometeorol. 61, 487–512. https://pubmed.ncbi.nlm.nih.gov/27568190/.

EIU, Economist Intelligence Unit, 2015. The cost of inaction: Recognising the value at risk from climate change. https://impact.economist.com/sustainability/net-zero-and-energy/the-cost-of-inaction.

EU, 2019. European Commission. Retrieved from The European Commission. Technical Expert Group on Sustainable Finance (TEG). https://ec.europa.eu/info/publications/sustainable-finance-technical-expert-group_en.

EU, 2020. Technical report. Taxonomy: Final report of the Technical Expert Group on Sustainable Finance. https://ec.europa.eu/info/sites/default/files/business_economy_euro/banking_and_finance/documents/200309-sustainable-finance-teg-final-report-taxonomy_en.pdf.

FAO, 2023. FAO Action Plan 2022–2025 for the implementation of the FAO Strategy on Climate Change. https://www.fao.org/3/cc7014en/cc7014en.pdf.

Finance Norway, 2020. Klimarisikorapportering – En veiledning for å komme i gang. https://www.finansnorge.no/siteassets/tema/barekraft/klimarisiko/klimarisikorapportering–en-veiledning.pdf.

Hanssen-Bauer, I., Førland, F.J., Haddeland, I., Hisdal, H., Mayer, S., Nesje, A., Nilsen, J. E.Ø., Sandven, S., Sandø, A.B., Sorteberg, A., Ådlandsvik, B., 2017. Climate in Norway 2100 – a knowledge base for climate adaptation. NCCS Rep. 1. https://www.miljodirektoratet.no/globalassets/publikasjoner/M741/M741.pdf.

Hofgaard, Ø.H., 2016. LCC for ballastert jernbanespor: https://ntnuopen.ntnu.no/ntnu-xmlui/bitstream/handle/11250/2409916/14066_FULLTEXT.pdf?sequence=1&isAllowed=y.

IPCC, 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland.

IPCC, 2021. Climate Change 2021 - The Physical Science Basis, Working Group I contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Chapter 1. https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report.pdf.

IPCC, 2022. Climate Change, 2022. WG 3. Mitigation of climate change, Summary for policymakers https://report.ipcc.ch/ar6wg3/pdf/IPCC_AR6_WGIII_SummaryForPolicymakers.pdf.

Kaya, Y., Yamaguchi, M., Geden, O., 2019. Towards net zero CO_2 emissions without relying on massive carbon dioxide removal. Sustain. Sci. 14, 1739–1743. https://link.springer.com/article/10.1007/s11625-019-00680-1.

Ministry of the Environment, 2010. Adapting to a changing climate - Norway's vulnerability and the need to adapt to the impacts of climate change. Official Norwegian Reports NOU, No. 10. https://projects.eionet.europa.eu/2018-eea-report-national-cciv-assessments/library/national-documents/norway/nou201020100010000en_pdfs/download/en/1/nou201020100010000en_pdfs.pdf?action=view.

Norconsult, 2020. Jernbanens fortrinn og Norges klimarisiko: "Bedre klima for pengene". https://www.jernbanedirektoratet.no/contentassets/c44764b9127d4949ac6fe379ef7d75e4/rapport–jernbanens-klimafortrinn.pdf.

Norwegian government, 2018. Key takeaways - Climate risk and the Norwegian economy. NOU, No. 17. https://www.regjeringen.no/en/dokumenter/nou-2018-17/id2622043/?ch=1.

Norges offentlige utredninger (NOU), 2018. Klimarisiko og norsk økonomi. No. 17. https://www.regjeringen.no/contentassets/c5119502a03145278c33b72d9060fbc9/no/pdfs/nou201820180017000dddpdfs.pdf.

Norwegian Environmental Agency (Miljødirektoratet), 2020. Klimatilpasning i infrastruktur og samferdselssektoren. https://www.miljodirektoratet.no/myndigheter/klimaarbeid/klimatilpasning/klimatilpasning-i-sektorer/infrastruktur-og-samferdsel/.

O'Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., van Ruijven, B.J., van Vuuren, D.P., Birkmann, J., Kok, K., Levy, M., Solecki, W., 2017. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Glob. Environ. Chang. 42, 169–180.

O'Neill, B.C., Tebaldi, C., van Vuuren, D.P., Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., Lamarque, J.-F., Lowe, J., Meehl, G.A., Moss, R., Riahi, K., Sanderson, B.M., 2016. The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. Geoscientific Model Development 9, 3461–3482. https://gmd.copernicus.org/articles/9/3461/2016/gmd-9-3461-2016.pdf.

O'Neill, B., van Aalst, M., Zaiton Ibrahim, Z., Berrang Ford, L., S. Bhadwal, Buhaug, H., Diaz, D., Frieler, K., Garschagen, M., Magnan, A., Midgley, G., Mirzabaev, A., Thomas, A., and Warren, R., 2022. Key Risks Across Sectors and Regions. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, Roberts, D.C., Tignor, M., Poloczanska, E.S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., Okem, A., Rama, B. (eds.)]. AR6 WGII Chapter 16. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 2411–2538. https://doi.org/10.1017/9781009325844.025.

Statistics Norway (SSB), 2020. Flere reiste med tog. https://www.ssb.no/transport-og-reiseliv/artikler-og-publikasjoner/flere-reiste-med-tog-i-2019.

Copernicus Data Store (CDS), 2023. https://cds.climate.copernicus.eu/#!/home (Assessed 7 September 2023).
TCFD, 2017. Recommendations of Task Force of Climate-related Financial Disclosures – review of local relevance – European Union. https://www.tcfdhub.org/home/recommendations.
Torvanger, A., Alnes, K., Berg, A., Marginean, I., 2019. Climate science for the financial sector: Managing climate risk in Norway and Sweden, Report No. 15, CICERO, Oslo. https://pub.cicero.oslo.no/cicero-xmlui/handle/11250/2625592.
United Nations (UN), 2015. The Paris Agreement. https://unfccc.int/sites/default/files/english_paris_agreement.pdf.
van Eupen, M., Sandstad, M., Johansen, A.N., Schwingshackl, C., Sillmann, J., Gallo, F., Lepousez, V., Clapp, C., Hubert, R., de Bruin, K., Cardona, M, van Veldhoven, F., Marginean, I., Daloz, A.S., Dahl, M.S., Dejonckheere, S., 2023. Screening for climate risk: the ClimINVEST online climate indicators platform. Physical climate risk and finance: Insights from climate experts and investors to inform clima te risk management. https://www.arcgis.com/apps/MapSeries/index.html?appid=24aa80957be242a794114cd4c9054518.
van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J.F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S.J., Rose, S.K., 2011. The representative concentration pathways: an overview. Clim. Change 109, 5–31. https://doi.org/10.1007/s10584-011-0148-z.