RISK2050

A STUDY ON THE VULNERABILITY OF THE NATIONAL ECONOMY IN THE FACE OF PHYSICAL RISKS.

THIS STUDY WAS COMMISSIONED BY LUXEMBOURG STRATEGY, THE STRATEGIC FORESIGHT DIRECTORATE OF THE MINISTRY OF THE ECONOMY, LUXEMBOURG IN 2022.

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The RISK2050 study was commissioned in 2022 by Luxembourg Strategy, the strategic foresight directorate of the ministry of the Economy, Luxembourg, and conducted by the University of Luxembourg in 2022-2023. The content and findings of the study are those of its authors and do not necessarily reflect the opinion of Luxembourg Strategy, the ministry of the Economy or the Government of Luxembourg.

Final report submitted in November 2023.

Acknowledgements: We would like to express our sincere gratitude to all those who have contributed to the completion of this report. Special appreciation goes to the stakeholders who devoted their time and wholeheartedly participated in workshops, interviews and the survey.

How to cite this report: Zlatanova, K. et al. (2024) RISK2050: study on the vulnerability of the national economy in the face of physical risks. University of Luxembourg, commissioned by Luxembourg Strategy, the strategic foresight directorate of the ministry of the Economy, Luxembourg.

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List of abbreviations

C3S	–	Copernicus Climate Change Service
CBD	–	Convention on Biological Diversity
CDP	–	Carbon Disclosure Project
CSRD	–	Corporate Sustainability Reporting Directive
DATer	–	Département de l'aménagement du territoire
DNB	–	Dutch Central Bank
ECB	–	European Central Bank
EEA	–	European Environment Agency
EIB	–	European Investment Bank
EIOPA	–	European Insurance and Occupational Pensions Authority
ESPON	–	European Observation Network for Territorial Development and Cohesion
GDP	–	Gross Domestic Product
GHG	–	greenhouse gasses
IEA	–	International Energy Agency
IPBES	–	Intergovernmental Panel on Biodiversity and Ecosystem Services
IPCC	–	Intergovernmental Panel on Climate Change
MECDD	–	Ministère de l'Environnement, du Climat et du Développement durable (Ministry of the Environment, Climate and Sustainable Development)
MEAT	–	Ministère de l'Énergie et de l'Aménagement du territoire (Ministry of Energy and Spatial Planning)
NACE	–	Nomenclature of Economic Activities
NECP	–	National Energy and Climate Plan
NGFS	–	Network for Greening the Financial System
OECD	–	Organisation for Economic Co-operation and Development
PDAT	–	Programme directeur d'aménagement du territoire (Master Program for Territorial Planning)
PBL	–	Netherlands Environmental Assessment Agency
RCP	–	Representative concentration pathway
SME	–	Small and medium enterprises
STATEC	–	Institut national de la statistique et des études économiques du Grand-Duché de Luxembourg
UN	–	United Nations
UNDRR	–	United Nations Office for Disaster Risk Reduction
UNEP	–	United Nations Environment Programme
GW	–	Gigawatt
UL	–	University of Luxembourg

Executive Summary

The RISK2050 study is an effort to better understand the vulnerability of Luxembourg's economy to physical environmental risks. It was commissioned by Luxembourg Strategy in 2022 and was undertaken by an interdisciplinary consortium of researchers at the University of Luxembourg.

Economic productivity is exposed to environmental threats caused by overshooting ecosystem limits and the resulting climate change, resource scarcity and biodiversity loss. This report explores the impact of these hazards on six economic sectors in Luxembourg: four productive – Industrial Manufacturing, Construction, Forestry and Food processing; and two supportive – Energy and Logistics.

Aggregated findings from scientific publications have served as a basis for developing a risk matrix consisting of 23 hazard indicators (8 for climate change and biodiversity loss each, and 7 for resource scarcity). The probability and severity of these threats and their economic impact in Luxembourg by the year 2050 have been estimated.

Afterwards, empirical data on how local stakeholders representing the six economic sectors perceive the evolution of these threats by 2050 was collected and compared with the projected estimates. Observations were collected through workshops, interviews and an online survey, where 80 participants took part across all methods. This comparative process allowed to reveal perception gaps – inconsistencies between the perceived and projected risk, visualised in the Risk Matrix (Figure 0.1).

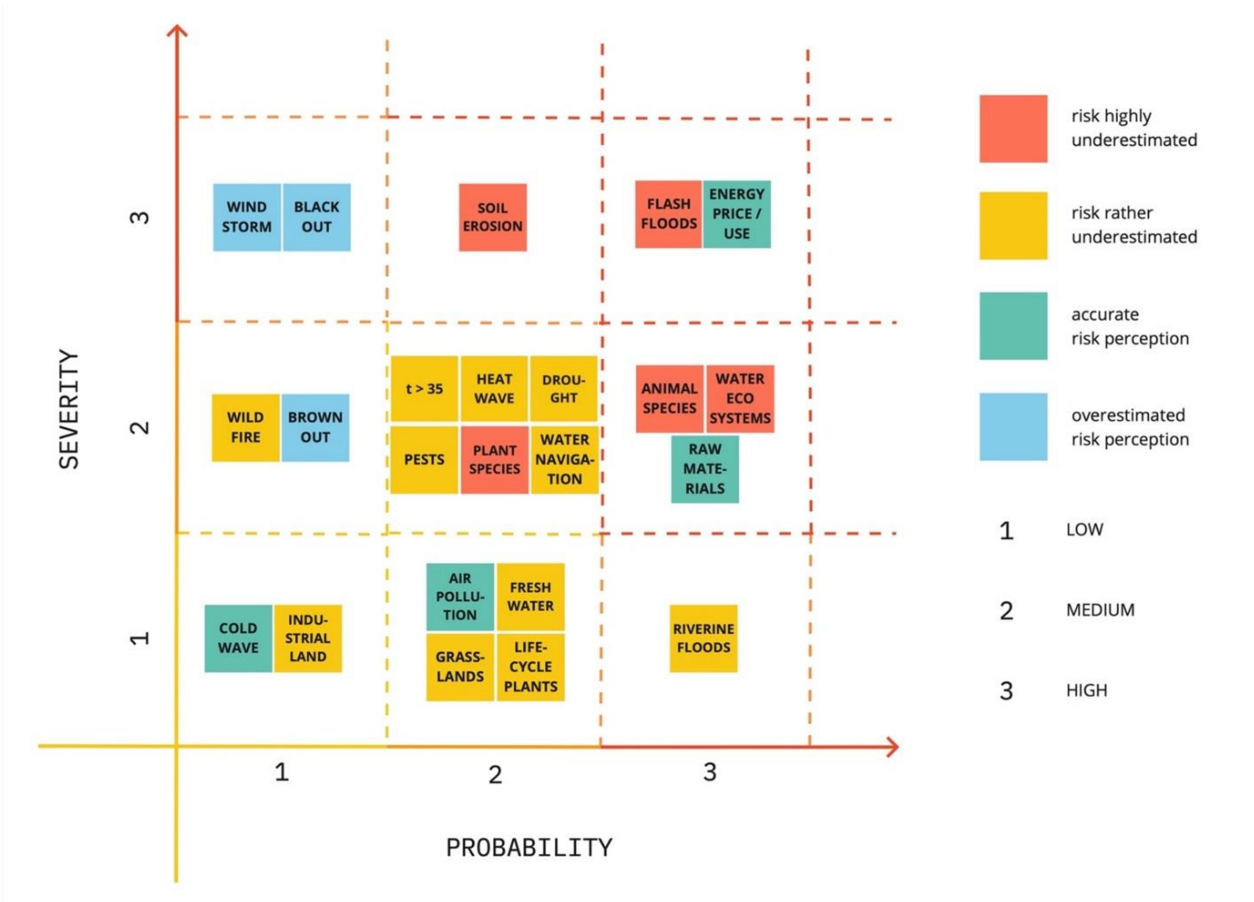

Figure 0.1. Risk matrix showing the gap between projected and perceived risk levels.

In summary, the majority of respondents have ranked resource scarcity as the threat posing the highest risk. More specifically, simultaneously increasing prices and demand for electricity reflect the highest concerns, followed by the scarcity of raw materials. In both regards, the risk is intensified by the ongoing "green" transition and requirements for implementing green energy and recycled materials. Respondents share a concern that the requirements come ahead of the actual availability of these resources. Our literature analysis has revealed that the energy transition will indeed put pressure on the demand for specific raw materials (classified as *critical* by the EU), but the prices of these technologies show a declining trend which should make them more accessible in the near future. The economic sector most exposed to these risks is Industrial Manufacturing, whereas the Energy sector perceives this as a market opportunity.

Climate change threats are perceived, on average, as posing medium-scale risks. It is worth mentioning that we encountered instances of climate scepticism among participants which starkly contrasts with the projections by the international scientific community predicting severe climate changes with increasing confidence every year. Nevertheless, the majority of participants demonstrate awareness that the risks of climate change, even if not highly impactful yet, are expected to increase in impact by the year 2050. Local stakeholders are mostly concerned by extreme wind events and extremely high temperatures. Even though there has been an observed trend for declining wind speeds in Europe over the last decades, there is some probability that warming temperatures might cause more cyclonic wind events in the future. Nevertheless, this threat is slightly overestimated by participants, compared to projections. Some of the economic sectors (Industrial Manufacturing, Logistics, Food Processing) expect more indirect impacts by the increasingly warming temperatures, such as higher electricity consumption for indoor cooling. Whereas other sectors (such as Forestry, Construction and the production aspect of Food Processing), expect more direct effects on crops, trees, and people working outdoors. The discussion on physical risks from climate change was often mixed up with a discussion on transition risks from climate change (changing regulations, taxes, policies, and consumer demands, beyond the scope of this study), which reflects a need for clarifying the difference between the two in public discourses.

The results from the risk analysis show that biodiversity loss-related indicators are predominantly underestimated by stakeholders in Luxembourg, except for representatives of the Forestry and Food sector. Indicators reflecting ecosystem degradation, such as the decline in pollination, soil erosion and pest outbreaks, are often not even perceived as low-risk threats, but as "irrelevant" altogether. This is alarming because it suggests a lack of awareness that biological diversity is a prerequisite for well-functioning ecosystem services which support directly or indirectly all economic activities. In the list of recommendations, we advise companies to perform self-assessment checks which can help them to better understand the links between nature and the economy.

The discrepancy between differently perceived groups of threats, such as climate change-related hazards perceived as higher risk than biodiversity-related ones, for example, suggests a tendency to overlook the connection between the two. In reality, diverse vegetation in mixed-use spaces and thriving wetland ecosystems can mitigate the risks from floods, for example.

After identifying the most relevant risks for Luxembourg and estimating their perceived levels, this report provides a series of recommendations on how companies, industry representatives and policymakers can adapt to and mitigate these risks. These recommendations are divided into four groups of action steps - technical, operational, and behavioural, governance-related, as well as territorial and nature-based.

Chapter 1. Introduction

In August 2022, the ministry of the Economy in Luxembourg commissioned the University of Luxembourg to conduct a study (RISK2050 Study) focusing on the exposure and vulnerability of selected economic sectors in Luxembourg to physical threats arising from climate change, biodiversity loss, and resource scarcity. The primary goal of the study was to assess the extent to which Luxembourg's industries are exposed to risks resulting from these threats. The context for this study arises from the need for both theoretical and empirical knowledge to support strategic foresight in transforming Luxembourg's economy. This transformation is driven by factors such as reaching biophysical limits, diminishing returns on investments, and livelihoods at risk. The study built upon existing scenarios and projections on a global, European or national scale to assess the threats.

Emissions of greenhouse gases (GHG) stemming from human activity are causing unprecedented changes in the climate on the planet. Scientists warn that temperatures globally will continue to increase in the near term (by 2040) in any socio-economic scenario, mainly due to accumulated emissions (IPCC, 2023). However, every additional increment of a degree of warming will intensify multiple and simultaneous climate-related hazards. Some of the associated impacts from these hazards globally are an increase in heat-related mortality, biodiversity loss in land, freshwater and ocean ecosystems, and a decrease in food production and water availability, among others. The projected increase in frequency and intensity of heavy precipitation will increase rain-generated local flooding and landslides, and will potentially lead to severe consequences for people, infrastructure, and economies. Our effort has been to discern the threats specific to the geographical location of Luxembourg and to explore the potential impacts of them.

The planetary supplies of minerals, metals, fossil resources, and land, fundamental to our economies today, are limited and non-replenishable. On the other hand, natural resources such as water and energy sources are renewable, but their exploitation often relies on the use of limited raw materials, or their rate of replenishment does not correlate with our demands. Pressure on resources and calls for circularity and sufficiency are topics reaching high-level political discourses (European Commission, 2023a). Tradeable resources such as raw materials are subject to market and political forces for trade and distribution, facing a variety of scenarios by 2050 (Schimpf et al, 2017). Water scarcity is expected to expose population and economic activity at risk due to climate change and poor water management (European Commission 2023b). How each of these threats can be scaled down to the territory of Luxembourg?

Biodiversity loss is an umbrella term referring to the decline in the variety of living organisms on the planet, including the extinction of species. Thriving biological variability *(biodiversity)* in ecosystems, species and genes reflects the health and resilience of nature and, in turn, the formation of nature's contribution to people, also referred to as "ecosystem services" (IPBES, 2019). In recent years there have been growing initiatives to incorporate the value of nature's contributions in economic debates (Dasgupta, 2021), and there is an increasing number of software initiatives to assess the cost-effectiveness of possible Payments for Ecosystem Services (PES) such as subsidies, tax-relief schemes, and others (Valatin et al, 2022). Ecosystem service accounting estimates and tracks the flows or quantities that our society is using from nature as if they were transactions between two economic sectors. Studies suggest that the value of seven ecosystem services totalled 172 €billion in the EU in 2012 (European Commission, 2020b). Others oppose "price-tagging" and financialising natural assets as a tool for continuing economic growth since economic growth is attributed to be one of the main drivers of biodiversity loss (Spash & Hache, 2021; IPBES, 2019).

The RISK2050 study selected specific sectors in Luxembourg for assessment based on criteria such as employment importance, relevance to sustainable economic development, and pertinence for future policymaking policymaking (see sample in Section 2 – Fieldwork). The selected sectors encompass both productive and supportive industries, including Industrial Manufacturing, Construction, Forestry, Food Processing as well as Energy and Logistics. The report at hand summarizes the outcomes of the three phases of the RISK2050 study. The First Phase aimed to identify and scrutinize existing studies, reports, and scenarios, at both international and national levels, to understand the extent of the threats at hand for Luxembourg. The Second Phase focused on empirical data collection – we collected first-hand insights from local stakeholders regarding how they perceive these threats and anticipate their implications. Lastly, the Third Phase was allocated for analysing the results and building up recommendations for adaptation and resilience.

Chapter 2. Contextualising physical risks

The research objective of the RISK2050 project is to understand the physical risks faced by Luxembourg's economy, or, in other words, the degree to which Luxembourg's economy is vulnerable to physical threats. We base the notion that the economy is vulnerable to physical threats on scientific frameworks such as the planetary boundaries (Rockström et al., 2009), and subsequently, doughnut economics (Raworth, 2012), which suggest that humanity puts pressure on certain planetary functions, which are necessary to sustain safe and habitable conditions for life (Figure 2.1). If these planetary functions are disrupted, and six of them already are, including novel entities, CO_2 concentration and radiative forcing, biosphere integrity, land-system and freshwater change, and biogeochemical flows (Richardson et al, 2023), this will compromise the social foundations for the well-being of people, part of which is a well-functioning economy.

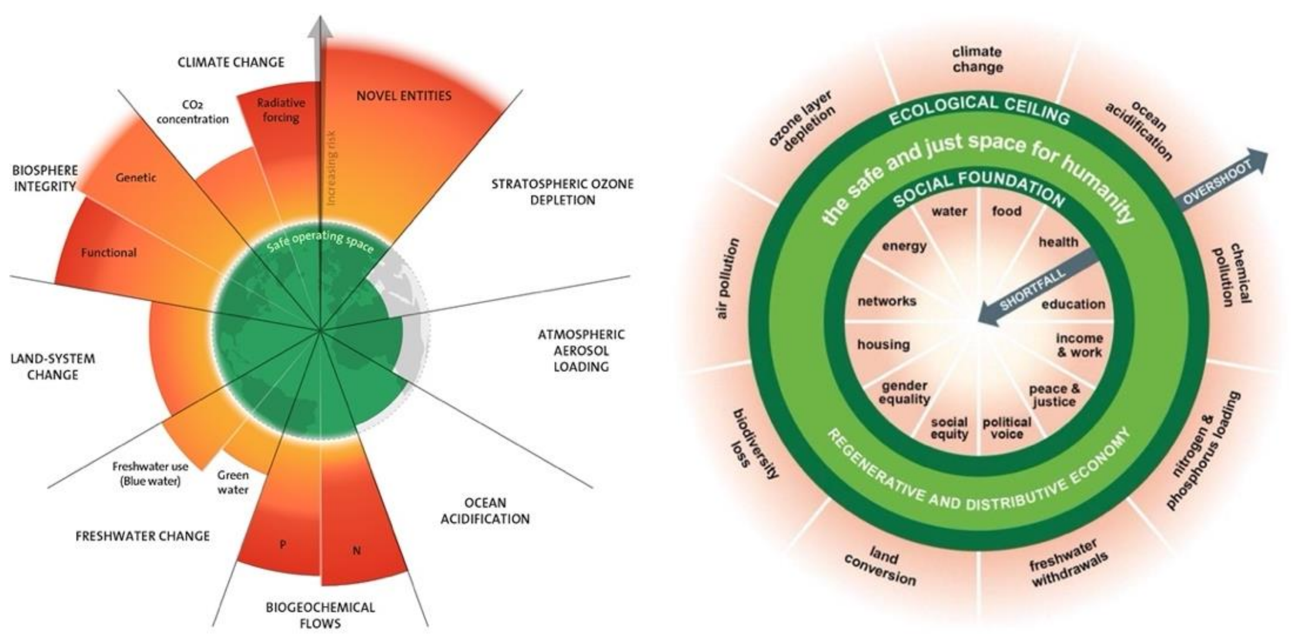

Figure 2.1. Planetary boundaries and doughnut economics frameworks. Sources: Richardson et al, 2023; Raworth, 2012.

Accordingly, our objective is to understand the impact of pushing the ecological ceiling beyond its limits on the economy. To what extent will crossing some of the planetary boundaries influence economic activities in Luxembourg? How vulnerable are selected economic activities to this threat?

To answer these questions, we need to consider how the economy is dependent on these planetary functions. Recently, there has been increasing effort to better understand and quantify the relationship between nature and the economy to fill the gaps in (mis)valuing either ecosystem or economic services (Dasgupta, 2021; DNB & PBL, 2020; NGFS, 2023). One way to do this is to follow the Ecosystem Services approach, which is a strategy to understand socio-environmental dependencies and interactions (Beaumont et al, 2017). Most economic activities rely directly or indirectly on ecosystem services, such as biomass materials for energy, soil stability as support against landslides, natural purification of freshwater and air, to name a few (WEF, 2020). Some of these ecosystem processes happen in the background of global value chains, which is why it is often easy to forget how important they are, nevertheless, failure to receive them may have large economic impacts. Therefore, it is not surprising that *climate action failure, extreme weather, biodiversity loss, environmental damage by humans* and *natural resource crisis* are considered by business stakeholders some of the top 10 most severe risks globally over the next decade (WEF, 2023). Human alteration of ecosystems through land use (e.g. urbanisation, forestry and agriculture), pollution, and extinction of species are impacting the quality of ecosystem services. These planetary functions, which cater for or clean after our economic activities, are expected to stop providing at the same rate or the same quality as before (IPBES, 2019), which will have direct and indirect economic implications.

These potential adverse consequences for the economy are understood as risks. Following a classical risk analysis approach (ECB, 2022; Renn and Walker, 2008), which estimates risk as the product between the probability of occurrence of events and the severity of consequences emerging from such events (Risk = Probability x Severity), we first estimate the status and evolution of threats[1], then evaluate the exposure levels, and finally combine the likelihood and severity of impact from these threats. To advance the risk assessment process, both the risk drivers and exposed subjects have been operationalised.

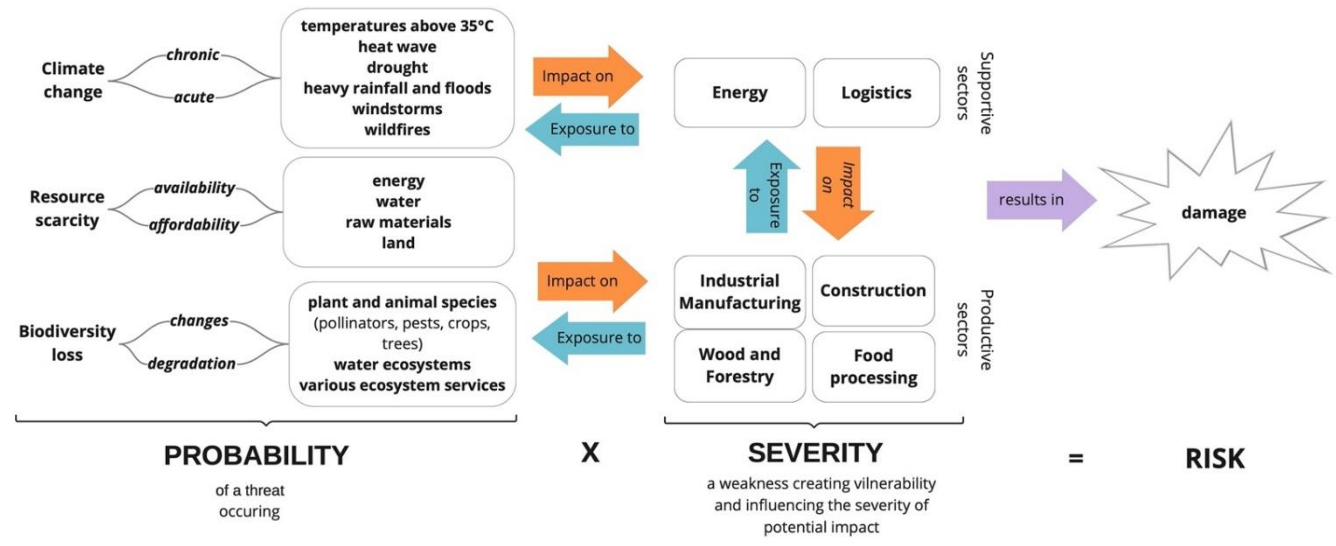

Figure 2.2. A schematic visualisation of the risk assessment approach for RISK2050.

The economy of Luxembourg as a subject is studied here through six well-represented economic sectors in the country: Industrial Manufacturing, Forestry, Food Processing, Construction, Energy and Logistics[2]. Economic sectors of interest were selected based on employment-related importance (STATEC, 2022), relevance for the future sustainable economic development in the country, and underlying feasibility in terms of policymaking for the commissioning institution. Out of the six economic sectors, two - Energy and Logistics - are categorised as supportive, while the other four as productive. The supportive industries are categorised separately because any failure to deliver their supportive functions converts them into threats to the productivity of the other sectors.

Furthermore, the overarching threat of "overshooting planetary boundaries" was divided into three topics: climate-related, resource-related, and biodiversity-related threats. Each topic has been further categorised into separate indicators of relevance for Luxembourg, as identified by the European Environment Agency (EEA), and the Luxembourg Environment Agency, based on geographical and socioeconomic factors. A schematic summary of the risk drivers, their selected relevant indicators and their correspondence to the risk assessment approach can be found in Figure 2.2.

This study undertakes a qualitative exploration of how the economic activities of companies can be impacted by the identified threats. Our main interest is in physical (or material) risk, understood as any impact on capital, liquidity, operations, or a combination of all. As a point of reference, the IPCC's approach (Pörtner et al, 2022) to climate change risk assessment (Figure 2.3) is also based on the interaction between the hazards of the physical climate system and the exposure and vulnerability of socioeconomic activities and ecosystems, once again reiterating how coupled the different systems are. The IPCC methodology includes exposure and vulnerability as separate factors in the risk assessment, whereas the RISK2050 study sees exposure and vulnerability as two sides of the same coin affecting the severity of potential damage (definitions included in the Glossary).

[1] Synonymously used with: hazard, risk driver.

[2] More details regarding the represented industries per NACE codes and number of employees according to STATEC aggregation can be found in Annex Section A.1.

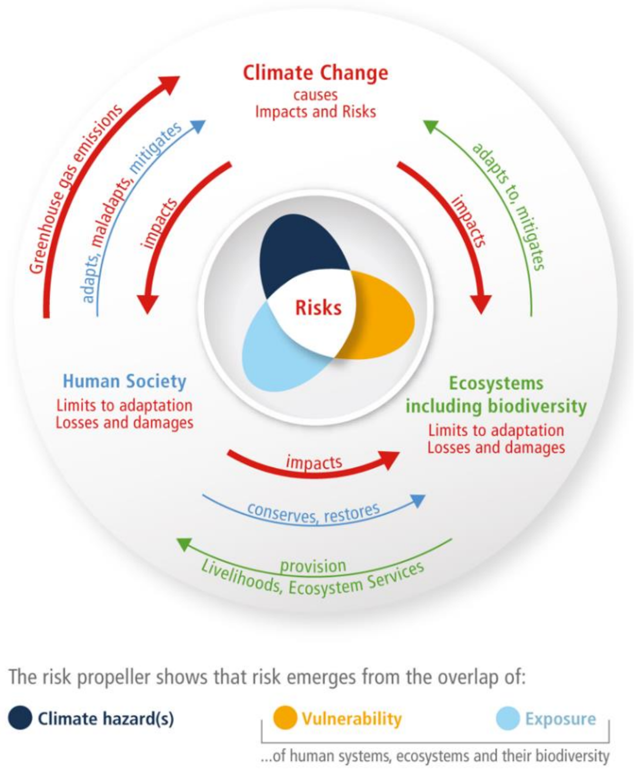

Figure 2.3. Main interactions and trends from climate risks. Source: Pörtner et al, 2022.

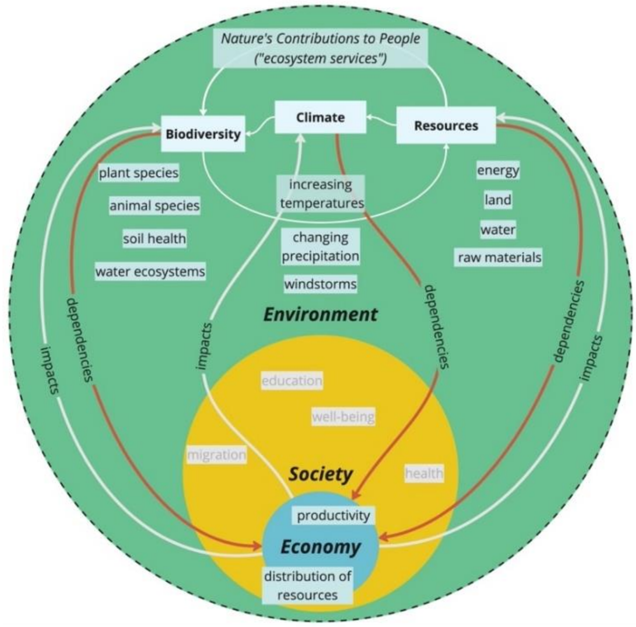

Figure 2.4. Conceptual framework of the RISK2050 project.

Figure 2.4 is a visualisation of the resulting conceptual framework for the RISK2050 project based on the existing theoretical frameworks, strategic risk assessment approaches and operationalisation process outlined above. The figure symbolises the economy (denoted by some of the values it contributes to the social foundation for people, such as labour, production, wealth, and distribution of resources) embedded within the natural environment (denoted by the three topical areas for this research – climate, resources, biodiversity, among many others ecosystem functions that the environment contributes). The red and white arrows symbolise the links and interdependencies between the different areas. The arrows labelled "dependencies" are most likely generating exposure and can be a source of vulnerability and will be detailed in this study. The mutual relationship between nature-economy impact and dependencies within the field of finance is most recently referred to as double materiality, as it aims to capture both the financial (impact) materiality of environmental risks but also the environmental impact (materiality) of economic activities.

A further note on the labels used throughout the study: we have adopted the words "climate change", "biodiversity loss" and "resource scarcity" as labels to categories for practical reasons and for reader accessibility. However, we believe that these topical umbrella terms do not necessarily capture the evolving complexity of these phenomena. To avoid underestimating the importance and inevitability of ecosystem degradation, we might refer to these threats as *crises*.

Chapter 3. Methodology: Integrating Existing Studies and Fieldwork into a Risk Analysis

The methodology of the present study relies on three pillars. First, a review of existing literature, scientific case studies and scenarios, risk mitigation strategies and related policy reports was conducted to understand the extent of the threats at hand for Luxembourg (see Section 3.1 as well as report Phase 1). Building on the findings resulting thereof, fieldwork in Luxembourg has allowed to scrutinise sector specific perceptions of and exposures to risks (see Section 3.2 as well as report Phase 2). Both sources have led to an extended risk analysis for the targeted industries (Section 3.3). Finally, actionable recommendations for both the corporate sector and for policy makers could be identified with the help of stakeholder inputs and joint discussions of findings between the Luxembourg Strategy team and the University's research consortium (Section 3.4).

3.1. Review of literature

The desktop research process was based on the conceptual framework of the study described in the previous chapter and aimed to provide a comprehensive and systematic review of the latest academic publications, industry reports and scientific observations for each of the three threats and its potential impact on each of the six economic sectors selected. The area of Luxembourg has been used as the scope of the study, as clearly defined in the objectives of the research project, and wherever not possible European data has been consulted. National climate and environmental reports have served to describe the current condition of indicators in the country.

The Copernicus Climate Change Service (C3S) and The European Climate Adaptation Platform Climate-ADAPT have been the point of reference for all climate-related projections for Europe and Luxembourg. The C3S offers open access to a large database of climate data and model projections based on satellite observations, where area-specific results for RCP 4.5 and 8.5[3] can be generated via their online application tools. The database of all application tools can be found on the Copernicus Climate Data Store Webpage[4]. In addition, the Climate-Adapt online tool, sourcing data from C3S, provides regional projections for a variety of indicators. Additionally, these results are supported by the latest IPCC reports and other academic publications relevant to the geographical area of Luxembourg. Most of the projections do not exhibit substantial differences between the RCP 4.5 and 8.5 scenarios in terms of climate impact for Luxembourg, therefore not every indicator is discussed under both scenarios.

3.2. Fieldwork

For the qualitative analysis, empirical data has been collected to better understand the perception of local stakeholders on risk and exposure of their economic activities to the threats. The methodology was guided by a three-step strategy involving focus group workshops, an online survey, and semi-structured expert interviews as data collection methods (Figure 3.1). These methods were employed in a sequential and complementary manner, building on preliminary findings from the conducted literature review. The overall sample comprises 80 participants (a more detailed sample composition can be consulted in Annex Section A.2). In some cases, there has been an overlap of respondents across the different methods. The results from the different methods complemented each other in such a way that the survey was able to provide an aggregated evaluation of actors' perceptions, whereas the interviews allowed us to get a better understanding of details and nuances. The initial round of stakeholder workshops gave space for a rich spectrum of ideas to emerge, out of which some priority risks not identified during the literature view stood out. In addition to representative experts from the six economic sectors, water management stakeholders were consulted to better understand the potential impact of water scarcity overall. The terminology for some concepts was often adapted to everyday language in the course of the fieldwork to avoid scientific jargon. Participants were asked to assess the evolution of risk associated with each threat over time, from now (2023), providing a mid-term checkpoint at 2035 and a final position at the year 2050.

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[3] Representative concentration pathways (RCP) represent different scenarios used for modelling changes in the climate. They are based on global factors such as demographic changes, climate policies, resource consumption and intensity of lifestyles. The impact of these factors on projected GHG emissions is used for calculating the radiative forcing (denoted by the number 4.5 or 8.5 respectively), or in other words, the heating levels, The RCP 4.5 considers the political commitments accepted so far by countries, whereas the RCP 8.5 represents a future without any climate mitigation action (the so-called "business-as-usual") (Meinshausen et al, 2020).

[4] https://cds.climate.copernicus.eu/

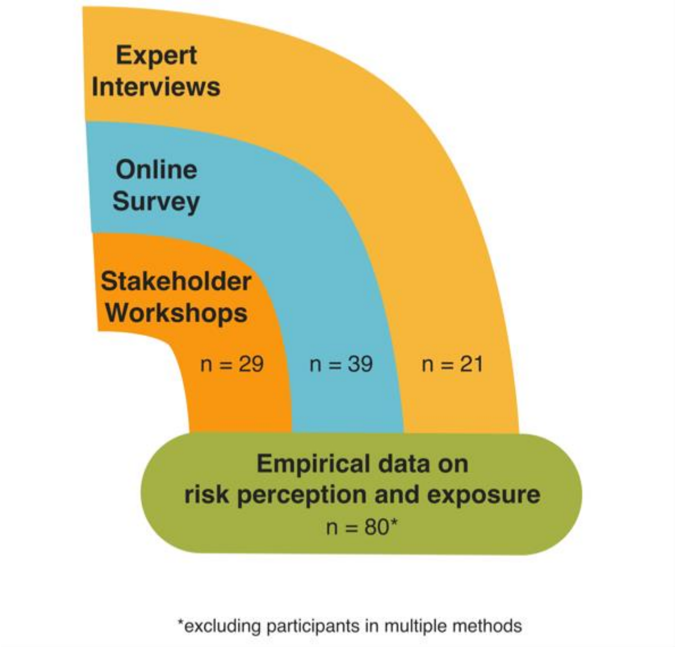

Figure 3.1. Illustration of the three-step methodological process.

Focus Group Workshops: The first step involved conducting a series of five focus group workshops from January to March 2023, with participation from 29 stakeholders representing all six sectors. The workshops provided an open platform for participants to discuss and identify primary threats associated with climate change, resource scarcity, and biodiversity loss. Through these workshops, new threats, such as industrial land importance and windstorms, emerged, enriching the scope for further data collection. The exploratory workshops yielded two primary categories of data. Firstly, an aggregated matrix with visual and numerical information on risks, resulting from an on-site exercise with stakeholders. The matrix was used in re-evaluating the initial steps of the risk analysis, namely the identification and classification of threats. Secondly, the interactions and discussions with stakeholders later underwent a qualitative review, focusing on identifying commonalities across sectors and specific industry-related insights. The insights obtained from both types of data significantly influenced the formulation of survey questions and the selection of threats to be addressed in the subsequent expert interviews. The following threats were added to the survey questionnaire and interview guide after receiving feedback from the workshop participants emphasising their relevance: availability of industrial land, extreme wind, and air pollution. A follow-up workshop was conducted in July 2023 to present the preliminary results to the initial workshop participants and interviewees, gather feedback and identify further research needs.

Online Survey: The second method was an online survey conducted for two months in April and May 2023, during which 39 valid responses were collected. The participants primarily represented private companies, with some contributions from non-profit organizations and public institutions. The survey encompassed self-assessment questions related to the risks associated with climate change, resource scarcity, and biodiversity loss. This method allowed for a semi-quantitative estimation of the relative risk levels associated with specific threats. The data resulting from the online survey was subject to descriptive statistical aggregation and visualisation for further qualitative analysis.

Semi-Structured Expert Interviews: Running in addition to the online survey, 21 semi-structured expert interviews were carried out between March and June. These interviews involved a diverse range of stakeholders, including business representatives, syndicates, public institutions, and non-governmental organizations. The interviews followed a semi-structured framework which enabled participants to estimate future levels of exposure, assess risks and opportunities, and discuss measures already taken or needed in the face of the identified threats. These interviews prioritized qualitative data collection to understand the underlying links and relationships associated with the threats. The expert interviews were recorded in audio format and subsequently transcribed to facilitate in-depth analysis. To structure the analysis, we developed a coding scheme that incorporated a hybrid approach, combining deductive elements (informed by existing literature and insights from focus group workshops) and inductive elements (emerging from an initial review of interview content). This method involved constructing analytical categories, or codes, by drawing upon pre-existing knowledge and incorporating novel aspects gathered from the interviews. We organized the categorization and aggregation of interview data using a mind map, which served as the foundation for subsequent interpretation.

3.3. Risk assessment and analysis

Risk assessment is a complex and context-specific exercise which depends on the type of organisation or activity, its goals and the potential impacts of threats. Good practices in climate-related and environmental risk management recommend the following steps for risk assessment (ECB, 2022; Renn and Walker, 2008):

1) Identification and estimation of threat;
2) Assessment of exposure and/or vulnerability;
3) Estimation of risk, combining the probability and severity of impacts based on the first two steps

In the context of our study, the literature review and consultation of national and international reports regarding the condition of the climate, biodiversity and resource exploitation have served as a stepping stone towards identifying and estimating the threats. The fieldwork has served as the next key step towards assessing the (perceived) vulnerability of the exposed economic actors. The results from the fieldwork are presented in an aggregated away across the methods used. The semi-quantitative online survey allows for an individual representation of its results, which represent only part of the overall sample. Nevertheless, the results from all different methods demonstrate very similar trends in terms of risk ranking of threats.

For the consequent risk analysis, we have developed a risk matrix estimating the level of risk arising from the likelihood and severity of impacts from each threat, based on the most relevant and credible scientific projections, presented in Chapter 8. In addition, based on the empirical data, we have detected which scientifically important threats are less represented in stakeholders' perceptions. Underestimating the level of risk arising from a threat can be alarming because it may suggest:

- lack of anticipatory measures;
- lack of adaptive measures;
- lack of knowledge or awareness;
- need for further support.

3.4 Policy recommendations

To address the identified threats and associated risks, our team has formulated a set of recommendations tailored to three key stakeholder levels: companies, industries, and policymakers. The recommendations span four topical groups: technical, operational, governance, and nature-based interventions. Derived from various sources, including literature theories, observations during empirical fieldwork, input from stakeholder workshops, and feedback from conferences and internal discussions, these recommendations aim to provide a holistic response to the multifaceted challenges. References and links for further information are provided for each recommendation, comprising an extensive database of tools for adaptation and resilience.

Part I. Review of the Literature

Chapter 4. The Climate Crisis: Threat and Exposure

4.1. The climate crisis as a threat

Europe is experiencing faster warming than any other continent on the planet, as temperatures increase at twice the global average rate (Copernicus Climate Change Service, 2023). Figure 4.1. shows a five-year average temperature over Europe in comparison to previous years. The trend has had a continuous increase over the last 40 years. The year 2022 was record-breaking in many respects for Europe, including the warmest summer, longest sunshine duration, and record loss of glacier ice from the Alps. It is considered that climate change will exacerbate all kinds of extreme weather events, such as floods, heat waves, cold waves, and windstorms (Seneviratne, 2021).

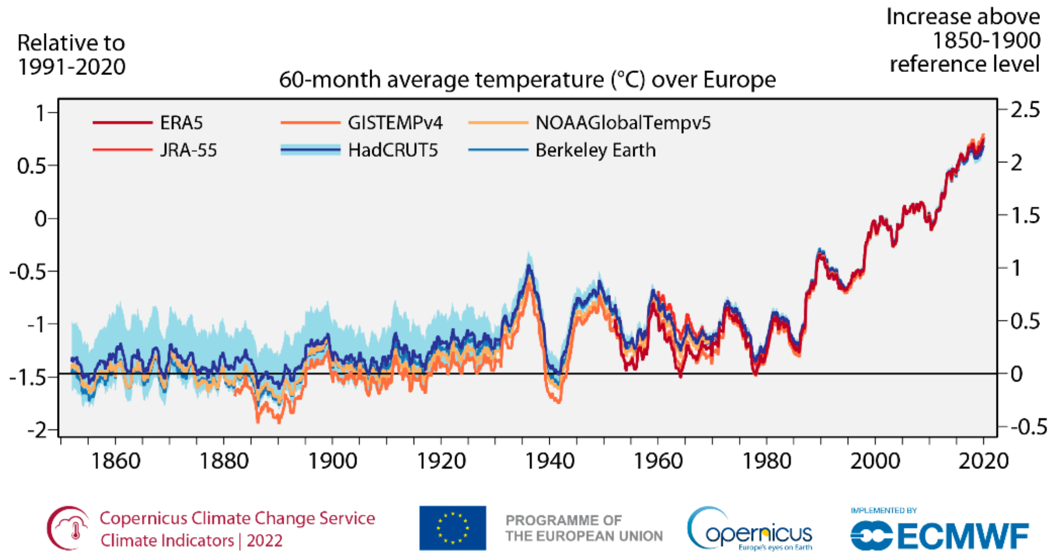

Figure 4.1. Average temperature over Europe for a 5-year period compared to reference levels. Source: Copernicus Climate Change Service, 2023

How is climate change manifesting in Luxembourg?

Luxembourg is already recording a 1.5°C warming of the average annual temperature over recent years compared to the period 1951-1980[5]. This means that during the year the warm days are warmer than before, or the number of warm days is higher than before. This is a type of chronic change because it happens gradually over a long period of time. The average annual temperature in Luxembourg is expected to increase by almost 3°C from 8.3°C in 1951-1980 to about 11°C by 2050 in both RCP 4.5 and 8.5. Moreover, these scenarios project that **temperatures above 30°C and even above 35°C** will be experienced in Luxembourg[6]. Temperatures between 33°C and 35°C, with an average temperature of 23°C the previous day, are categorised as dangerous and require an alerted level of vigilance, whereas temperatures above 35°C are categorised as extremely dangerous and require the highest level of vigilance according to Luxembourg's National Emergency Plan in the case of bad weather[7] (Figure 4.2).

Having several successive hot days (above 30°C for Luxembourg) is considered **a heat wave**[8]. Heat waves are an example of an acute, or extreme, weather event because they cause significant stress over a short period of time. The occurrence of heat waves in Luxembourg has increased in recent years and is expected to increase more in the future. Projections forecast an enhanced probability of heatwaves across all of Europe (Russo et al., 2015). For Luxembourg, studies project a 25% probability of severe heat waves annually (Smid et al, 2019), or on average 1-2 more heatwave occurrences annually, both warmer and longer lasting (Junk et al, 2019)

[5] www.meteolux.lu/climat
[6] https://climate-adapt.eea.europa.eu/en/metadata/indicators/maximum-temperature
[7] https://infocrise.public.lu/fr/intemperies/plan-gouvernemental.html
[8] There are varying definitions of heatwaves. According to the Copernicus Climate Change Service classifying an event as a heat-wave is context-specific and is usually related to a consecutive number of days with temperature higher than the upper average in the area.

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D'URGENCE
APPELEZ LE **112**

INTEMPÉRIES	NIVEAU ORANGE	NIVEAU ROUGE
CHALEUR	**GRANDE CHALEUR** températures entre 33°C et 35°C avec une température moyenne du jour précédent supérieure à 23° C	**CHALEUR EXTRÊME** températures supérieures à 35°C avec une température moyenne du jour précédent supérieure à 23° C
FROID	**GRAND FROID** températures entre - 11°C et - 15°C	**FROID EXTRÊME** températures inférieures à - 15°C
NEIGE OU PRÉCIPITATIONS VERGLAÇANTES	**NEIGE OU VERGLAS MODÉRÉS** neige entre 11 et 25 cm endéans 12h ou précipitations verglaçantes sur l'ensemble du pays	**NEIGE OU VERGLAS FORTS** neige supérieure à 25 cm en 12h ou précipitations verglaçantes sur l'ensemble du pays en fonction des dégâts attendus
ORAGES	**ORAGES FORTS** grêle entre 1 et 3 cm ou rafales de vents entre 90 et 110 km/h ou pluie entre 25 et 35 l/h CAPE entre 1000 et 2500 J/kg	**ORAGES VIOLENTS** grêle supérieure à 3 cm ou rafales de vents supérieures à 110km/h ou pluie supérieure à 35 l/h CAPE suéprieure à 2500 J/kg
PLUIES	**PLUIES FORTES** entre 31 et 45 l/m^2 en 6h ou entre 41 et 60 l/m^2 en 12h ou entre 51 et 80 l/m^2 en 24h	**PLUIES TORRENTIELLES** supérieures à 45 l/m^2 en 6h ou supérieures à 60 l/m^2 en 12h ou supérieures à 80 l/m^2 en 24h
RAFALES DE VENT	**VENTS VIOLENTS** vents violents entre 90 et 110 km/h	**TEMPÊTE TRÈS VIOLENTE** vents supérieurs à 110 km/h

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Figure 4.2. Level of alertness for different manifestations of extreme weather events, as classified in the National Emergency Plan in the case of bad weather. Source: Ministère d'État, 2021.

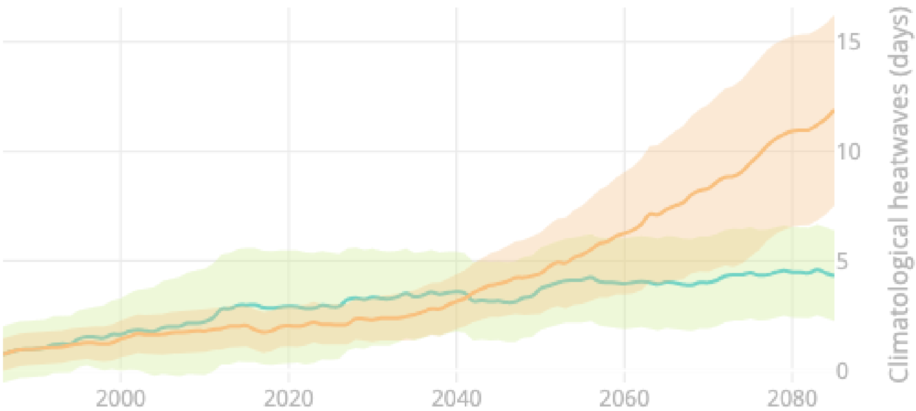


Figure 4.3. The projected trends of annual number of days in a year within prolonged periods of unusually high temperatures under RCP 4.5 (green) and RCP 8.5 (orange). Source: European Climate Adaptation Platform Climate-ADAPT.

Figure 4.3. shows the projected number of heat wave days for Luxembourg from the two RCP scenarios. Both scenarios develop close together by 2050, indicating an average of up to 5 extremely hot days per year (European Climate Adaptation Platform Climate-ADAPT). The timeline of this study is the year 2050, but it is important to emphasise that most climate models project an increase in heat wave instances under RCP 8.5 by 2100 in Europe, which means an annual occurrence of heat waves more severe than any before. This alarming increase can be partially explained by land-atmosphere feedback: severe heat waves correlate with reduced precipitation leading to **drought**; this deficit in soil moisture may reduce evapotranspiration, allowing temperatures to rise further (Lin et al, 2022).

Rising average temperatures and more intensive heat waves are expected to influence the **precipitation** patterns in Luxembourg. The net amount of annual precipitation is not expected to drastically change, but seasonal differences are anticipated. Figure 4.4a plots the projected deviations from the 1981-2010 seasonal averages from an ensemble of climate models, and Figure 4.4b plots the monthly projected changes in total precipitation. Both figures suggest that in both RCP 4.5 and 8.5 scenarios by 2050, summer months are expected to experience decreased precipitation of under 10%, whereas winter and spring months are estimated approximately 20% and 10% increase respectively, without significant changes for autumn months, despite a larger margin of error.

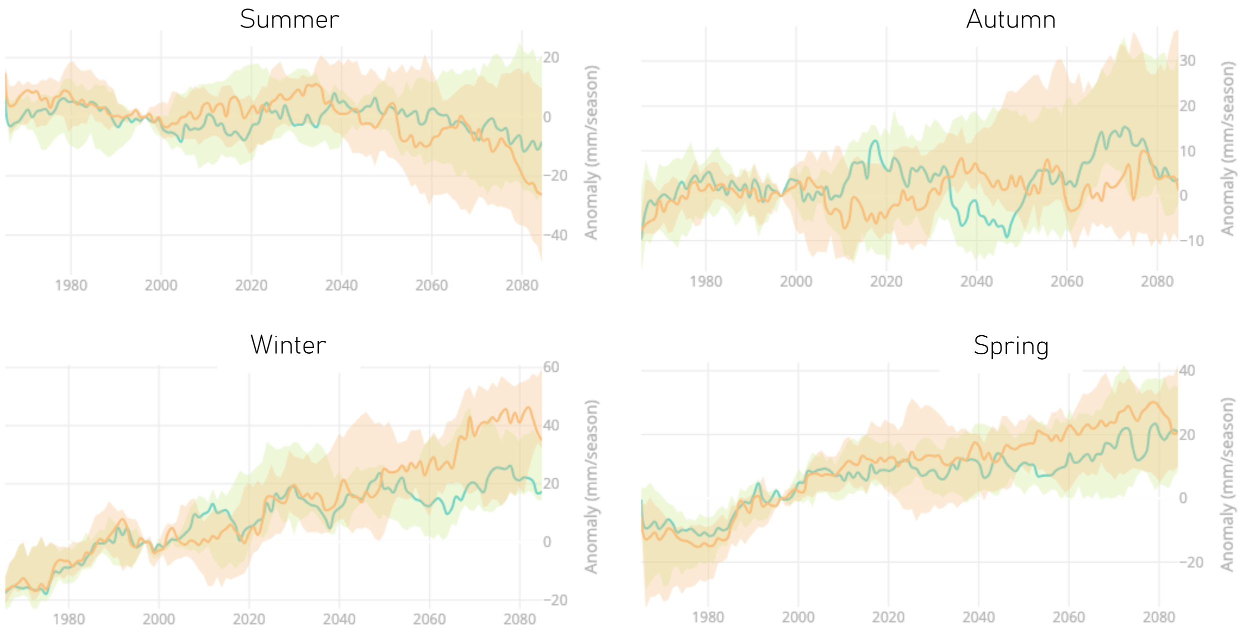


Figure 4. 4a. Projected deviations (anomalies) from the 1981-2010 averages in seasonal precipitation for RCP 4.5 (green line) and RCP 8.5 (orange line) in Luxembourg by 2080. NOTE: Plots not to scale. Source: European Climate Adaptation Platform Climate-ADAPT.

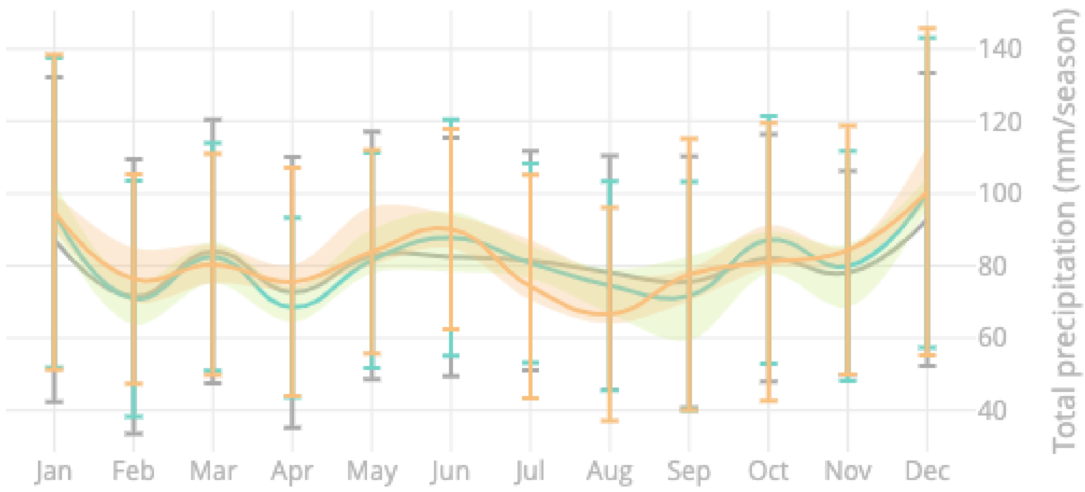


Figure 4.4b. Projected trends in monthly values of total precipitation in Luxembourg for the period 2041-2070. Grey line – historical average 1980 – 2010 based on ERA5 model. Green line – projected trend for RCP 4.5, orange line – projected trends for RCP 8.5, and envelope of their likely values (at 66% probability of occurrence) from an ensemble of climate models. Source: European Climate Adaptation Platform Climate-ADAPT.

In addition to the regularity of rainfall, it is important to consider other aspects of rain events. Very warm temperatures are expected to cause more intense rainfalls, which are associated with a probability of **flash floods** occurring. Flash floods are floods which happen suddenly due to very large amounts of rain in a relatively short period of time (usually in a matter of hours), compared to riverine floods where water levels gradually increase. Furthermore, intense rainfall increases soil erosion, and can negatively impact infiltration, such that groundwater recharge is reduced overall. In other words, even if the same amount of rain falls, if they are intense rain events, most of it is drained overland (flooding) and does not infiltrate into the groundwater.

Drought, a result of heat and decreased precipitation, is a pre-condition for a variety of related threats, one of which is **wildfires**. Historically, wildfires have not been a threat to Luxembourg, but this is expected to change as the number of days with high fire danger is projected to increase from 0.8 days on average in 2010 to 5.6 days in 2050[9].

[9] https://climate-adapt.eea.europa.eu/en/metadata/indicators/high-fire-danger-days

Climate models project an overall *decrease* in the probability of **cold waves** occurring in Luxembourg to less than 5% per year by 2050 (Smid et al, 2019). The minimum temperature in the country is expected to increase by two degrees, and the number of frost days is expected to decrease by 30% in 2050, which is the equivalent of 20 days less per year on average[10].

Wind speed is a climatological variable which is difficult to predict in the long term, and climate models often show disagreement both in the consistency of their historical trends compared with observed trends, and in projected future trends (Wohland et al, 2019; Zha et al, 2021; Donat et al, 2011). Hundreds of tornadoes are registered in Europe annually, although the tornado in southwestern Luxembourg in August 2019 took many by surprise. Despite this tornado being a very recent event, studies overall point towards a decrease in wind speeds over Europe (Seneviratne et al, 2021). Nevertheless, severe convective storms associated with tornadoes, hail and strong winds are expected to have a slight increase in frequency and amplitude by 2050, because the overall environmental and climatological changes favour more extreme events (Ranasinghe, 2021). Studies show that extreme weather events related to warm temperatures and heavy precipitation are correlated with the trend of warming average global temperatures (Fischer and Knutti, 2015). Luxembourg is susceptible to extreme weather events, including storms and heavy rainfall, which can result in infrastructure damage and disruptions (Sousa et al., 2018).

Summary of all assessed climate-related threats and the adopted definitions:

extreme wind	windstorm or tornado events
wildfires	occurrence of a wildfire
cold waves	occurrence of a continuous period of colder than average days
heat waves	occurrence of a continuous period of warmer than average days
t > 35°C	occurrence of temperatures above 35°C
drought	occurrence of prolonged periods without or with decreased precipitation
riverine floods	flooding events caused by overflowing of rivers
flash floods	flooding events caused by heavy rainfall

4.2. Economic implications

Physical climate hazards threaten business operations across all sectors globally, of which the manufacturing industry has the largest proportion of assets exposed to climate hazards (Moody's, 2021). Typically, economic and financial risks are divided into two categories: **physical** and **transition risks** (as visualised in Figure 4.6 and Table 4.1). **Physical risks** are those immediate adverse impacts, such as damage and loss, caused by more frequent and severe environmental factors such as heat waves, floods, storms, heat stress, and changing growth duration. **Transition risks** are those related to the economic transition to net-zero carbon emissions, such as policies and regulations that limit or price greenhouse gas (GHG) emissions, or changes in consumer preferences. Such transitions could mean that some sectors of the economy face big shifts in asset values or higher costs of doing business, such as abatement costs, carbon price, reduction in demand for fossil fuels, and changes in prices of electricity and crops. Climate-related risks can be further categorised as **direct** or **indirect**. The **direct** risks concern impacts on operations and infrastructure, whereas the **indirect** ones stem from impacts through disruptions along supply and value chains or other diffusion channels of the company. For the context of this research, we are mainly focusing on **physical risks**, understood as any impact on physical assets, production processes, and operations as a result of the climate risk drivers outlined earlier (Sussman and Freed, 2008).

An assessment of some of the quantifiable climate change impacts in Europe estimates a welfare loss of between 83 €billion/year (0.65% of GDP) and 42 €billion/year (0.33% of GDP) for RCP 8.4 and 4.5 respectively (Feyen et al, 2020). Economic losses caused by weather- and climate-related extreme events for the period 1980-2022 in Luxembourg amount to a total of 1 252 €million, or 2 700€ per capita, of which only half have been insured (EEA, 2023). Increasing average temperatures and heat waves will hamper worker productivity and labour supply throughout most of Europe (van Daalen et al, 2022). Slightly more than half of all firms in Luxembourg have reported that their business activities are already affected by the physical threats of climate change through minor impacts (EIB, 2021). Furthermore, about 40% of companies in the country have reported to be investing in climate-related measures to tackle these risks, which is slightly below the EU average.

[10] https://climate-adapt.eea.europa.eu/en/metadata/indicators/frost-days

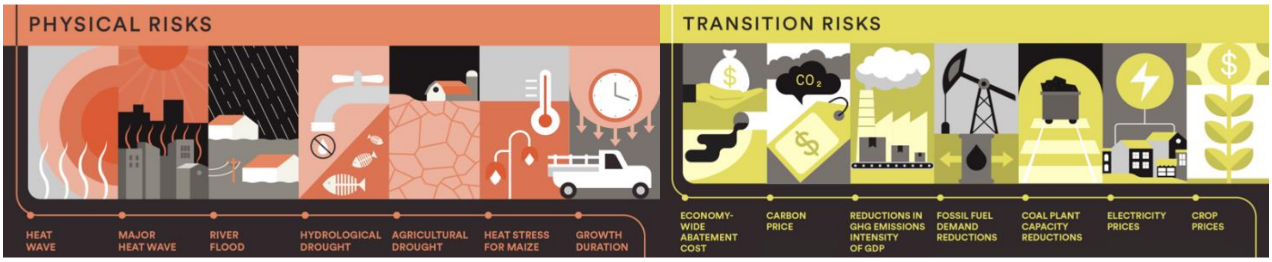


Figure 4.5. Physical risk from left to right: heat wave, major heat wave, river flood, hydrological drought, agricultural drought, heat stress, growth duration. Transition risks: abatement costs, carbon price, reductions in GHG emissions intensity of GDP, fossil fuel demand reduction, coal plant capacity reductions, electricity prices, and crop prices. Source: Gambhir et al, 2022.

Table 4.1. Examples of the types of climate risks: physical, transition, direct and indirect.

Examples of climate risks	Physical	Transition
Direct	damaged roof from a storm event	company's costs increase due to local carbon pricing policies
Indirect	key component shortage due to damage to the supplier's infrastructure from a storm event elsewhere	company's costs increase due to higher prices incurred from suppliers due to carbon pricing policies elsewhere

The economic sectors listed as most exposed to this risk are agriculture, forestry, mining and quarrying, as well as construction. Industrial Manufacturing and the variety of sub-sectors it represents are also vulnerable to decreased productivity The heat may trigger workers to take more breaks for rehydration and cooling off and to slow down the work process overall. When it is too hot, the working hours suitable for work in these industries may decrease due to health reasons. France and Belgium are already experiencing up to a 2% decline in labour supply over recent years (Ibid). More than half of the workers at an automobile parts manufacturing plant in Europe have reported headaches and fatigue due to non-optimal working conditions in summertime (Pogačar, 2018). Furthermore, a day with temperatures above 32°C at a plant in China has had an observed negative impact on total factory output estimated at thousands of dollars (Zhang et al, 2018). An estimated 20% decline in economic productivity due to higher temperatures is expected in Luxembourg by the end of the century (Dasgupta et al, 2022). In addition, heat stress may obstruct industrial cooling processes, and increase expenses for air conditioning in most Industrial Manufacturing sub-sectors (UNEP FI, 2023). Warmer temperatures will have a direct impact on energy consumption and cost in two ways: on one hand, for maintaining safe working conditions for employees through air conditioning in industrial workplace settings (which is particularly important with heat-related processes); on the other hand, for maintaining safe conditions for their equipment - controlling temperatures for the production process involving cooling machinery, cooling to prevent excess heat from chemical reactions, cooling of plastic and metals during manufacturing, and to avoid damage to sensitive components. Even though most of the cooling in these processes is achieved through water use, which will also experience increasing demand, higher ambient temperatures will affect energy demand overall (IEA, 2018). On the other hand, milder winters have already reduced the demand for heating in Luxembourg, and Europe in general, over the past two decades (Figure 4.6) (IEA, 2022).

Studies project that energy demand for heating will outbalance the increased demand for cooling if Europe's population is constant, but accounting for growth in population net energy demand will increase (Spinoni et al, 2018). Projections for specific countries (Belgium and Switzerland) project an increase in cooling demand between a factor of 2.4 and 5.5, whereas heating demands may decrease between 20% and 60% on average (Mutschler et al, 2021; Ramon et al, 2020). The Energy sector, covered in details in Chapter 5, will increasingly rely more on renewable energy sources - wind, solar and water. However, these sources vary in daily, seasonal and annual availability (Després and Adamovic, 2020). For example, Central Europe may face increasing wind "droughts" in future autumn-winter periods, particularly in RCP 8.5, whereas, despite the increasing average temperatures and heat waves, solar energy "droughts"[11] are also expected to increase across Western and Central Europe (Kapica et al, 2023). Average wind speeds in Luxembourg have decreased by 2.2% in 2020 compared to the 1970s, which creates a -12.7% decrease in capacity for onshore wind power generation[12] (Copernicus Climate Change Service, 2021).

[11] Also known as *dunkelflaute*, a period of time in which little or no energy can be generated with wind and solar power.
[12] a 10% reduction in wind speed leads to a 27% reduction in power output (Copernicus Climate Change Service, 2021)

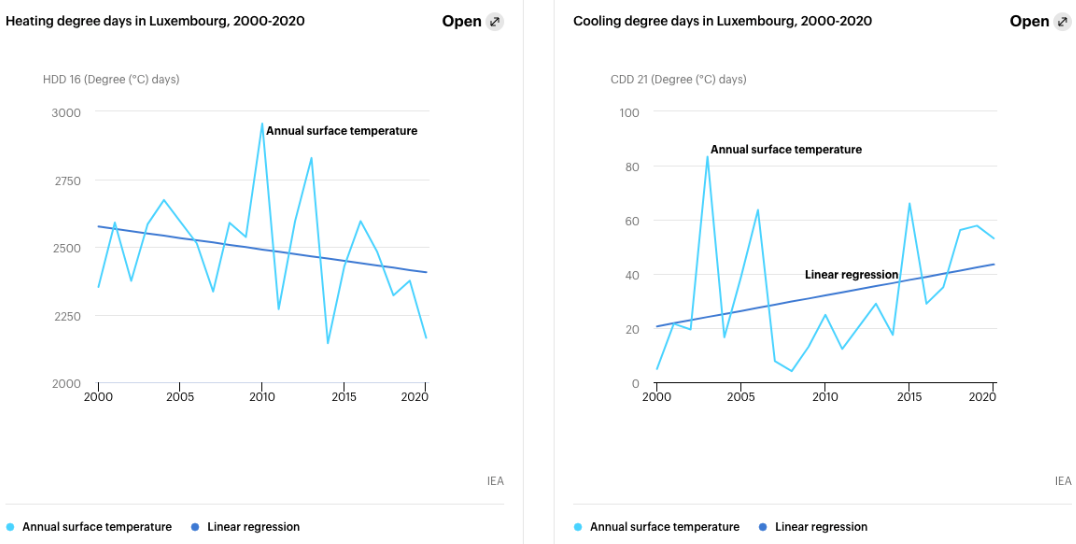


Figure 4.6. Patterns of change in heating degree days (left) and cooling degree days[13] (right) for Luxembourg in the past two decades. The regression line computed by the IEA. Source: IEA, 2022.

The **Construction** sector is also vulnerable to suboptimal working conditions, decreased productivity and labour supply shortages. The National Climate Adaptation Strategy has identified that extreme weather events and high summer temperatures affecting the indoor climate of buildings are impact priorities (MECDD, 2018). Furthermore, the chronic climatic shifts affect the energy requirements of buildings and the suitability of locations for new development projects (WBCSD, 2020). The building industry is further vulnerable to heat stress, increased cooling demand, potential significant damage from flash floods, and heightened weather-related damage affecting property insurance (German Environment Agency, 2019). Similar studies on the perceived risks by stakeholders divide the risks into two groups – those related to the construction *process* and to already *completed* projects, where physical and transition risks overlap (Smith, 2013). The construction process is exposed to occupational health and safety risks for workers, risks for the quality and supply of materials, waste management, compliance to changing regulations, changing energy demands, and preparedness to pay for unexpected events. The finished products are exposed to higher heat load, compromised energy and water efficiency, and increased insurance claims.

In today's globalised economy, reliable **supply chains** are critical for the functioning of most economic activities. However, factors such as supply chain complexity and geographic concentration can substantially influence the level of vulnerability (McKinnon and Kreie, 2010). The more specific a supplied product is, such as microprocessors for specific car models, for example, the more vulnerable the supply chain is. The degree of difficulty of transportation and storage, such as food products requiring cool transport, also affects the feasibility of supply chains. Suppliers are often be located in faraway places where they may be exposed to various hazards – climatic, geological, geopolitical, and sourcing from producers geographically concentrated in exposed areas increases vulnerability (Pappis, 2010). A combination of factors can have significant effects on supply chain vulnerabilities, such as long and complex supply chains, e.g. automobiles and smartphones, which also rely on highly specific products often sourced from geographically restricted areas can more easily experience market tensions and shortage of supply, especially when relying on just-in-time delivery models rather than generating stocking and distributing existing stocks over several sites (Lepousez and Derouet, 2022; Mantin et al, 2021).

Food processing, together with **Forestry** and timber processing, are industries more directly dependent on and exposed to nature, organic materials, and ecosystem services (whereas industrial manufacturing is still dependent on nature and ecosystem services but more indirectly, usually working with secondary materials and components transformed via industrial mechanical processes). This direct dependency translates into systemic changes in the development of biological materials - warming temperatures will not only affect the growth cycle of plants and crops in the area but will also spur the migration of species, which will change the local biodiversity composition. Climate change may influence production through shifts in growing degree days and precipitation, potentially displacing producers geographically. The wine industry in Luxembourg is expected to grow in the future[14], but it will also undergo profound changes in the types of wine produced due to the changing climatic conditions (Molitor and Junk, 2019). Furthermore, earlier ripening exposes the plants to a variety of health-

[13] Heating degree days (HDD) and cooling degree days (CDD) are weather-based technical indexes designed to describe the energy requirements of buildings in terms of heating or cooling (Eurostat, 2023).
[14] https://www.statista.com/outlook/cmo/alcoholic-drinks/wine/luxembourg#analyst-opinion

related risks. Additionally, the study identified risks across various supply chain stages, from increased cooling demand in storage and processing to disruptions in the distribution network, trade restrictions, and changing consumer preferences at the retailing stage. These risks may lead to higher insurance and asset stress, with impacts on food safety and regulations. In order to better understand the potential impact on the Food industry, it is important to understand the composition of the Food System in Luxembourg. There are a variety of stakeholder groups which depend on each other (Reckinger, 2020). and each stakeholder group would need to undertake its own risk analysis to have a more comprehensive picture. The RISK2050 project focuses on the post-harvest food value chain, related to food processing, storage, and distribution. This part of the value chain is highly dependent on reliable and resilient supply chains, and on energy intensive processes for manufacturing food products. The climate crisis may affect production through changes in growing degree days and precipitation, which together may lead to geographical displacement of producers and labour disruption (Godde et al., 2021; Guerin, 2022; Reardon & Zilberman, 2018).

The climate change factors of precipitation and temperature will have direct, indirect, and cascading effects on forests (Romeiro et al, 2022). One of the biggest concerns is that forests will lose their economic value due to the loss of more economically valuable species under changing climate conditions (Hanewinkel et al, 2013). **Forests** are directly exposed to the increasing risk of wildfires due to increasing temperatures and drought. In addition, warmer temperatures and reduced precipitation have a cascading effect on reducing tree defences which may indirectly lead to root rots and bark beetles, making trees more susceptible to wind damage. Over the past decades, windstorms have caused more damage than fires and pest outbreaks (Forzieri et al, 2020), but this trend may be reversed with the projections of decreasing winds and increasing temperatures causing more favourable conditions for fires and pest outbreaks (e.g., the bark beetle). Approximately 58% of European forests are vulnerable to multiple natural hazards, such as windstorms, fires, and pests (Forzieri et al, 2021). In Luxembourg, two-thirds of the trees are either damaged or decaying due to changes in the climate (Forest inventory). Beech trees, which are native species for the region, dominate forested areas in Luxembourg today. However, one of the risks identified for this geographical area, is an estimated beech growth decline of 20-30% by 2050 under RCP 8.5, due to increased temperatures and droughts (Martinez del Castillo et al, 2022). The impacts of climate change hazards, such as increased fires and pest outbreaks, are expected to influence timber markets. Climate-related physical risks to the forestry sector depend on multiple factors such as tree species composition, forest health, soil type, ecosystem dependencies, geography, forest fragmentation, and surrounding land use.

Another physical risk which may affect any economic sector is floods – an increasing threat related to changes in the climate trends. Differentiation is necessary between flooding from rivers for whole catchments, caused by long-lasting precipitation when a warning is possible, and flash floods, caused by short and heavy rainfall events mostly on a local level when it is nearly impossible to issue an alert beforehand. Floods are a recurring event in Luxembourg, but recent years have seen an increase in flash floods as observed, e.g., in July 2016 on Weisse Ernz (Larochette), May/June 2018 on Weisse Ernz, Schwarze Ernz and Attert, July 2021 in Pfaffenthal/Grund. Floods can physically damage facilities and equipment or disrupt power supplies. The Industrial Manufacturing industry is greatly interconnected on a global scale and depends significantly on shipping and water transportation. In 2021, extensive rainfall led to severe flooding of the Rhine River in Germany. This flooding had a significant impact on the logistics and distribution of major German steel companies, causing delays and disruptions in their supply chains (S&P Global, 2021). As a result of the flood, the prices of North European Hot-Rolled Coil Steel surged by almost EUR50 per metric ton.

Luxembourg experts have evaluated the majority of economic assets in the country, including industrial and commercial zones, energy (except for wind turbines) and transport (except for Findel airport), to be highly vulnerable to floods, more than to any other hazard (Kleeschulte et al, 2020). Managed forests were not considered vulnerable to floods by the experts, however.

Table 4.2 provides an overview of the risks for each economic sector from each threat, based on the literature review. The risks listed in the table are associated with either higher costs, financial losses or other adverse consequences which may disrupt the workflow of the company and force them to redirect spending. The listed risks stem from a literature review covering not only Luxembourgish sources but also European and international publications. Therefore, this table represents a deduced list of risks which hypothetically can apply to Luxembourg as well, based on findings elsewhere. Similar synthesis tables are to be found in Chapters 5.2 and 6.2 respectively as well. Further details regarding **droughts and their impact on the availability of water as a resource,** stemming from changing climate trends, are discussed in Chapter 5. Luxembourg has developed a National Energy and Climate Plan (NECP) as part of the European Union's commitments. It outlines strategies for reducing greenhouse gas emissions and enhancing climate resilience (MECDD and MEAT, 2018).

Table 4.2. Summary of climate-related physical risks for selected economic sectors in Luxembourg, based on the literature review (the references can be consulted in Annex A.4).

Climate crisis	Economic sector					
	Industrial Manufacturing	Construction	Forestry	Food Processing	Energy	Logistics
Average temperature increase	Decreased productivity of workers; Decline in labour supply; Increased costs for cooling and temperature regulation	Decreased productivity of workers; Decline in labour supply; Increased costs for cooling and temperature regulation	Roots rot; Pests outbreaks (e.g. the bark beetle); Wildfires; Migration of species; Lower quality of timber	Changes in types of crops suitable for growing; Changing growth cycles; Changes in the style of wines produced;	Grid expansion pressure; Volatility of voltage supply (Brownouts);	Increased costs for cooling and temperature regulation for storage and transportation of temperature-sensitive materials and products; Disrupted flights due to technological requirements for weight regulations during heat.
Heat waves	Temporary production halts; Damage to temperature-sensitive materials	Temporary production halts; Damage to temperature-sensitive materials			Grid overload from sudden spur in demand;	
Drought	Shortage of water consumed in the production process; Shortage of water as a coolant; Obstructed supply chains by water freight	Shortage of water consumed in the production process; Obstructed supply chains by water freight	Reduced growth and timber produced / harvested; Susceptibility to pests; Decay of timber supply	Reduced harvest; Shortage of water consumed in the production process (e.g. beverages); Increased demand for irrigation;	Hydropower-generation productivity decline[15] Potential conflict between shipping and energy production	Disrupted and declined productivity of freight waterways transportation
Precipitation and riverine floods	Damage to production facilities; Damage to materials, machinery or products; Temporary shutdown; Heavy disruptions in supply chains; Damage to electronic components; Pollution and waste spill-over caused by floods and storms may incur legal liability;	Damage to construction projects; Damage to materials, machinery or products; Temporary shutdown; Heavy disruptions in supply chains;	Impact on timber harvest due to soil erosion and washing off nutrients; Damage to assets and machinery in wood processing industrial areas.	Impact on harvest due to soil erosion and washing off nutrients; Damage to assets and machinery in food processing industrial areas.	Compromised infrastructure stability due to soil erosion; Damage to infrastructure leading to power outages	Damage to facilities, freight infrastructure, and vehicles; Disrupted and declined productivity of water, road, rail and air transportation
Heavy rainfall and flash floods						
Cold waves	Disruption in operations; Disruptions in supply chains; Power outages	Disruption in operations; Disruptions in supply chains;	Ice/snow load damage; Frozen soil; Root rot	Earlier ripening and frost;	Damage to grid infrastructure leading to power outage; Grid expansion pressure;	Disrupted and declined productivity of water, road, rail and air transportation

[15] The impact of drought on the production of renewable hydrogen from water: to cover the same amount of energy by hydrogen, as was covered in 2020 by natural gas (see Figure 5.1), would require 218m^3 of water (286kJ/mol in burning H2, 55mol/l for water). Comparing this to the 44 million m^3 of annual water consumption in Luxembourg (OECD, 2018), the water needed for hydrogen production is negligible.

Climate crisis	Economic sector					
	Industrial Manufacturing	Construction	Forestry	Food Processing	Energy	Logistics
Wildfire	Power failures from floods resulting in fires; Property damage; Disruptions in operations; Explosion of flammable liquids	Damage or loss of equipment;	Damage to machinery, disruption to operations, damage/loss of materials along the wood processing value chain; Loss of timber supply	Loss of harvest; Damage to infrastructure;	Damage to grid infrastructure leading to power outage;	Damage to freight infrastructure; Disrupted supply chains
Wind(storm)	Damage to infrastructure; Disruptions of operations due to power outage;	Damage or loss of equipment; Disruption of the production process	Damage to trees; Loss of timber supply	Damage to crops, decline in harvest	Damage to grid infrastructure leading to power outage; Damage to supply chain infrastructure; *Dunkelflaute*	Damage to freight infrastructure; Disrupted supply chains

Finally, even though the transition risks related to climate change are not the primary focus of this report, the literature review has shown that the Industrial Manufacturing sector is associated with a growing number of transition risks, summarised in Text box 4.1, but not explored in further detail. The risks are included here because in reality it is not always easy to make a distinctive boundary between physical and transition risks and readers will benefit from having a fuller picture.

Increasing carbon price Different mechanisms, such as carbon taxes and emissions trading systems (ETSs), are employed globally. As of now, 30 countries have implemented carbon taxes and nine have ETSs, with prices varying from under €5 to over €100 per ton of carbon dioxide (tCO_2). The metal and steel industry is particularly vulnerable to high carbon taxes, as a carbon price above €30/tCO_2 can threaten the viability of many steel producers, impacting both revenues and costs.
Public policy restrictions Transition-focused regulatory restrictions are increasingly impacting industrial sector companies. The EU has introduced updated environmental frameworks for the sector, implementing stringent permitting processes, encouraging energy efficiency and innovation, and enforcing stricter pollution limits.
Technological shift and advancement of low-carbon technologies Transitioning to lower-carbon fuels, increasing recycling, and adopting innovative production techniques offer the industrial sector opportunities to reduce its carbon footprint. Examples such as "green" ammonia, "green" steel, bioplastics, and bio-concrete point towards the implementation of renewable energy and bio-sourced materials to stay competitive.
Emerging legal risk Legal challenges are related to the failure to report correctly GHG emissions, to comply with environmental impact regulations. Companies are becoming more vulnerable to stringent litigations which may result in substantial penalties and other costly measures forced into compliance.
Rise in reputational risk As climate change impacts increase, and stricter environmental standards and regulations emerge, industrial firms will be increasingly vulnerable to campaigns against their high-emission practices, leading to heightened reputational risks.

Text box 4.1. Text box on transition risks for Industrial Manufacturing. Source: UNEP FI, 2023.

Chapter 5. Resource Scarcity: Threat and Exposure

5.1. Resource scarcity as a threat

The economic system is our way of distributing resources, services, and goods. In the context of climate resilience and net-zero emissions binding policies, we focus on a few natural and man-made resources which are expected to experience increased demand in the near future due to ongoing transition processes in various domains, such as the phasing out of fossil fuels, the expansion of renewable energy use, the electrification of previously nonelectric processes, new ways of building and producing, among others. This report estimates the vulnerability to these natural and man-made resources through their availability and affordability levels.

Energy, and more specifically affordable "green" energy, is considered a potentially scarce resource and thus a risk driver for companies. Luxembourg primarily relies on energy imports, with less than 3% of its energy being produced domestically[16] (Figure 5.1). This heavy dependence on imports poses risks, as supply reliability can be affected by political factors. Fossil fuels, especially direct use of oil and natural gas, account for a significant portion of Luxembourg's energy consumption, contributing to the climate crisis. To achieve its goal of net-zero emissions by 2050, Luxembourg plans to reduce or replace these fossil fuel sources with an emphasis on increasing electrification and efficiency (MECDD and MEAT, 2018). Electrification plays a crucial role in this process of energy transition, with electricity replacing fossil fuels in sectors like transportation, heating, and industry. The power sector is shifting toward renewable sources, and the increased electrification demands an expansion of the electricity grid.

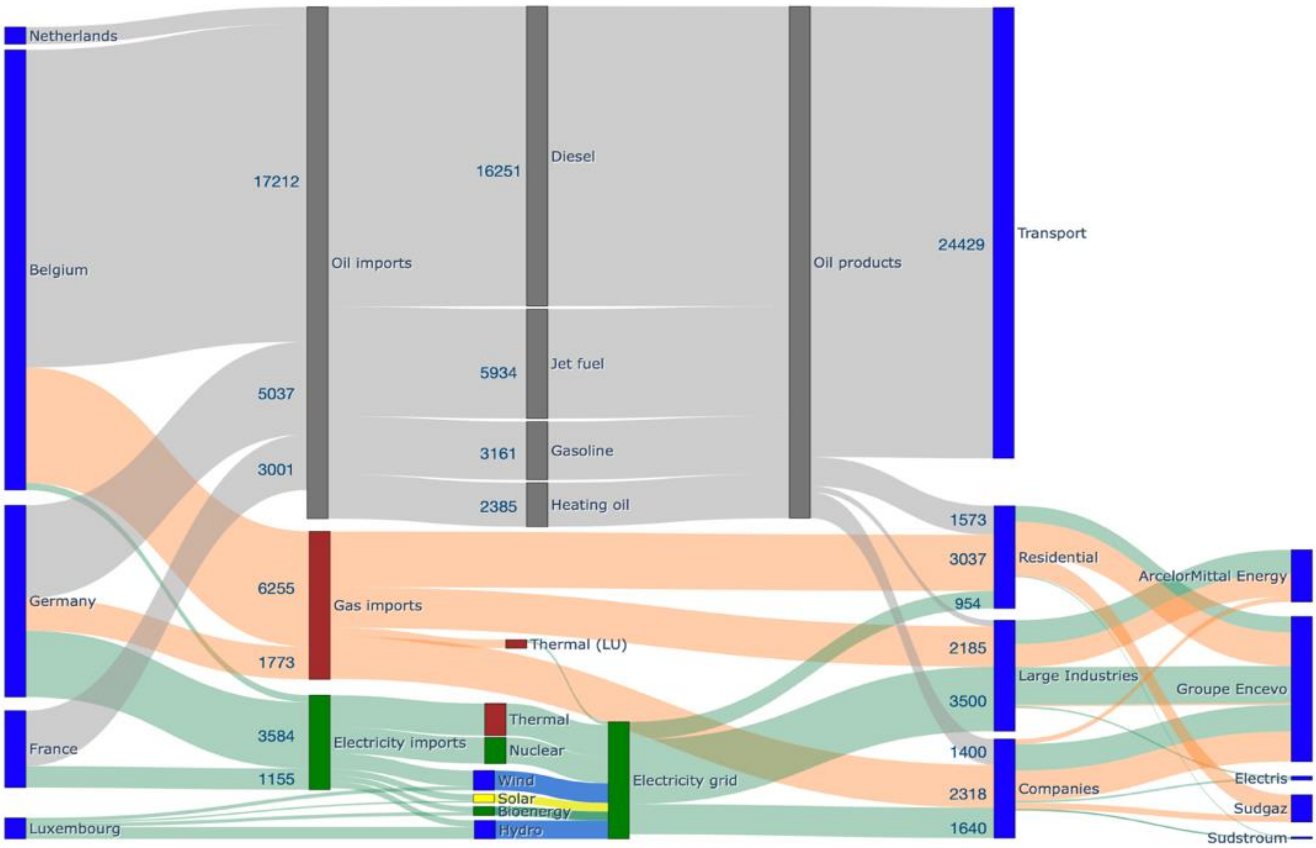
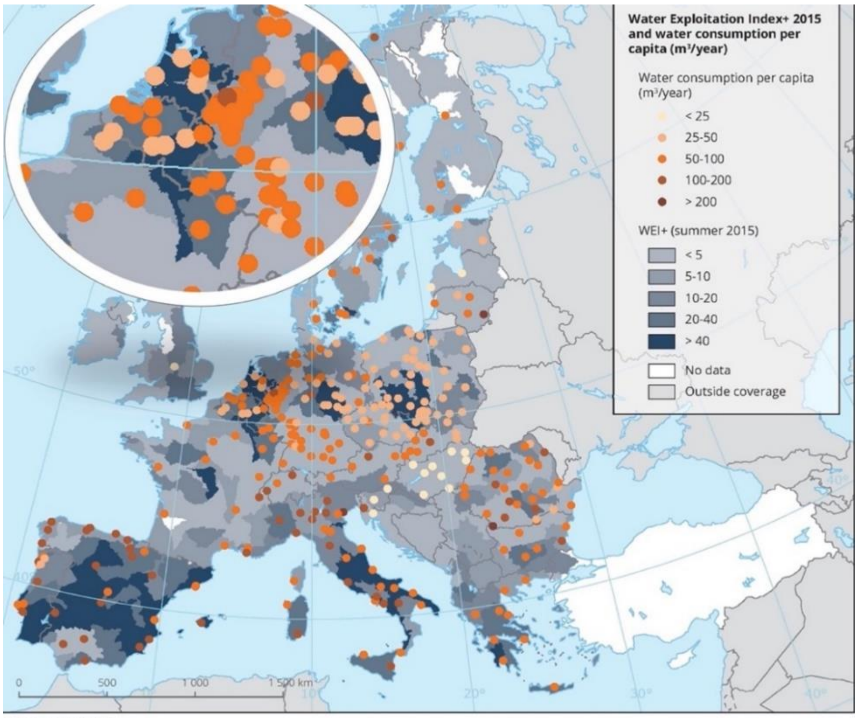


Figure 5.1. Physical energy flows in GWh from neighbouring countries (left) to Luxembourg and distribution of energy for different uses and users (right) 2020 data. Authors' computation. Data sources: Eurostat, ILR, Statec, Groupement Energies Mobilité.

16 This number is not in contradiction to the numbers from the PNEC, which states that in 2020 9,4% of the total energy consumption in Luxembourg was renewable. The numbers in PNEC contain imported renewable energy, e.g. in the form of biofuel, added to imported gasoline.

Water can be a threat in two dimensions: the scarcity of water may lead to droughts affecting freshwater supply, groundwater recharge and navigable water levels; while the excess of water from rainfall may lead to floods, as detailed in Section 5.1 (Scott, 2012; Velasco et al., 2018; Pamidimukkale et al., 2021). Even though water in Luxembourg is abundant (OECD, 2015), one-third of water bodies in Luxembourg are considered "at risk", based on EU criteria. Figure 5.2. maps the pressure on freshwater resources (water exploitation index[17]) for Europe, where Luxembourg scores 20-40% which indicates a relatively high degree of stress and unsustainable resource use. Freshwater in Luxembourg is used both as drinking water for households (approx. 60%), as a resource for industrial production (approx. 23%) and for agriculture (approx. 7%)[18]. Overall, water consumption in the country has been decreasing despite population growth, mainly due to water efficiency measures. Industrial water consumption is relatively low compared to other countries, primarily due to the decline of the steel industry and proactive measures taken by the industries themselves. Agricultural water consumption is also relatively low, but there is an expected increase due to growing regulations for locally produced food and a rising risk of droughts. Higher temperatures can lead to increased evaporation rates, which, combined with reduced water availability from decreased rainfall, can lead to water scarcity and intensify the impact of drought. However, large-scale industrial projects, like the proposed Google datacentre in Bissen or the consideration of a yoghurt factory near Bettembourg, could potentially lead to increased water consumption in the country. These and similar projects might involve using river water or treated wastewater for cooling or other subsidiary tasks, a practice common in other countries. Nonetheless, the increasing likelihood of droughts resulting from climate change poses a risk to such applications. Approximately 50% of the drinking water in Luxembourg comes from groundwater, and the remaining 50% is sourced from the water reservoir managed by the Syndicat des eaux du barrage d'Esch-sur-Sûre (SEBES). Drinking water reserves are projected to meet demand until around 2035-2040, but shortages are already anticipated, particularly during the summer months. To address these challenges, Luxembourg's National Strategy[19] is based on three key pillars: 1) protecting existing water sources, 2) promoting water-saving practices in households and industries, and 3) exploring new water sources. Ongoing considerations include the development of a novel water treatment facility on the Mosel River to prepare river water for industrial purposes. Additional explorations consider the use of treated greywater in households, such as for toilet flushing, and the utilization of treated wastewater in agriculture, specifically in viniculture and at the Mertert wastewater treatment plant.



Reference data: ©ESRI

Figure 5.2. Map of water consumption per capita and water exploitation index per river basin in Europe, with a zoom-in section on the Benelux area. Source: EEA, 2018.

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[17] The water exploitation index assesses the total freshwater used as a percentage of the total renewable freshwater available (Raskin et al, 1997).
[18] Water Management Administration Luxembourg
[19] A summary of publications regarding water-related risks can be found in Annex A.3.

A variety of metals, minerals and raw materials are used in the increasingly complex products and technologies we use today, especially in the context of transitioning to net-zero practices. The market for minerals and metals is highly globalised and European countries in general depend on imports, as visualised in Figure 5.3. The term 'critical raw materials' refers to a list of materials considered of strategic importance for the EU's economy that have high supply risk and low or no substitution options. As of 2023, there are 34 minerals or groups of minerals materials classified in the EU's list of critical raw materials (Figure 5.4). The application of these materials is of critical importance for developing technologies such as li-ion batteries, robotics, electric traction motors, and others, with application in the manufacturing of equipment for renewable energy generation, for the automotive industry, and others.

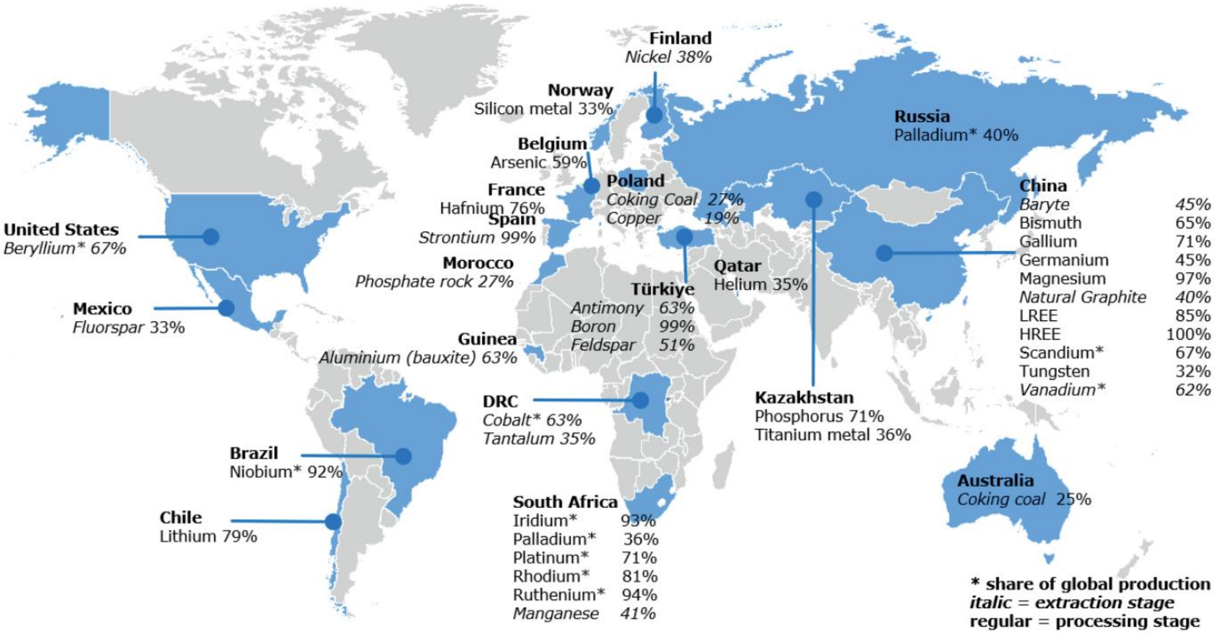


Figure 5.3. Countries representing the major suppliers of critical raw materials for the European Union. Source: European Commission, 2023b.

2023 CRMs vs. 2020 CRMs			
aluminium/bauxite	gallium	phosphate rock	vanadium
antimony	germanium	phosphorus	arsenic
baryte	hafnium	PGM	feldspar
beryllium	HREE	scandium	helium
bismuth	lithium	silicon metal	manganese
borate	LREE	strontium	copper
cobalt	magnesium	tantalum	nickel
coking coal	natural graphite	titanium metal	~~indium~~
fluorspar	niobium	tungsten	~~natural rubber~~

Legend:
Black: CRMs in 2023 and 2020
Red: CRMs in 2023, non-CRMs in 2020
~~Strike:~~ Non-CRMs in 2023 that were critical in 2020

Figure 5.4. The list of critical raw materials in 2023, including the newly added ones (in red) and the removed ones (stroked in blue). Source: European Commission, 2023b.

In addition to the list developed by the European Commission (2023b), another important material relevant to Luxembourg's economy is timber, accounting for approximately 10% of the construction in the country (Hennebert and Lambert, 2021). Besides construction, timber is relevant for the manufacturing of paper products and furniture as well.

Land as a resource is understood as land for development and production. European countries are constantly striving to maintain a balance between different land use demands such as urbanisation, agriculture, and nature preservation. Nevertheless, 1.26 million ha of land were converted to urban use in the 2000-2018 period, whereas only 176,000 ha were deurbanised. In Luxembourg, between 5000 and 10 000 m^2 of land (equivalent to a football pitch) were converted for development *daily* in the same period (ESPON, 2020). The EU's objective of "no net land take" by 2050 will pose a big challenge to overcome this trend for all member states (European Commission, 2021; Science for Environment Policy, 2016). Converting land from one use to another is a dynamic practice in Europe to meet the needs of a growing and changing population in terms of demographics but also cultural and economic activities. Nevertheless, the artificialisation of land, and urban sprawl as its main driver, leads to various adverse consequences not only related to biodiversity habitats but also to the quality of life of people, including increasing commute rates and decreasing air quality. The future distribution of land use and rate of land take highly depend on prioritised objectives and paradigms. For example, following the current trend, scenarios by ESPON foresee more than a 120% net increase in urbanisation in Luxembourg, mostly in response to housing needs and aspirations for housing types (ESPON, 2020). On the other hand, the Luxembourg in Transition project has proposed solutions for housing a growing population and its sustainable needs with zero net land intake, but only through rebuilding, overbuilding (vertically) and conversion of existing buildings and land sites (Figure 5.5, Luxembourg in Transition, 2021). Both approaches would require significant negotiations and trade-offs between stakeholders. Due to Luxembourg's small geographical size, land is a precious and finite resource. The current land distribution in the country is dominated by agriculture and forested areas (50% and 36% respectively), built-up, industrial, road and rail infrastructures combined cover 12%, and water bodies and natural surfaces cover about 2% (DATer, 2022). Land use choices and practices may serve as risk drivers or risk mitigators. For example, the artificialization of land is considered one of the largest drivers of climate change, whereas allocating more land for vegetation can prevent or mediate the impact of floods.

— 2021

— 2047

Figure 5.5. Example of land use conversion for meeting population's needs in a no-net-land-take scenario between year 2021 and 2047. Source: Luxembourg in Transition, 2021.

Summary of the assessed threats related to resource scarcity, and their adopted definitions:

blackout	occurrence of a temporary loss of electrical power supply
brownout	occurrence of a temporary reduction in power voltage
energy price/use	high price for electricity combined with high usage
raw materials	high price and limited availability of critical raw materials
industrial land	occurrence of vigorous competition for industrial land due to limited availability and high demand
water navigation	changes in the water levels of navigable water bodies
fresh water	decline in the reservoirs of fresh water
flash floods	flooding events caused by heavy rainfall

5.2. Economic implications

Lack of availability of water as a resource may become a threat causing numerous risks for industrial water-intensive processes such as food and beverage processing and manufacturing, cooling during metal and steel manufacturing processes, agricultural irrigation, and cement production (Figure 5.6). In addition, global supply chains relying on water freight are dependent on water levels. The industrial sector in Luxembourg uses around 23% of the water in the country, which is below the 40% European average for the four main industrial sectors of mining and quarrying, manufacturing, electricity and construction combined (Förster, 2014). Presently, 995 €billion of economic activity, including manufacturing, mining, construction and services, is exposed to water scarcity across the EU+UK, of which the majority is located in the Mediterranean area. Nevertheless, around 121 €billion of economic activity located in continental Europe is currently exposed to water scarcity, and this number is expected to moderately increase with the level of warming (European Commission, 2020c). Some of the key water-intensive industrial processes in the selected economic sectors include (Charles et al, 2009; European Water Association, 2018):

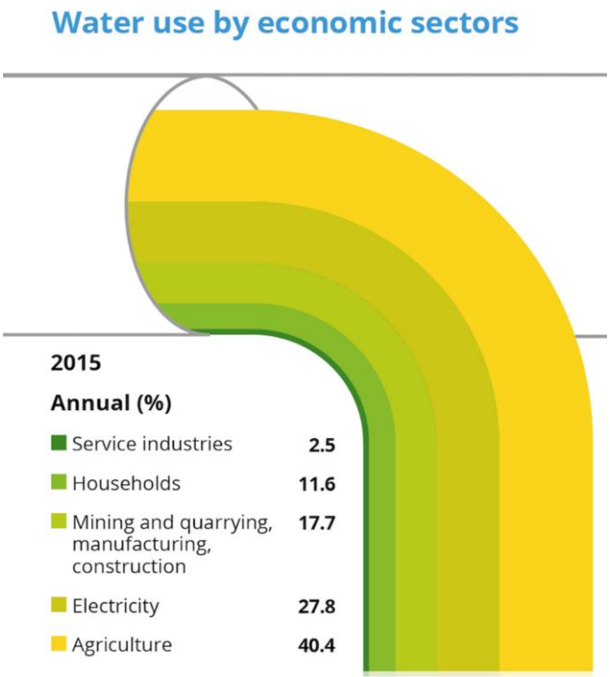


Figure 5.6. Water consumption by economic sector in Europe for 2015. Source: EEA, 2018.

- Various manufacturing industries, such as automotive manufacturing, electronics, and chemical production, use freshwater as a coolant, solvent, or for cleaning and rinsing during their manufacturing processes.
- Food and Beverage Processing: requires freshwater for cleaning, processing, and as an ingredient in food and beverage products. Meat processing and dairy production, well-represented in the food system in the country, require water for cleaning and processing agricultural products.
- The Construction sector uses water for mixing concrete, curing, and cleaning equipment and construction sites.
- Water is a crucial component in the Paper and pulp industry, where it is used to pulp wood fibres and as a cooling agent in various machinery.
- Water as a means of transportation is crucial for the logistics sector.
- Decreased water availability may impact hydro-energy generation.

All these processes are vulnerable to a decrease in the availability of water. In some cases, the impact of water scarcity can trigger restrictions on water usage, affecting both households and businesses (Phillips & Green, 2022). For example, European industry actors relying on the Rhine River for the cooling process and for transportation of raw materials feeding into the supply chain and finished products sent downstream the supply chain had experienced significant economic losses due to the 2018 drought impacting the river levels (UNEP FI, 2023). Nevertheless, most existing studies focus on the municipal and household levels, and there is a lack of specific studies at the national level in Luxembourg regarding industrial water use and associated risks, particularly on drought mitigation strategies.

It is worth noting that Luxembourg is highly reliant on import/export flows, which necessitates a closer analysis of the logistical infrastructure and the supporting Logistics industry to ensure the continuation of flows of goods when climate disruptions take place (Research Luxembourg, 2020). Below we review the potential impacts on the logistics infrastructure:

- Rail network: The rail infrastructure is rather limited meaning there is no redundancy or substitutability in case of disruptions. The local system connects to other parts of the European network, but detours might be lengthy. Several sections of the rail infrastructure are located next to waterways which are subject to floods.
- Waterways: certain goods rely on waterways (in particular, metal and bulk goods). Waterways are subject to two major climate events: floods and dry rivers (which may be due to lack of rain, lack of snow or lengthy heatwaves, among others). Luxembourg is highly susceptible to such events as the 2021 flooding demonstrated. The 2021 flooding impacted the Maas, Ahr, Mosel, and Rhine rivers (and their tributaries) — home to highly specialized manufacturing clusters.
- Intramodality: This can also be impacted by floods. Intermodal services in Belgium were halted during the 2021 floodings. Airports: there is one major airport in Luxembourg so there is no immediate substitution; several major logistic hubs and minor airports in the greater region exist. Those have the potential for some substitution. Weather conditions can disrupt airports and halt operations. The 2021 floodings had some limited impact on airports (Liege was briefly interrupted).

Although resource scarcity in the water sector is becoming a concern, national strategies in Luxembourg do not seem to comprehensively address these issues. For instance, reports on the scarcity of precipitation agents for wastewater treatment such as Fe- or Al-based chemicals, which were scarce in 2022 at waste-water treatment plants, emphasise the need for proper resource management in this sector. Additionally, there have been challenges related to CO_2 shortages, affecting the production of beer and carbonated beverages, and leading some smaller suppliers to cease production. On a positive note, some resource scarcities, such as phosphorus, which is a limited global resource, can potentially be mitigated through recovery efforts, particularly from wastewater sources. This suggests the need for more focused research and strategies to address resource scarcities and vulnerabilities within the Luxembourgish context.

Luxembourg's vulnerability to **electricity** supply disruptions stems from its reliance on imports. Interruptions in electricity supply can lead to production stoppages, equipment damage, and economic losses. Ensuring a stable and resilient energy supply is crucial for the economic viability of all businesses. Instabilities in the electricity supply carry various risks for industry. The most obvious and serious one is production interruption and the associated economic loss in the case of a blackout. Also, communication would be interrupted, with serious consequences for communication-based industries, an example here is communication with satellites. In addition, blackouts and even brownouts, i.e., mere fluctuations in the grid voltage and frequency, can cause damage to equipment and thus economic loss. A further risk in the case of insufficient electricity supply is a rise in prices, which can be significant, as seen by the current energy crisis. Furthermore, as a study of the industry in Taiwan showed, the indirect effects, i.e., economic losses in downstream industries because of electricity interruption for one industry, are even more significant in terms of economic losses (Wu, 2018). A worst-case scenario is a longer blackout for several days, which would have serious implications not only for production, but also for supply chains: without electricity, fuel stations do not work, and neither do many trains. However, given the redundancy of the European and the Luxembourgish electricity grid, the probability of such a scenario is low (Stankovski et al, 2023; Petermann et al, 2011; Bruh et al, 2011).

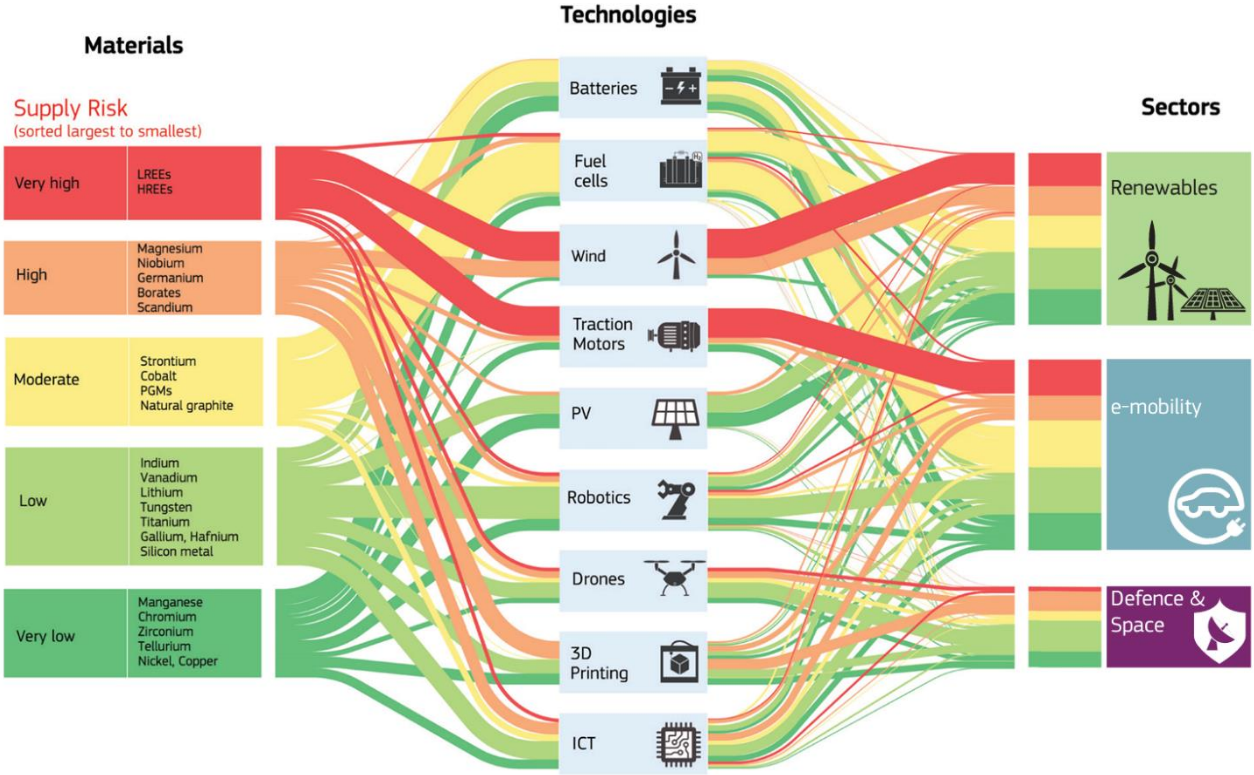


Figure 5.7. Flows of raw materials and their current supply for selected technologies and sectors. LREEs/ HREEs stand for Light/Heavy Rare Earth Elements. Source: European Commission, 2020a.

The **critical raw materials** identified by the EU are relevant for multiple economic sectors such as metallurgy and steelmaking, manufacturing of semiconductors, glass, batteries, expansion of electricity network and electrification of processes across sectors (Figure 5.7, European Commission, 2020a). The pledged transition to net-zero emissions in the energy sector is coupled with different materials-intensive processes such as the manufacturing of electric vehicles, batteries, solar photovoltaic systems, wind turbines, and hydrogen technologies (Gregoir and Van Acker, 2022). Some of the most demanded elements for these processes will be aluminium, copper, zinc, and silicon. For example, the manufacturing of electric vehicles to replace traditional vehicles will require a manifold increase in the demand for aluminium, copper, and lead. The manufacturing of solar photovoltaic systems and wind turbines is also expected to increase the demand for aluminium, copper, zinc and rare earth elements. Furthermore, both the expansion of energy systems based on renewable resources and the expansion of electric vehicles will increase battery production, which will drive demand for lithium, cobalt and nickel. Some of the materials in the EU's critical list have strategic importance for the food sector, particularly as fertilizers in agricultural processes, such as phosphorus and phosphate rock. There is an ongoing upward trend in the use of wood in construction in Luxembourg, which is expected to increase more in the coming years (Mantin et al, 2021). Despite the many environmental benefits of using wood as a renewable resource, the underlying risks related to the physical threats need to be assessed, including the double materiality related to the impacts on ecosystems from local harvesting.

The prosperity of all six economic sectors discussed in this study is bound to the physical exploitation of **land** for their activities. The Construction sector is expected to experience very high pressure from the restrictions on land intake, because it directly relies on land for the development of new construction projects, although renovation of existing buildings is a big share of its activities too. Industrial manufacturing demands specific areas designated as "industrial" land for establishing and expanding production facilities for manufacturing processes, warehouses, and associated infrastructure. Forestry requires land for the growth of trees and furthermore industrial assets for the processing of wood (e.g. sawmills). Food processing demands land for the manufacturing of meat and dairy products in technology-intensive industrial facilities. Energy, including grid expansion and especially the anticipated renewable energy systems, would require increased use of land as well. Logistics and warehousing are particularly land-intensive activities as well. Luxembourg is positioning itself as a logistics hub within Europe (C4L) which influences the allocation of land for warehousing and infrastructure development.

Table 5.1. Summary of resource-related physical risks for selected economic sectors in Luxembourg, based on the literature review (the references can be consulted in Annex A.5).

Resource scarcity	Economic sector					
	Industrial Manufacturing	Construction	Forestry	Food Processing	Energy	Logistics
Energy: insufficient availability of electricity brownout blackout high prices	Price increases; Disruptions to supply chains; Difficulty in securing enough electricity or fuels; Damage to equipment; Interruption of production and communication; Indirect losses in downstream industries	Price increases; Disruptions to supply chains; Damage to equipment; Interruption of production	Some energy-intensive activities along the value chain may be severely disrupted, such as sawmills	Product losses from temperature-sensitive storage failure; Damage to equipment; Interruption of production; Indirect losses in downstream industries	Pressure for increasing grid capabilities	Increased costs for fuels; Interruption in operations
Water: drought	Shortage of water consumed in production process es; Shortage of water as a coolant; Obstructed supply chains by water freight	Shortage of water consumed in the production process; Disrupted supply chains by water freight	Reduced growth and timber produced / harvested; Susceptibility to pests; Decay of timber supply	Disruptions due to shortage of water as an ingredient in products; Shortage of water for meat and dairy processing	Hydro-generation productivity decline[20]	Disrupted and declined productivity of freight transportation
Water: floods	Power failures from floods resulting in fires; Property damage; Disruptions in operations; Explosion of flammable liquids	Damage or loss of equipment	Damage to machinery, disruption to operations, damage/loss of materials along the wood processing value chain; Loss of timber supply	Loss of harvest; Damage to infrastructure	Damage to grid infrastructure leading to power outage.	Damage to freight infrastructure; Disrupted supply chains
Raw materials	Disrupted manufacturing of basic metals, fabricated metal products, motor vehicles, machinery, equipment and packaging	Disrupted supply chains of construction materials, e.g.: glass, cement, concrete, roundwood, metals, flame retardants, plasters, wood preservatives	Pressure for timber supply; Disrupted supply of fertilizers affects tree growth in nurseries.	Disrupted supply of fertilizers interrupting food supply chains;	Disrupted supply chains for manufacturing wind turbines, photovoltaic panels, batteries for energy storage, and grid expansion	Disrupted supply chains of steel and alloys for transport equipment and infrastructure
Land	Limited possibilities for the establishment or expansion of production facilities	Limited possibilities for development projects	Limited possibilities for expansion of tree stands.	Limited possibilities for establishment of production facilities or expansion of arable land	Limited possibilities for grid expansion and establishment of renewable energy systems	Limited possibilities for establishment and expansion of road and storage infrastructure

[20] The impact of drought on the production of renewable hydrogen from water: to cover the same amount of energy by hydrogen, as was covered in 2020 by natural gas (see Figure 5.1: 8000GWh), would require 1.7 million m3 of water (286kJ/mol in burning H2, 55mol/l for water). Comparing this to the 44 million m3 of annual water consumption in Luxembourg (OECD, 2018), the water needed for hydrogen production is about 4%. A very severe drought could thus also impact the ability to produce renewable hydrogen.

Chapter 6. Biodiversity Loss: Threat and Exposure

6.1. Biodiversity loss as a threat

Thriving biological variability *(biodiversity)* in ecosystems, species and genes reflects the health and resilience of nature and, in turn, the formation of Nature's contribution to people, also referred to as "ecosystem services" (IPBES, 2019). Nature's contribution to people is a concept reflecting the relationship between nature and people's quality of life. People can transform nature's contributions into positive benefits, but we can also depreciate and disrupt them. Societal development has negative effects on nature and biodiversity via patterns of land use, economic growth and impact on climate (IPBES, 2019). Therefore, the loss of biodiversity is considered a threat and can lead to economic risks. Trends in species survival have been monitored over the last decades and reveal alarming rates of animal and plant species extinction, and degradation of land and water sub-ecosystems, such as maritime life (Figure 6.1). Other indicators of biodiversity loss may include the spread of invasive alien species, decline of pollinators, habitat loss, and diminishing quality of water and forest ecosystems, labelled here *various ecosystem* services (a complete description can be found in Figure 6.2 and Table 6.1).

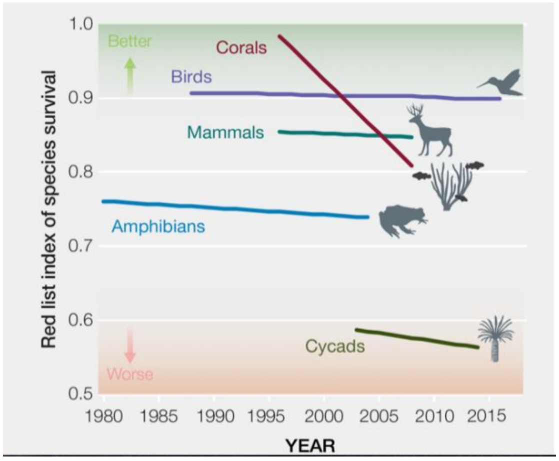


Figure 6.1. Global decline in Red List Index species survival since 1980. Source: IPBES, 2019.

An analysis of habitat loss trends in Luxembourg shows an increased fragmentation and loss of habitats as well as a reduction of ecological connectivity in Luxembourg from 1999 to 2007 with regard to selected species, and this trend will likely continue by 2030 (Babí Almenar et al, 2019). The reduction of ecological connectivity is associated with the loss and fragmentation of pastures, deciduous and coniferous woodlands, grasslands, and rocky areas, and the affected animals include butterfly species, amphibians, and small mammals such as the wildcat and the pine marten.

Figure 6.2. Visualisation of ecosystem services category according to the Common International Classification of Ecosystem Services (CICES).

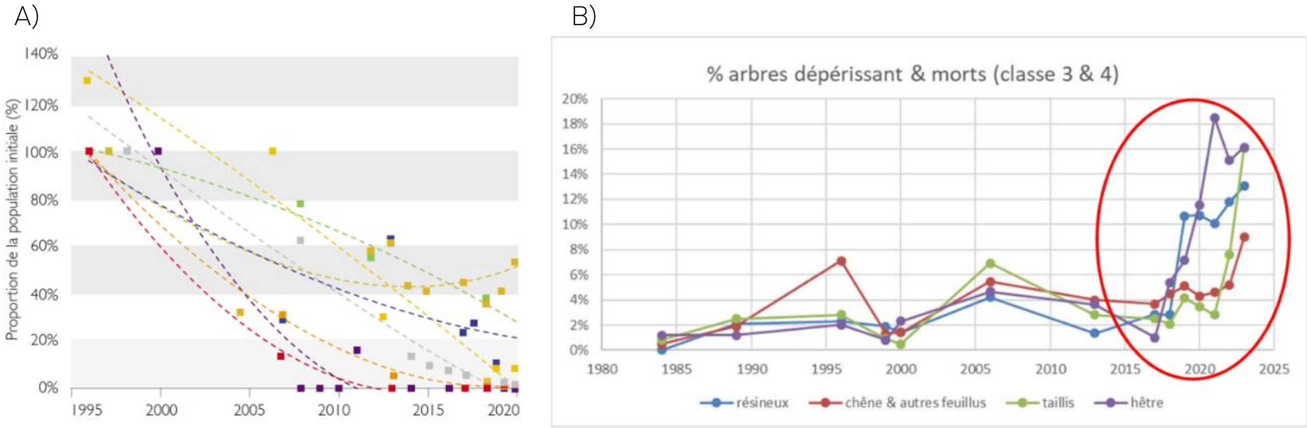


Figure 6.3. A) Evolution (in % of an initial population) of eight rare and/or endangered open habitat bird species, from 1996 to 2020. Source: Observatoire de l'environnement naturel, 2022. B) Comparative trends of decay and mortality for different tree species between 1985 and 2022. Source: Administration de la nature et des forêts, 2023.

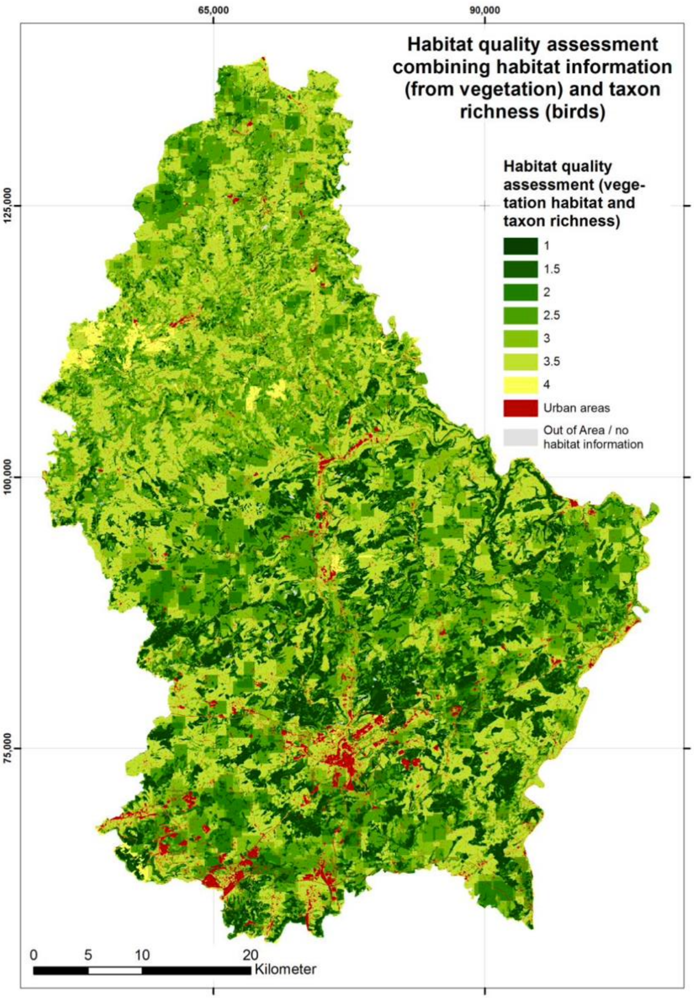


Figure 6.5. Ecosystem quality map integrating habitat (vegetation) and bird species richness information. Areas range from dark green (best quality) to yellow (least quality). Source: Becerra-Jurado et al, 2015.

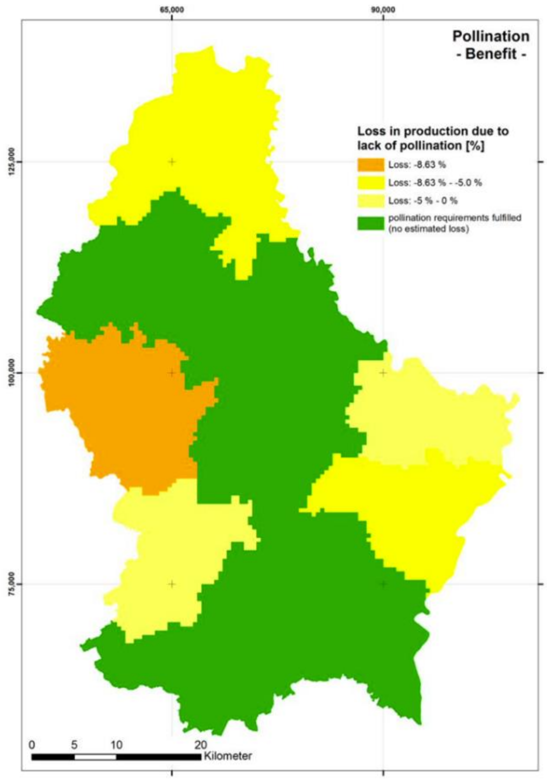


Figure 6.4. Potential loss in rapeseed production due to insufficient existing managed beehives providing pollination. Source: Becerra-Jurado et al, 2015.

The latest report on the condition of biodiversity in Luxembourg has concluded that a quarter of all habitats in the country, and *all* open environment habitats, are in bad condition (Observatoire de l'environnement naturel, 2022). Open environment habitats refer to agricultural and permanent grasslands, which coincidentally cover 60% of the territory (Statista, 2023). The bad condition of grasslands and open environments has consequences for a variety of species, which inhabit these areas, including birds and pollinating insects. The graph in Figure 6.3.A) plots the declining trend in the population of rare or endangered birds in the country, whereas the map in Figure 6.4 represents the spatial assessment of ecosystem quality measured by the observed presence of bird species and habitat vegetation (yellow colour represents lower quality of ecosystem functioning). Overall, the report concludes that agricultural activities lead to deteriorating open space habitats and their belonging species, which in turn negatively affects agricultural practices via diminishing soil quality and pollination. Figure 6.5 demonstrates the potential loss in rapeseed production (up to 8.6% in the area marked with orange) as a result of the decline in pollinating insects, particularly bees. Furthermore, more than half of the butterfly species and some clean water-dependent species are also in declining trends. Furthermore, the annual national forest inventory revealed an alarming deteriorating condition of more than half of the trees on the territory of Luxembourg (Administration de la nature et des forêts, 2023). Figure 6.3.B) emphasises a sharp increase in the share of decaying and dead trees in the country since 2018-2019. On a positive note, observations from targeted management in forests and the former open-pit mines demonstrate beneficial biodiversity results.

Table 6.1. Categorisation of Nature's contribution to people (NCP) as an updated version of the ecosystem services framework based on IPBES with a brief description for each. Source: Brauman et al, 2020.

Nature's contribution to people		Brief description
Regulating	Habitat creation and maintenance	The formation and continued production of ecological conditions necessary or favourable for living beings important to people
	Pollination and dispersal of seeds	Animal facilitation of pollen movement and seed dispersal of beneficial organisms
	Regulation of air quality	Filtration, fixation, degradation or storage of pollutants and gasses
	Regulation of climate	Emission and sequestration of greenhouse gases, biogenic volatile organic compounds, and aerosols; biophysical feedbacks (e.g., albedo, evapotranspiration)
	Regulation of ocean acidification	Regulation by photosynthetic organisms on land and sea of atmospheric CO_2 concentrations and thus seawater pH
	Regulation of freshwater quantity	Regulation of the quantity, location, and timing of the flow of surface and groundwater
	Regulation of freshwater quality	Ecosystem filtration and addition of particles, pathogens, excess nutrients, and other chemicals
	Formation and protection of soils	Soil formation and long-term maintenance of soil fertility, including sediment retention and degradation or storage of pollutants
	Regulation of hazards and extreme events	Amelioration of the impacts of hazards; reduction of size or frequency of hazards
	Regulation of detrimental organisms	Regulation of pests, pathogens, predators, competitors, parasites, and potentially harmful organisms
Material	Energy	Biomass-based fuels such as biofuel crops, animal waste, and fuelwood
	Food and feed	Food and feed from wild, managed, or domesticated organisms from terrestrial, freshwater, and marine sources
	Materials and assistance	Cultivated or wild materials and direct use of living organisms for industrial, ornamental, company, transport, labour, and other uses
	Medicinal and genetic resources	Naturally derived medicinal materials; genes and genetic information
Nonmaterial	Learning and inspiration	Capabilities developed through education, knowledge acquisition, and inspiration by nature for art and technological design
	Experiences	Physically and psychologically beneficial activities, healing, relaxation, recreation, and aesthetic enjoyment based on contact with nature
	Supporting identities	The basis for religious, spiritual, and social cohesion; sense of place, purpose, belonging, or rootedness associated with the living world; narratives, myths, and rituals; satisfaction from a landscape, seascape, habitat, or species
	Maintenance of options	Capacity of nature to keep options open to support quality of life in the future

Summary of all assessed biodiversity-related threats and their adopted definitions:

soil erosion	wearing away the upper layer of soil
pests	occurrence of pest infestations
air pollution	decline in the quality of air
grasslands	deteriorating conditions of grasslands
water ecosystems	deteriorating conditions of water ecosystems
plant species	changes in the type of plant species present or decline in their numbers
lifecycle plants	occurrence of changes in the lifecycle of plants, e.g. earlier ripening
animal species	changes in the type of animal species present or decline in their numbers, e.g. decreasing number of pollinators

6.2. Economic implications

There has been an increasing effort to translate natural assets into economic terms. The Dasgupta Review raises the concern that the conventional way of measuring prosperity and wealth via economic output (GDP) fails to account not only for the lost natural capital but also for the consequential economic costs associated with this loss (Dasgupta, 2021). This systemic lack of better accounting for natural assets within economics makes it extremely difficult to estimate the impact of biodiversity loss on the economy. Due to long global value chains, some companies may fail to recognise and measure their direct or indirect dependence on biodiversity and ecosystem services, which is a major concern in mainstreaming biodiversity monitoring and reporting activities in the manufacturing industries (Convention on Biological Diversity (CBD), 2018). Initiatives related to transparency in financial investments have put forward the practice of double materiality, which aims to reveal not only how an investor's assets may be significantly compromised by environmental factors, but also how financial investments may incur a significant impact on the environment. Assessments on ecosystem service dependencies and the impact of biodiversity loss have revealed that financial assets worth billions of euros are indirectly dependent on the provisioning of ecosystem services to business processes (DNB & PBL, 2020). Industrial manufacturing benefits from various ecosystem services provided by nature, such as water purification, pollination, and climate regulation. Biodiversity loss can disrupt these services, potentially affecting production processes or increasing operational costs.

Biodiversity-related economic risks are again divided into physical and transition risks. Physical risks are those stemming directly from ecosystem processes such as loss of pollinating species or other ecosystem services such as soil quality. Transition risks are related to changing regulations in terms of pollution and the environmental impact of business activities (refer to Figure 4.6). Due to long global value chains, some companies may fail to recognise and measure their direct or indirect dependence on biodiversity and ecosystem services, which is a major concern in mainstreaming biodiversity monitoring and reporting activities in the manufacturing industries (Convention on Biological Diversity (CBD), 2018). Globally, the economic sectors most directly dependent on nature/ecosystem services are construction, forestry, agriculture, and food, beverages and tobacco production (Herweijer et al, 2020). These sectors rely on either the direct extraction of resources from forests and oceans or the provision of ecosystem services such as healthy soils, clean water, pollination and a stable climate, at different stages of the production processes. Despite those three most vulnerable economic sectors it is important to consider that the energy, logistics, and manufacturing sectors experience numerous "hidden dependencies", typically along their value chains.

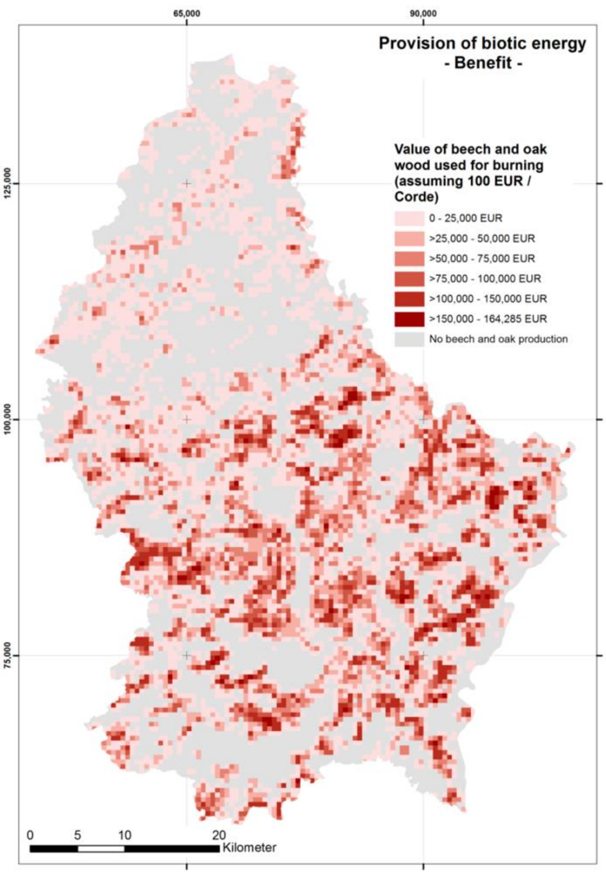


Figure 6.7. Map showing ecosystem benefit for provision of biotic energy. Source: Becerra-Jurado et al, 2015.

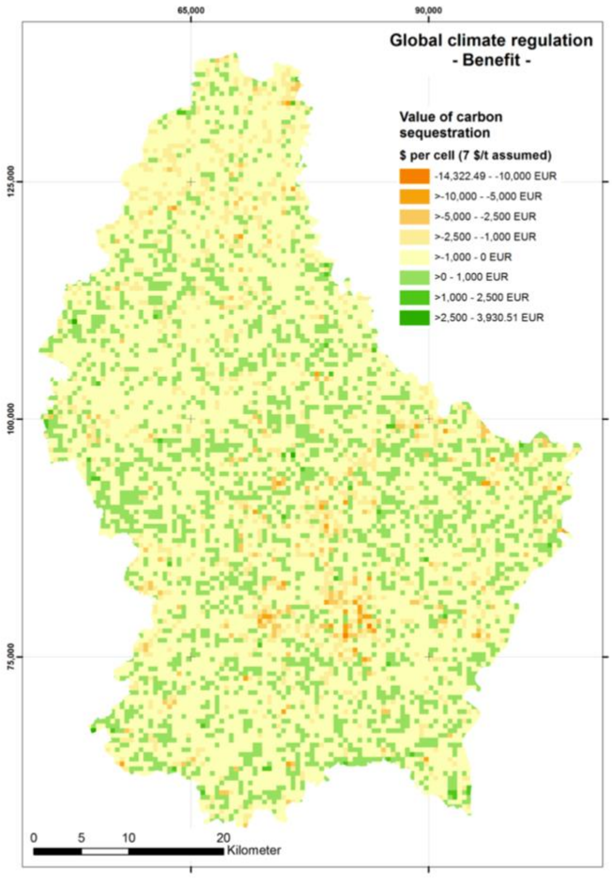


Figure 6.6. Map showing ecosystem benefit for global climate regulation. Source: Becerra-Jurado et al, 2015.

Forests provide several ecosystem services, many of which are in trade-off when increasing the application of one service decreases the benefits supplied by another service. For example, timber production and biodiversity have a negative relationship, which means that prioritising forest management for timber harvest would lead to a decline in the forests' biodiversity (Selkimäki et al, 2020). An assessment of the ecosystem services in Luxembourg (Becerra-Jurado et al, 2015) has estimated the value of the provision of bio-energy, measured by the price of beech and oak-wood used for heating[21] (Figure 6.6). Another ecosystem service – climate regulation, has been measured as the value of carbon sequestration per location in the country, reflecting healthy forest distribution (Figure 6.7).

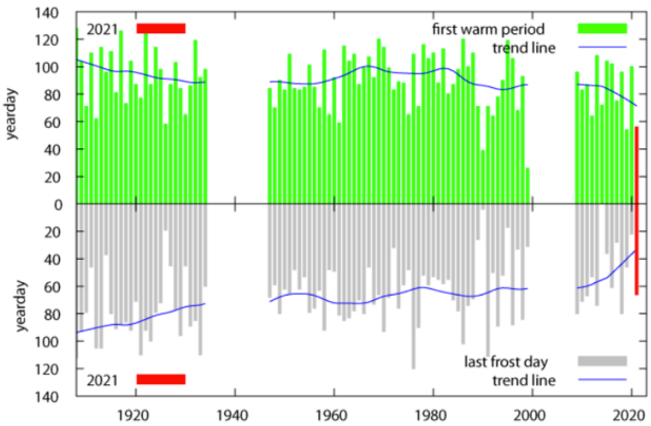


Figure 6.8. Day-of-the-year of the end of the first ≥10-day period with daily maximum temperature > 10°C (green bars) and the last Frost Day observed at Trier-Zewen. Source: Copernicus Climate Change Service, 2021.

The direct impact of animal and plant richness decline on industrial manufacturing, construction, energy and logistics is not straightforward, as these industries primarily focus on human activities related to producing goods and services. Industrial manufacturing most often relies on the regulating ecosystem services such as, for example, the automotive sector's dependency depends upon access

[21] Corde: volume unit representing two cubic meters of stacked wood (1 Corde = $2m^3$ of stacked wood)

to water and on the ability of ecosystems to filter and decompose organic wastes and pollutants in water (ten Have et al, 2012). Ecosystems provide many of the raw materials needed in construction, such as timber, stone, sand, and gravel. Forests, for example, are essential sources of timber for structural elements and wood-based products. Quarries and riverbeds provide sand and gravel for concrete production. Furthermore, with the transition to net-zero emission in the construction sector, other bio-sourced building materials such as hemp, straw bales, and cork will increase in demand. There are also indirect and interconnected ways in which the variety of species and broader ecosystem services can influence these sectors, such as supply chain disruptions when sourcing materials from regions where the ecosystem is compromised. Furthermore, regulatory changes may obstruct the expansion of industrial sites or the allocation of sites for development when the overall trends in animal population richness are low.

Besides the human-induced changes to ecosystems and biodiversity via predominantly land-use practices, human-induced climate change exacerbates biodiversity loss risks. For example, changes in the climate lead to changes in the lifecycle of plant species, which makes some crops unsuitable or exposes them to the risk of early frost. Observations in the Trier – Zewen Mosel wine region demonstrate a trend of bringing the first warm day and last frost day closer together (Figure 6.8.), increasing the risk of early frost in plants and potential economic impacts for agriculture, viticulture and the Food sector in general, including food processing (Copernicus Climate Change Service, 2021).

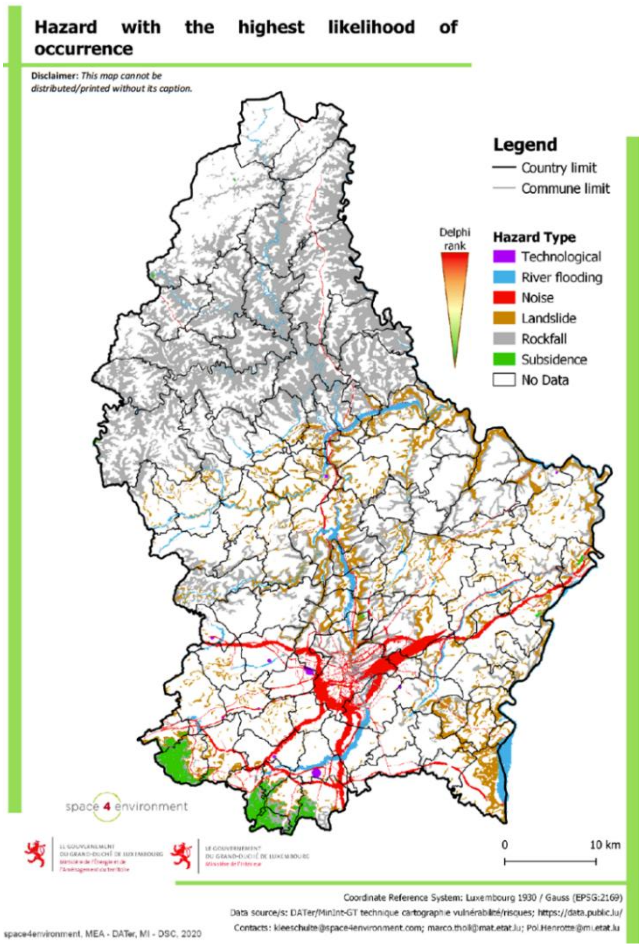


Figure 6.9. Map of Luxembourg showing the results of spatial analysis for the highest likelihood of occurrence for six hazards. Source: Kleeschulte et al, 2020.

Many of these threats are interdependent, for example, the deteriorating conditions of grasslands impact the decline in pollinating species. Changes in the water ecosystem may lead to water stress in trees and crops, making them more vulnerable to pests and diseases. Furthermore, disturbed water cycles (from extremes such as droughts and heavy rainfall) may exacerbate soil erosion, which is also driven by other factors such as agricultural practices and the use of chemicals. Landslides and swelling-shrinkage of clay soils are classified as posing high risk among the geological hazards encountered in Luxembourg (Kleeschulte et al, 2020). Clay soils are particularly sensitive to repeated cycles of droughts and floods, which are likely to be exacerbated by climate change. Artificialisation of land cover leading to reduced biodiversity further increases the vulnerability to these drought-flood cycle. As a result, the quality of construction buildings may be undermined by creating cracks. The map in Figure 6.9 shows the spatial occurrence of the selected threats in the study. Subsidence events are most likely to occur in the south-western areas of the country where previously mines were located. Rockfall is predominantly likely to occur in the northern part of the country. Landslides are more spatially spread out, although mostly mapped in the central part of the country, where the slopes created by the river canyons are steeper.

Table 6.2. Summary of biodiversity and ecosystem services (ES) related physical risks for selected economic sector in Luxembourg, based on the literature review (the references can be consulted in Annex A.6).

Biodiversity loss	Economic sector					
	Industrial Manufacturing	Construction	Forestry	Food Processing	Energy	Logistics
Animal species change	Indirect impact: Expansion of industrial sites might be legally obstructed if the diversity of animal species is declining overall	Indirect impact: Development sites might be legally obstructed if the diversity of animal species is declining overall	Decreased timber harvest due to pests (bark beetle e.g.); Disrupted dispersal of seeds and pollen facilitated by animals	Decreased harvest due to decline in pollinating species; Decreased harvest due to pests; Disruptions in food supply chains	Possible challenges of grid expansion and maintenance in conservation areas	Indirect impact: supply chains may be disrupted due to conservation practices at supplier sites
Plant species change		Disrupted supply of timber due to declined forest productivity; Disrupted supply of other bio-sourced building materials	Disrupted balance in forest ecosystems due to invasion of alien species;	Decline in harvest due to changes in lifecycles and early frost;	Decline in bioenergy produced from crops	Disrupted and declined productivity of freight transportation
Water ecosystem changes	Disrupted operations due to lack of water purification services	Disruptions in construction processes and finished products from changes in surface and ground water flows.	Reduced growth and decline of produced timber; Susceptibility to pests;	Economic losses in the fishery and related supply chains; Disrupted operation due to lack of water for cleaning and processing	Hydro-generation productivity decline	Damage to freight infrastructure; Disrupted supply chains
Various ecosystem services	Filter and decomposition of waste; Disrupted operations due to lack of land mass stabilisation, erosion control, and climate regulation;	Disrupted operations due to lack of land mass stabilisation, erosion control, and climate regulation	Reduced growth due to decline in soil quality; Disrupted tree growth due to failure in bio-remediation	Decline of crop yields due to loss of natural pollinators, soil erosion, climate regulation, and water cycles. Food processing facilities are indirectly exposed to supply chain disruptions, land subsidence, and stringent regulations for new site locations.	Damage to infrastructure due to lack stabilisation of land masses and erosion control	Disrupted operations due to lack of land mass stabilisation, erosion control, and climate regulation

Part II: Risk assessment

Chapter 7. Exploring Perceptions of Vulnerability: Overview and analysis of empirical data

The aggregated results collected across all three methods demonstrate substantial differences in the importance attached to the three different threats – climate change, resource scarcity and biodiversity loss. Most notably, resource scarcity has been associated with the highest perception of risk by all stakeholders, particularly the availability and affordability of "green" electricity. In second place, climate change is most often perceived as a potential threat in the future. Biodiversity loss is notoriously underrepresented and even considered irrelevant by the majority of participants, excluding representatives of the Food and Forestry sectors.

This chapter summarises the results of relevance for the different sectors per threat, where applicable. The different methods were consistent in collecting responses for each individual threat, allowing for comparison of their relevance. However, the survey introduced a question assessing all threats taken together. The availability and quality of electricity supplies and a stable political, regulatory, and socioeconomic environment were considered the most vulnerable aspects of the production process by the majority of participants in the online survey, when considering the combination of all physical threats and their potential impacts (Figure 7.1). Both aspects lie to a large extent outside the capabilities of businesses to regulate themselves, which may be the reason why they feel vulnerable.

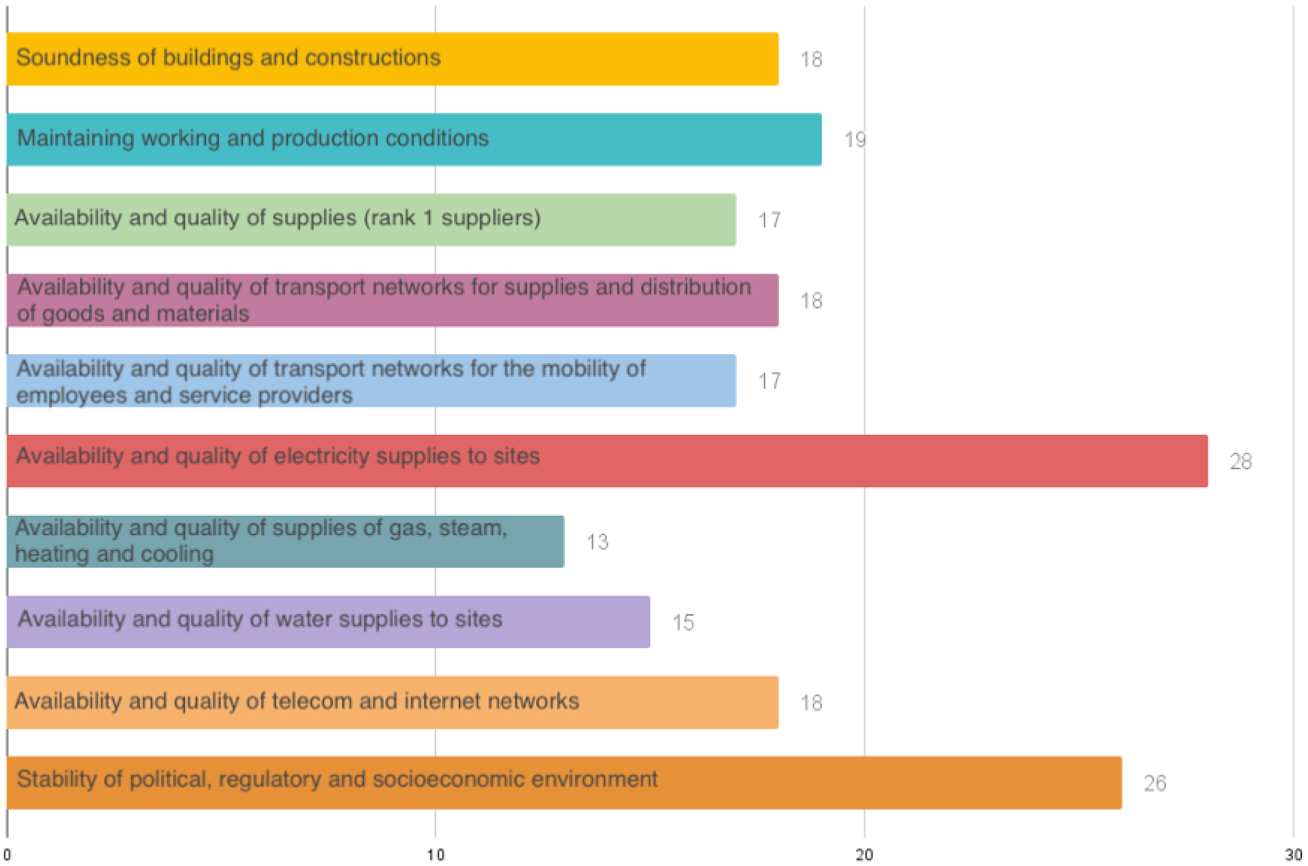


Figure 7.1. Ranking of the vulnerability of production process aspects by number of survey participants responses.

7.1. Climate

General overview

The findings indicate that businesses expect to face significant risks associated with climate change and climatological factors. Overall, the participants share the same opinion that the risks stemming from climate change will grow over time if appropriate mitigation policies are not effectively implemented in a timely manner. Participants express growing concerns about extreme weather events like tornadoes and floods. Extreme winds are highlighted as a potentially severe and damaging factor in both the short (by 2035) and long term (by 2050), emphasizing their potential impact on various sectors. Participants believe that the probability of extreme weather events is on the rise, making them feel increasingly vulnerable. The unpredictability and low probability of such events can make investing in extensive protective measures seem less worthwhile. Some participants mentioned that these environmental threats are not yet fully integrated into their risk assessment processes, while others are taking steps to prepare for them despite their unpredictability. Recent unprecedented events, such as the tornado in southwestern Luxembourg in August 2019 and the devastating flood events in July 2021 have heightened this feeling of vulnerability. Stakeholders have reported that floods pose a high risk to businesses due to potentially disrupting their global value chains, making them vulnerable to transportation disruptions.

Higher temperatures directly affect the working conditions of employees, particularly in industries like steel and aluminium remelting plants where employees already work in elevated temperatures. This necessitates shift work with increased labour requirements. Regulating temperatures in factories and office buildings through air conditioning adds to utility costs. Challenges to secure proper waste management become essential to safeguard sensitive materials for recycling from adverse weather conditions.

Participants have been invited to reflect on their vulnerability levels in the short term by 2035 and the long term by 2050. Most of them, however, reported difficulties in estimating how impactful the threats would be in the future. Stakeholders have found it difficult to rely on climate projections and, most importantly, to translate them into potential consequences.

To better understand exposure to climate-related risks, some participants have implemented various measures. These include monitoring temperature changes, seeking redundancy in energy sources, and diversifying and monitoring their suppliers. However, some interview partners express concerns that they still lack sufficient data and information regarding the exposure of certain components, materials, and critical systems, such as servers and information system networks, to the threat of increasing temperatures.

At the local level, heavy rainfall and riverine floods may disrupt and damage multiple transportation networks and infrastructure components, including roads, railways, and waterways. Addressing the issue of flooding on sealed surfaces, such as loading and parking stations, requires substantial investment in solutions like water pumps. Concerns have also been raised by private stakeholders about the drainage capacity of existing sewage systems during extreme rainfall. Water management organizations confirm the increasing pressure on water networks, particularly in the northern part of the country, due to shifting population distribution. These organizations highlight that the impacts of droughts may pose greater challenges than heavy rain and flooding. For instance, the required balance between wastewater discharged from sewage treatment plants and available freshwater becomes a concern when overall water body levels are low. Businesses located in historically flood-prone areas perceive themselves as well-prepared and do not consider floods as high-risk threats due to their preparedness. Nevertheless, some stakeholders are beginning to recognize heavy rainfall as a potential flood risk alongside traditional riverine flooding. However, certain actors, more remote from water bodies, still do not view floods as a significant threat. It's essential to acknowledge that floods pose not only immediate damage and blockage risks but also long-term threats like landslides and soil erosion, impacting transportation infrastructure networks, machinery clogging, damage necessitating replacements, extended cleaning, and potential production stoppages. Prolonged heavy rainfall may additionally affect the quality of outdoor-stored raw materials required in the construction sector.

During the empirical data collection process, climate scepticism and a tendency to focus more on transition risks were notably prevalent. Some research participants exhibited doubts about climate change and its impacts. Additionally, there was a general tendency to pay greater attention to transition risks rather than physical risks associated with climate change. One significant challenge identified during this process is the limited understanding and internalization of the distinctions between transition risks and physical risks. These distinctions may not be well-recognized among the stakeholders consulted. As a result, addressing this issue would require additional efforts focused on education and raising awareness about the differences between these two types of risks.

Sector-specific findings

Perceptions related to climate change exposure can be broadly categorized into two main groups: direct exposure and indirect exposure. Among these categories, the economic sectors of forestry, food production, and water management, which have a direct interaction with natural resources, exhibit a heightened level of vulnerability to climate change. This increased vulnerability stems from their reliance on natural capital and ecosystems. In contrast, other sectors such as manufacturing and supportive industries are less directly dependent on natural resources and, as a result, experience relatively lower levels of vulnerability to climate change impacts.

Industrial Manufacturing

Industrial Manufacturing representatives share a common stance that higher temperatures and heatwaves will primarily impact them indirectly by increasing their electricity consumption for air conditioning, without directly affecting their products. These actors were keen on discussing various transition risks associated with climate change mitigation policies, including expectations of increased emissions-related taxation and higher costs tied to policy regulations. The perceived importance of these transition risks far outweigh that of the physical risks for Industrial Manufacturing actors. To stay ahead of competitors and mitigate such risks, they are implementing measures such as reducing emissions by shortening supply chains, transitioning to renewable energy sources, and embracing principles of circularity, including recycling.

Construction

The construction sector lies in the middle ground between direct and indirect impacts of climate change. Increasing temperatures and heatwaves may directly affect its operations, temporarily halting production processes due to worker discomfort rather than affecting the product itself. Additionally, industry and manufacturing representatives allocate indirect climate change-related risks to issues within the supply chain and transportation of goods. This encompasses the vulnerability of global supply chains to diverse climate-related events in various geographic locations. These events can differ significantly in terms of type and impact, affecting delivery time, mode, cost, and even the availability of certain products.

Forestry

An ongoing concern is the "spruce dieback," where entire forest stands lose vitality due to changing climate conditions before reaching the economically valuable maturity stage. The spruce tree, widely planted across Europe for its rapid growth, is no longer resistant to rising temperatures, leading to reduced productivity in the forest industry. Forest management needs to encourage diversification of tree types, focusing on more climate-resilient trees such as the beech and oak. However, such diversification will pose economic challenges throughout the wood production value chain, as some sawmills are exclusively equipped for processing spruce timber, necessitating investments in new equipment for processing new types of timber. Additionally, it is important to acknowledge that this approach may lead to decreased harvesting efficiency in the future.

Another concern for the wood sector and timber harvest in particular are pest outbreaks, especially the bark beetle, which is damaging trees and their productivity. The increasing temperatures, heat waves and droughts are making the trees more vulnerable as their protection capacities are depleted. Some of the challenges the wood sector are facing related to climate change are to adapt its supply chains and increase its independence from long-distance imports. To support regional production, planning and approval processes need to be adjusted for new types of renewable building materials from a variety of tree species, in order to adapt to the spruce dieback situation while maintaining profitability.

Food processing

Luxembourg's food sector is undergoing a shift from conventional to more organic agricultural practices as part of an effort to counter the concerning trends of biodiversity loss and deteriorating soil health. Experts have emphasized that implementing policy targets for an increased share of organic agriculture introduces several transition risks. Organic production relies on thriving biodiversity and healthy soil, which are presently in a state of decline. Consequently, it is expected that the initial transition to organic practices will result in reduced harvest yields. Furthermore, the market for organic products is experiencing a sharp decline in demand, influenced by the overarching economic crisis. As a result, stores specializing in organic products are being forced to shut down due to a substantial decrease in consumption, despite a previous upward trend.

Experts have pointed out that achieving the targets for organic food production would lead to a significant reduction in the number of cows in the country. This would free up more space for growing food crops instead of animal fodder, ultimately reducing the quantity of locally produced beef. Adhering to the natural cycles for animal maturation, reproduction, and production for human consumption would mean a lower availability of (local) beef throughout the year. Retailers may need to extend their supply chains, incurring higher costs, to maintain an uninterrupted supply of beef. Overall, the availability of food products would vary according to seasonality and natural cycles when transitioning to organic agriculture practices and pursuing a more locally resilient food system. This stands in contrast to the current scenario of year-round abundance facilitated by global supply chains.

The physical risks associated with rising temperatures would impact the types of crops grown, potentially necessitating the cultivation of new varieties in place of traditional ones. Heatwaves and resulting drought periods would place increased demands on irrigation water and create favourable conditions for the proliferation of diseases and insects. Furthermore, warmer temperatures could elevate the risk of early ripening, followed by late spring frost, which could harm the entire annual yield. The alternating cycle of heavy rainfall and drought would also affect soil conditions, exacerbating erosion and nutrient runoff. These changes in food production would, in turn, have consequences for food retailing, wholesale, storage, and distribution. They would create greater consumer demand for certain foods that might not be locally available, thus necessitating imports from elsewhere. This would lead to increased costs related to logistics and supply chain risk exposure. Maintaining suitable cool temperatures for food storage in warehouses or transportation containers to compensate for warmer outdoor temperatures would require higher energy consumption, involving both electricity and cooling fuel.

Energy

For energy providers and grid operators, physical threats such as floods, soil erosion resulting from floods, and windstorms are considered high risks. These events could potentially damage their infrastructure. While warmer temperatures are not viewed as a direct physical threat, they are seen as an indirect driver of increased electricity demand, which affects their value chain as suppliers. Participants have not identified wildfires as a significant threat in their discussions.

Transportation

Droughts and high temperatures typically lead to reduced water levels along the Moselle River. This reduction in water levels can disrupt transportation and lead to higher prices for delivering bulky products and materials, such as finished metal goods, sand, and gravel. These items often lack feasible alternatives for transportation by road. To address this challenge, participants are actively working on creating redundancy in alternative transportation modes and routes. Additionally, they are exploring options for redundancy in stockpiling and diversifying their suppliers, although these approaches may not always be practical.

7.2. Resources

General overview

Several key points have emerged from the discussions with stakeholders:

- Increasing Energy Prices: Stakeholders express a shared concern about rising energy prices. This concern is not solely due to the current situation, such as the impact of the war in Ukraine, but is expected to persist due to the increasing demand for electricity and green energy in general. This has prompted many industry actors to explore the self-generation of electricity to reduce their vulnerability.
- War in Ukraine: The war in Ukraine is currently an extremely impactful event, and stakeholders feel that it exacerbates the already growing risk of unaffordable energy. The combination of both factors is expected to reach its peak in the coming years, and then to stabilize and decrease in importance over the mid-term horizon, approximately by 2035, as opposed to climate change threats which are only expected to increase with time.
- Regional Dependencies: Local conditions of scarcity for certain minerals and raw materials, such as cobalt, nickel, and aggregates, are attributed to regional dependencies and market specificities. The scarcity is not necessarily related to physical scarcity of these materials.
- Scarcity of Industrial Land: Industrial land is identified as a significant concern in Luxembourg due to its scarcity. There is anticipated competition for land resources coming from various sectors, including industrial manufacturing, agriculture, forestry, construction, and, notably, the energy sector. This competition for land resources poses a challenge for businesses. Figure 7.2 provides an illustration of the expected increase in pressuring demand for land, driven by multiple net-zero transitions taking place simultaneously in various economic sectors including Construction, Energy, Food, and Industrial Manufacturing. To draw a comparison with other resources, a similar plot emphasising the demand for water from the various economic sectors is pictured on Figure 7.3

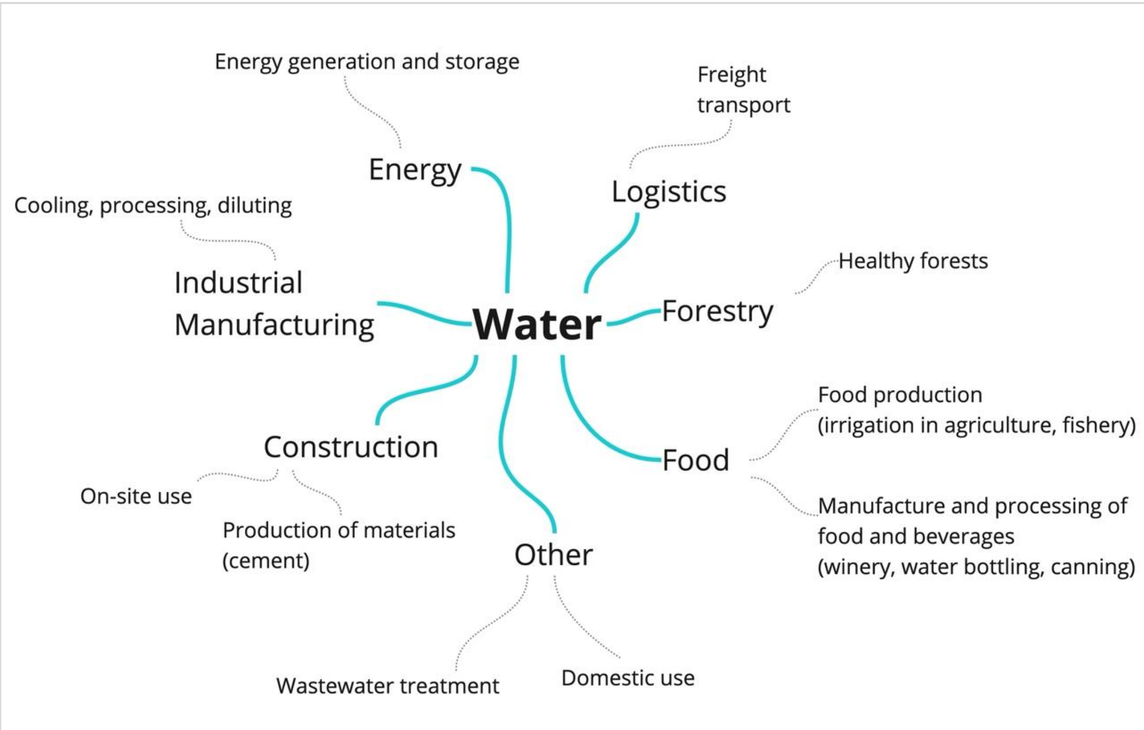


Figure 7.2. Pressure on the demand for water from the studied economic sectors. Based on aggregated findings.

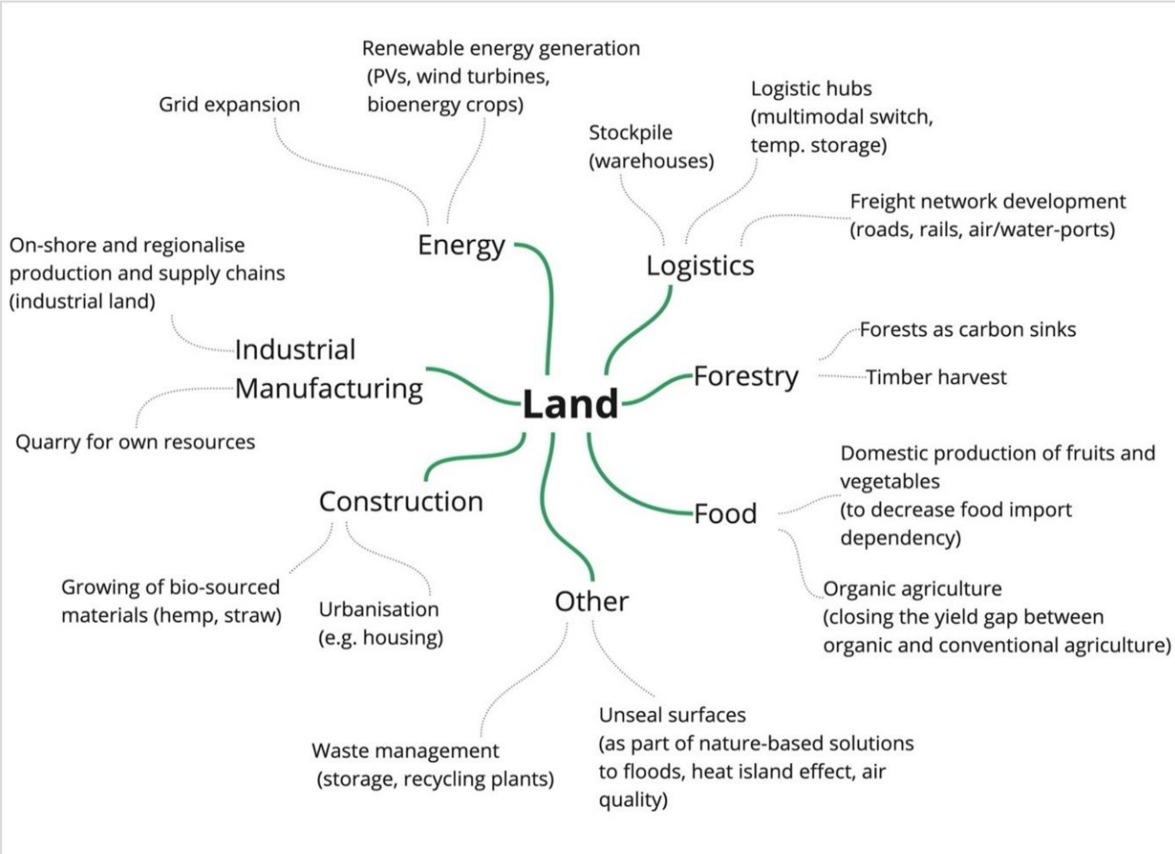


Figure 7.3. Pressure on the demand for land from the studied economic sectors. Based on aggregated findings.

Furthermore, Figure 7.6 provides an extracted list of raw materials on which the production processes of the online survey participants depend. The most frequently mentioned one is secondary materials, referring to recycled materials. This reflects the growing regulatory and market demands for implementing circularity practices, however, actors are concerned that the technical feasibility of circular practices is still not possible due to low recycling levels.

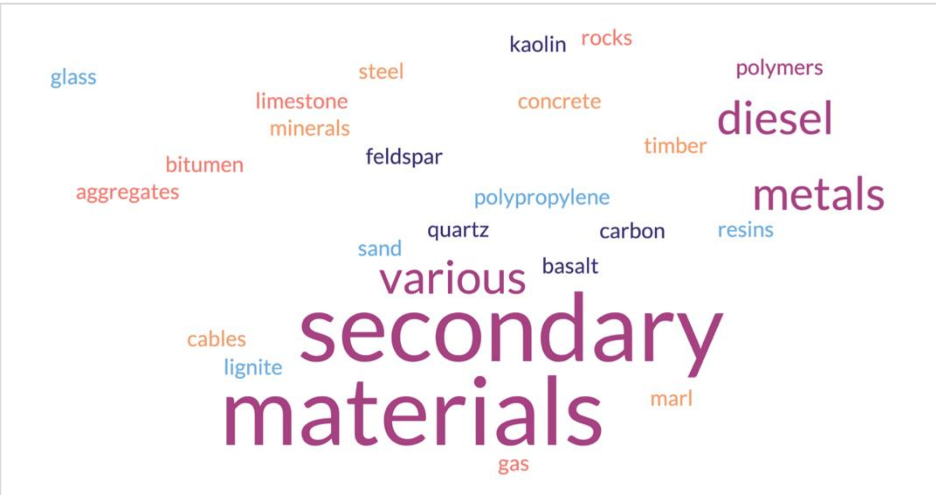


Figure 7.4. Raw materials on which depend production activities, as indicated by the online survey participants. The size of the word reflects the frequency of mentioning. Not sector-specific.

Sector-specific findings

The represented economic sectors and activities demonstrate reversed exposure to resource scarcity threats compared to the climate change ones: The industry and manufacturing businesses, but also water management bodies, transportation and storage, are much more vulnerable to the **availability and affordability of electricity**, compared to food production and forestry. Most production units run their equipment on electricity or are in the process of electrification (e.g., kilns and furnaces). This is critical for their operations, therefore many actors have temporary backup solutions such as self-generating options (backup generators are usually diesel-based).

Industrial Manufacturing

As already mentioned, the concern for rising electricity prices and actual availability of renewable energy has dominated the observed risk perceptions. Regarding the other resources, the majority of industry participants involved in the fieldwork do not rely heavily on freshwater for their operations. The main competition for freshwater typically occurs between private households and agricultural irrigation. The increased demand for growing fruits and vegetables in the country is expected to raise water consumption in agriculture, which may lead to higher pesticide use, impacting water quality. A decrease in groundwater levels is anticipated, but this demand could be offset by introducing an additional source of drinking water from the Moselle River after purification. Experts from water management institutions have stressed that data centres, a growing sub-industry, could conflict with the water needs of the population and potentially cause shortages in the future.

Regarding raw materials, vulnerability varies significantly depending on specific economic activities. Interview partners generally don't perceive raw materials as scarce; instead, they highlight unequal global distribution and hindered exploitation of domestic reserves (e.g. through mining). As circularity and sustainability objectives gain importance, industries are increasingly trying to incorporate reuse and recycling into their processes, placing pressure on various secondary materials like steel scrap, plastic, wood, and other construction materials.

For instance, the production of new cement mixes and steel products relies on metal scraps, which are currently available, but facing growing competition, leading to an expected decrease in availability in the near future. Metallurgy is expected to shift towards reduced ore rather than scrap, resulting in steel with different qualities that will require new standardization and regulation procedures. In the case of cement, the use of secondary materials is critical for reducing CO_2 emissions.

Construction

The construction sector is also under pressure to adopt circularity principles, not only in the materials used but primarily in the construction process and planning. Future buildings should be designed for easier disassembly and the separation of building materials for reuse or recycling, which could alleviate the demand for new materials. The use of organic materials in construction should be considered at the planning stage. Currently, the market for building with organic materials is underdeveloped, and market prices do not reflect the real costs if these materials become the new norm. The demand for land use for the production and consumption of organic building materials is expected to compete with other sectors, including agriculture, tourism, recreation, and ecosystem conservation.

Furthermore, there is a growing emphasis on the indirect emissions of buildings. This highlights the importance of reducing and regulating energy and water consumption as well as maintenance work through the proper installation of sensors, measuring and control devices. However, the technology and operation of "smart" buildings need further development to deliver more reliable and efficient results.

Food processing

The storage and distribution of food also represent a highly energy-intensive process. Companies are actively working on climate mitigation efforts by adopting less polluting cooling systems for the transport refrigeration systems, alternative to the energy of the diesel engines. They are also optimizing electricity usage through automated storage facilities. During warmer periods and heat waves, the consumption of coolants for transportation equipment is expected to increase. Rising energy prices, both for electricity and fuels, will impact the air conditioning of storage facilities, heating of greenhouses, transportation for distribution, and other operational costs. This, in turn, is likely to result in local production and imported products becoming more expensive and scarcer.

Changes in the European Union's Common Agricultural Policy subsidies, coupled with the increasing costs of electricity and transportation fuels, will have an impact on the final price of food for consumers. Business owners anticipate that consumers will allocate a larger portion of their income to food purchases. While they do not view the availability of food as a significant risk, they acknowledge that the types of food consumed may change over time, which could also influence their choice of suppliers.

Wood and forestry

While forests play a crucial role in maintaining biodiversity and providing ecosystem services, experts suggest that the timber industry need not be overly constrained by legislation. For timber to stay economically valuable, industries should be flexible in adapting to available and suitable tree species. In other words, rather than planting less resilient species to meet industry (e.g. construction) demands, forest experts suggest that all industries using timber should better adapt to the variability of tree species. One significant risk identified is the competition for land use with other economic sectors, including construction, renewable energy production, and forestry, which could impact food production and subsequently food availability. Agroforestry, as a mixed-land-use approach, has the potential to address some of these land-use competition challenges. However, several obstacles need to be addressed, including difficulties with machinery in tree-rich environments, farmers' limited knowledge of silviculture practices, and the lack of a clear regulatory framework. Another risk identified for the future management of forests: assuming a more varied composition of trees in a forest stand, the harvesting process might be less efficient and economic.

Energy

Electricity providers and grid operators are working on various strategies to meet the growing demand for electricity in a resilient manner. These strategies include doubling capacity, strengthening grids, and developing the network infrastructure. This not only presents a significant business opportunity by expanding the market and improving efficiency but also poses several challenges. One of the major challenges is the uncertainty in quantifying future electricity consumption due to multiple simultaneous electrification processes, such as the adoption of air conditioning, heat pumps, and hydrogen technologies. Additionally, the concern of potential bottlenecks has emerged. EU-level policies indirectly lead companies to simultaneously demand the same materials, like technical components (cables, chips, transistors), which are becoming increasingly difficult to obtain due to distributor aggregation and lack of locally available resources. This situation prolongs supply chains and lead times.

The transition to more renewable energy sources to meet the growing electricity demand is another challenge. Decentralized generation is a key aspect, and the question of where local production will take place remains uncertain. Some expect a focus on less-populated northern regions of the country for installing photovoltaic panels and/or wind generators, while others see potential in urban rooftops for photovoltaic installations. Nevertheless, there is a consensus that increasing self-generation at the country or regional level is essential to reduce dependency on imports.

While most businesses do not foresee very prolonged electricity outages, their primary concern is the affordability of electricity. Recent geopolitical developments have significantly impacted electricity prices, causing companies to be highly alert to potential price increases due to anticipated higher electricity consumption in the future. However, participants generally believe that this issue will persist and is likely to peak within the next 10-15 years, followed by adjustments and solutions before 2050. This differs from climate change threats, which are expected to increase significantly beyond the year 2050.

Logistics

In the realm of transportation and machinery, diesel remains a vital fuel source for heavy machinery and transport vehicles of all modes. Electrifying large vehicles and machinery is not seen as a feasible solution in the near future. As a result, participants are hopeful that hydrogen-based solutions will become available to meet their energy needs.

7.3. Biodiversity

General overview

Companies' self-assessment results indicate a low or non-existent expected impact from the degradation of agricultural or pharmaceutical genetic resources. Furthermore, they report a rather low dependence on ecosystem services. Some key findings:

- The competing interests for the benefits of forests have been raised as an issue, some suggesting that forests should be prioritized for providing ecosystem services such as fresh air, freshwater and recreational aspects rather than raw material (timber).
- Soil erosion is expected to impact forests and crops in agriculture. In addition, soil erosion exacerbated by climate change effects such as excessive rainfall, may compromise the stability and safety of energy infrastructure such as gas network pipes due to the earth's movement and lack of support for the pipes.
- Participants express significant concerns about air pollution and the deteriorating conditions of open environments, particularly grasslands. These concerns are seen as both short and long-term threats.

The economic sectors dependent on natural resources, ecosystems and biodiversity, such as organic agriculture, forestry, and water management, for example, have considered the topic of biodiversity loss and ecosystem degradation as pertinent. These sectors are facing a direct impact on the composition of species – trees, crops, pollinators, algae, for example, because of changes in the climate which is an important ecosystem element. Non-climate-related drivers of biodiversity loss such as agriculture practices, forest management, land use, and exploitation of resources are indirectly perceived through the lens of climate change because of all the feedback loops connecting them.

Most of the other participants involved with industry, logistics, energy, and manufacturing have regarded these questions as irrelevant. Some of the participants seemed unfamiliar with their dependence on ecosystem services and this concept altogether. Participants have shared that environmental threats in general and biodiversity loss, in particular, are not yet included in their internal risk analyses. However, companies which perform ESG reporting seem disproportionately aware that their activities have an *impact on* biodiversity loss and some larger companies have specific commitments to offset this impact.

The majority of firms do not consider their activities exposed to biodiversity loss, including those being recognisably more exposed to the provisioning of natural and geological resources such as quarrying for sand, gravel, limestone. On the other hand, some of them have shared concerns regarding the increasing environmental regulations and requirements when needed to expand their sites, or for re-naturalisation after the site has been exhausted, which in some cases constrain their business development. Nevertheless, the most common link made between biodiversity loss/ecosystem degradation and economic risks was made in relation to the health and well-being of the workforce, and for society in general.

Sector-specific findings

Forestry

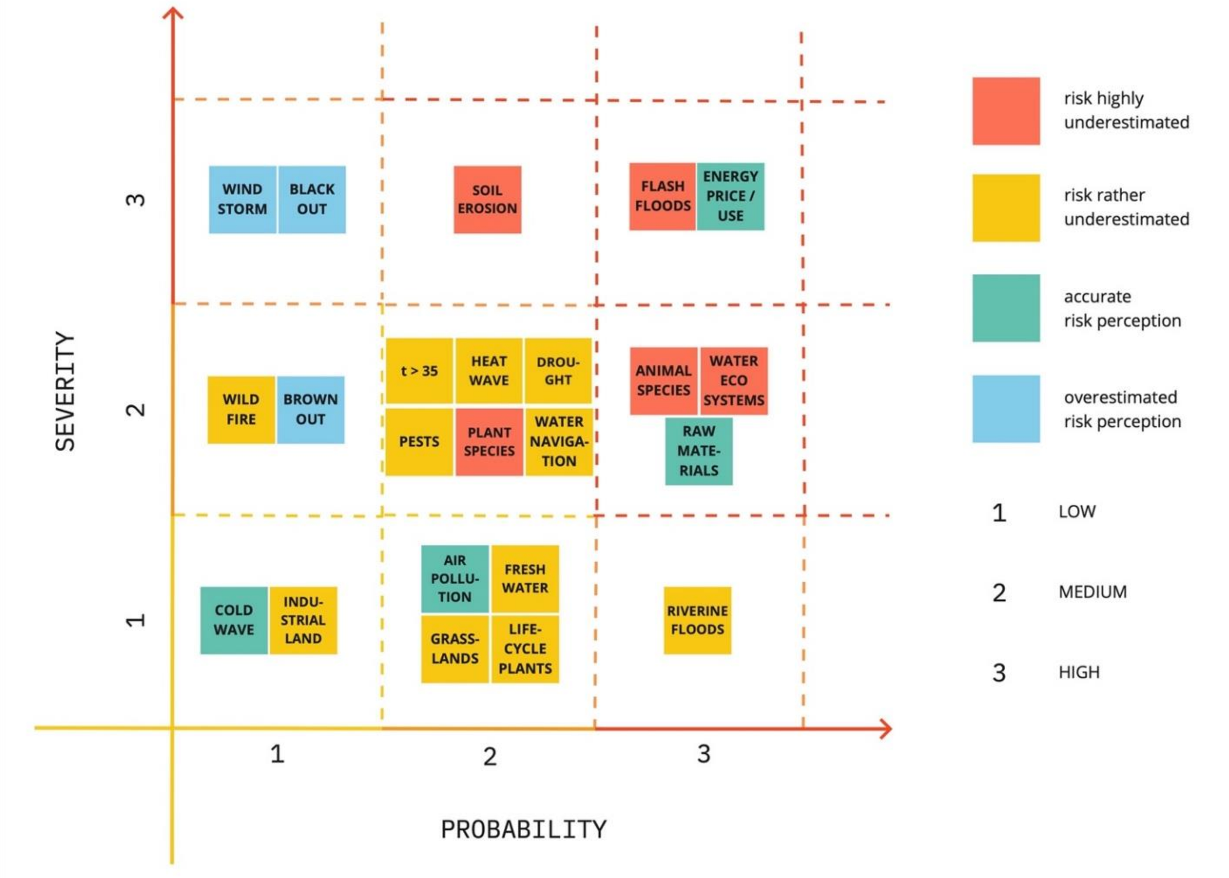
The overall changes in the climate are expected to alter the biodiversity of forests in Luxembourg with high probability. Some of the species will naturally migrate northwards in search of their best climate conditions. Meanwhile, other species are entering this geographic belt from the south. This may lead to the temporary co-existence of various species from two climatic regions, before eventually, the most suitable ones will settle. Due to the longevity of the production cycle process of tree growth and forest formation, it is hard to predict which tree species will be the most suitable ones in the future. Experts stress that forest management is important for introducing and supporting a variety of species, especially more climate-resilient ones such as the oak, whose roots stem deeper into the ground, able to access water reserves unreachable for the beech. Experts further advise that the most resilient-prone action today would be to encourage the presence of a large possible variety of tree species on each stand. Luxembourg is positioned favourably to adopt such diversified forest management practices because of the decentralised ownership and management of forests. Nevertheless, one possible economic impact in the future could arise from the decreased efficiency when harvesting timber from such diversified forest stands.

Food processing

All risks discussed were a result of climate change-driven alterations in crops, fertility, harvest yields, and food availability altogether (refer to Chapter 7.1). Food distributors and suppliers rely on global value chains to fill in the potential lack of or changes in locally available products.

Chapter 8. Risk Analysis and Discussion

The aim of the risk analysis is to bring together the review of the literature with the fieldwork findings to identify inconsistencies between the perceived levels of risk (observed) and the projected levels of risk (synthesised earlier). The risk matrix in Figure 8.1 plots all threat indicators according to the probability and severity levels indiscriminately aggregated from the consulted literature. Due to insufficient data available from publications on shorter timescales for all threats, the timeline of this risk matrix is 2050. The colour code represents the matching level between risk perception (based on empirically collected data) and risk projection[22]. Further explanation for each threat indicator label can be found below the matrix. As emphasised by the colour code, participants underrate several threats, such as flash floods, threats related to droughts, heat waves and water scarcity, and virtually all biodiversity-related threats.



Key for labels

extreme wind: windstorm or tornado events
wildfires: occurrence of a wildfire
cold waves: occurrence of a continuous period of colder than average days
heat waves: occurrence of a continuous period of warmer than average days
t > 35°C: occurrence of temperatures above 35°C
drought: occurrence of prolonged periods without or with decreased precipitation
riverine floods: flooding events caused by overflowing of rivers
flash floods: flooding events caused by heavy rainfall
blackout: occurrence of a temporary loss of electrical power supply
brownout: occurrence of a temporary reduction in power voltage
energy price/use: high price for electricity combined with high usage
raw materials: high price and limited availability of critical raw materials
industrial land: occurrence of vigorous competition for industrial land due to limited availability and high demand
water navigation: changes in the water levels of navigable water bodies
fresh water: decline in the reservoirs of fresh water
soil erosion: wearing away the upper layer of soil
pests: occurrence of pest infestations
air pollution: decline in the quality of air
grasslands: deteriorating conditions of grasslands
water ecosystems: deteriorating conditions of water ecosystems
plant species: changes in the type of plant species present or decline in their numbers
lifecycle plants: occurrence of changes in the lifecycle of plants, e.g. earlier ripening
animal species: changes in the type of animal species present or decline in their numbers, e.g. decreasing number of pollinators

Figure 8.1. Risk matrix showing the gap between projected and perceived risk levels.

[22] As an intermediate step, a comparison between perceived and actual risk ranking for all threats has been made. A negative difference of 2 orders means "highly underestimated", of 1 order – "rather underestimated", no difference means "accurate perception", and any positive difference means "overestimated". Underestimated low-risk threats suggests that these threats were mostly perceived as "irrelevant" by participants (see Annex A.8).

Biodiversity-related threats are highly interconnected reflecting the systemic relations in the planetary ecosystem. A lack of awareness of these interlinkages may create problems in various socio-economic regards. Multiple transition processes addressing the climate, resources and biodiversity crises together convene towards a transformation from a fossil-based economy into a bio-based one, with bio-sourced materials playing a central role. However, climate change mitigation and biodiversity conservation strategies may conflict with each other in different cases. The joint work between IPCC and IPBES stresses that some climate mitigation strategies, such as the expansion of bioenergy crops, for example, could be devastating for ecosystems and should be applied in a very controlled way (Pörtner et al, 2021). Bioenergy crops (trees, perennial grasses, or annual crops) should be used for a maximum of 15% of total primary energy produced globally, to avoid monocultures over a very large share of total land area (Ibid).

Another bio-sourced material dependent on thriving biological diversity, wood, is expected to increase in use throughout Europe as a means towards carbon neutrality in the construction, energy, and manufacturing (e.g. packaging) sectors (Nepal et al, 2021). However, the current condition of forests is fragile, as witnessed in Luxembourg, due to multiple stressors such as a long tradition of monoculture management, stress from warming temperatures, and exploitative logging. The expansion of the implementation of wood-based materials presents a substantial market opportunity, but also holds a number of risks. For example, simultaneous and sudden pressure on timber production may have the opposite effect on GHG emissions; or in case domestic sustainable production of wood (nationally or at EU level) fails to meet the growing demand, supply chain-related emissions will have an opposite effect as well, and will still pose supply risks (O'Brien & Bringezu, 2017). Construction energy efficiency regulations are among the strongest drivers of timber demand. A forest-based bio-economy with increased wood-based construction, biochemicals and bio-fuels would require a 15% increase in harvest and a 14% increase in employment, but also a 25% decrease in carbon stock (Jonsson et al, 2021). The sawmilling industry and its by-products would have a crucial role in such a bio-economy. On the other hand, energy efficiency in the construction sector can be achieved in combination with other bio-based building materials such as straw, hemp and cork, which the EU has the potential to produce (Göswein et al, 2021). The yearly level of wood consumption in Germany cannot be supplied by the yearly timber generated in the country alone, and if hypothetically everyone consumed at current German levels, this would create a gap between sustainable levels of production and exceedingly high levels of consumption (Figure 8.2; Beck-O'Brien et al, 2022). The underlying threat of competition for scarce land use is recognised as a major concern for forestry (Mishra et al, 2021). Careful harmonisation between consumption and conservation strategies for wood is necessary at all stakeholder levels, including policymaker and industry, in order to avoid sectors such as construction, energy and manufacturing to experience economic impact from failure to meet overexaggerated expectations.

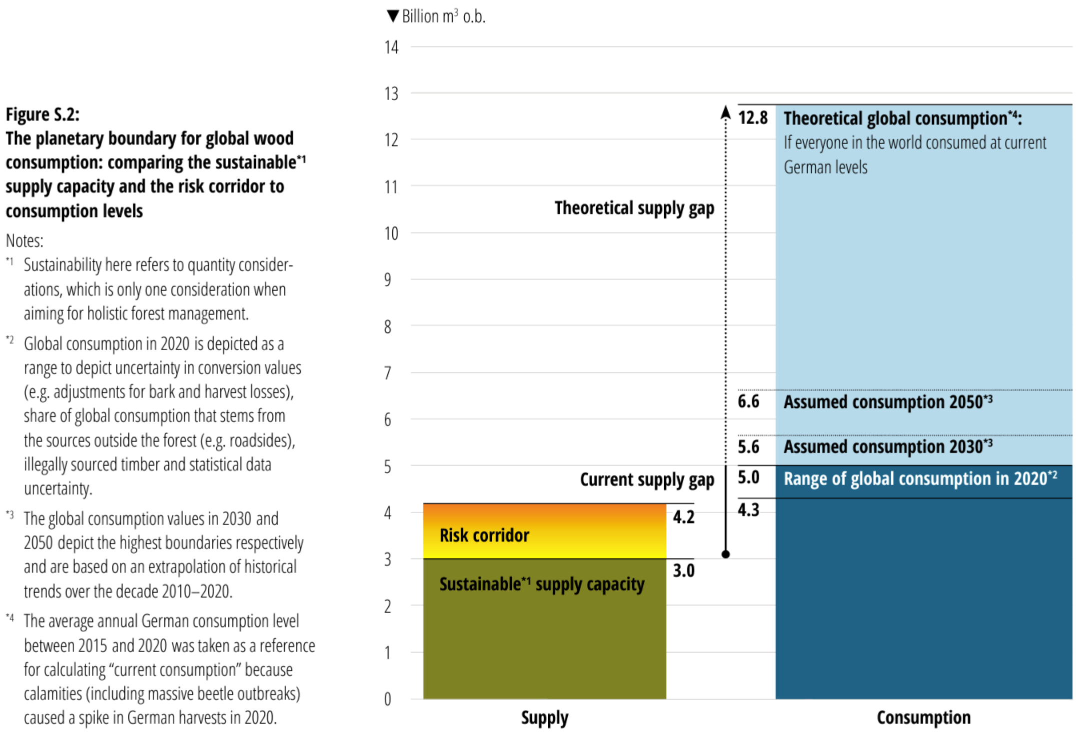


Figure 8.2. The potential gap between sustainable supply of timber, and current and future estimated consumption levels. Source: Beck-O'Brien et al, 2022.

Another important threat, which is often overlooked, is flash floods. As described in Chapter 4, flash floods pose a severe risk because they can strike suddenly leaving little time for precautionary measures. Sealed surfaces, often found on industrial and urban land, make companies particularly vulnerable to flash floods even far from water bodies, as the Geoportail tool maps out (extract from the geoportail.lu seen on Figure 8.3). The impacts from both riverine and flash floods are very similar, however, the difference lies in the degree of anticipation and preparation. Most companies geographically located in the floodplain of a river have flood protocols in place, whereas companies located in what is perceived to be a safe zone may not yet have such protocols. This lack of awareness and preparedness is considered to aggravate the relative level of risk from flash floods as a threat overall.

The systemic connections between some threats are often obscured in stakeholders' perceptions, which leads to results showing riverine and flash floods as important risks while biodiversity loss as a less important risk, for example. In reality, biodiversity, as an indicator of thriving ecosystems, has the capacity to decrease the severity and frequency of floods via multiple mechanisms: vegetation can retain water reducing the amount of precipitation reaching soil surfaces, root systems increase infiltration of water into the soil and reduce surface water runoff, and floodplains reduce the severity of a flood wave by providing space for the water (Vári et al, 2022). Slightly more than 1% of Luxembourg's territory, mostly on croplands and grasslands, is sealed by impermeable materials, which is in the upper average for the EU (EEA, 2022). Cities are increasing in their total surface area, and at least half of urban areas are sealed surfaces, meaning that the soil is covered by impermeable material. This not only increases flood risk but also often affects fertile agricultural land, puts biodiversity at risk, and contributes to a heat island effect. The project Luxembourg in Transition offers comprehensive solutions on how to achieve zero net land intake in the future while meeting the social needs of the population (Luxembourg in Transition, 2021).

Figure 8.3. Map depicting the flash flood risk at the Bettembourg/Dudelange industrial area. Yellow indicates moderate, orange - high and red - very high water depth and flow velocity. Source: Administration du cadastre et de la topographie, 2023.

Our fieldwork has confronted us with instances of climate skepticism, and a greater emphasis on transition risks, underlying the need for enhanced education and awareness-building regarding the differentiation between transition and physical risks associated with climate change. Claims by participants that energy-intensive industrial processes which already operate at very high temperatures (e.g. steelmaking) could hardly be impacted by the warming climate contrasts our expectations based on scientific projections regarding heat stress at heat-intensive workplaces (see Chapter 4). Nevertheless, working conditions were hardly mentioned by research participants, and the attitude towards heat-stress-related hazards revealed a rather technocratic approach. Overall, most responses demonstrate underlying confidence in the means of technological modifications, digitalisation or organically evolving solutions for overcoming challenges in the foreseen future, for example, regulating temperatures with air-conditioning; solving high energy demands with technologies which are still under development (e.g. hydrogen, carbon capture); overcoming supply chain volatility with digital twins of routes, among others.

Furthermore, some company decision-makers struggle to align their personal values regarding climate and biodiversity mitigation with the cost-efficient management of the company. For example, industry actors have shown a willingness to engage in partnerships with regional suppliers if such were available and more cost-efficient. Furthermore, experts have indicated that sustainable solutions, such as construction with bio-based materials or organically produced food, are still the exception rather than the norm. Economic actors expect the market for such solutions to develop further but doubts regarding the compatibility between conventional economic principles (expansion and growth) and ecosystem safeguarding question the ability of the market to organically evolve and solve these problems (Hickel and Kallis, 2020). Overall, many have reported a need for external incentives, either market or policy-driven, which would put everyone in the same boat, rather than some companies investing ahead of others in adaptation and mitigation solutions at the expense of profits, while their competitors opt not to. Nevertheless, some acknowledge that being ahead of the regulations and market pressures to invest in new solutions may be valuable by fostering competition.

On the other side, stakeholders acknowledge those threats not highlighted in red as being relevant. For example, our findings capture an increased level of concern from businesses regarding the reliability and affordability of electricity, thereby anticipating the objectives of Luxembourg's National Climate and Energy Strategy. The prevalence of high-risk perceptions regarding energy indicators suggests a relative sense of awareness and urgency for action which can be expected to mobilise businesses to actively counterbalance this threat and implement adaptive measures. These results reflect stakeholders' distress that the requirements to use green energy are coming ahead of its actual availability in technical terms. However, some stakeholders might be positioned better than expected to meet these demands: as presented in Chapter 5, half of the energy consumed by industries already comes from electricity rather than directly from fossil fuels. Transitioning to an entirely renewable electricity grid would require a mix of energy sources. Although current levels of hydrogen and e-fuel production are insufficient to replace fossil fuels use, the projected exponential increase in production, similar to wind, power and batteries, is expected to eventually be able to meet expanding needs at decreasing costs (Way et al, 2022; MEAT, 2021). The total electricity demand will increase by a factor of three, driving up also the demand for high power voltage capacity for industrial actors. grid operators and energy providers have revealed that, in technical terms, they are well on track to expanding grid capacities and securing the network infrastructure to accommodate the increasing demand, as far as domestic production of renewable energy is concerned (Creos Luxembourg, 2020; Creos Luxembourg, 2021). The imported part of the energy consumed is beyond their control and will always present a certain degree of vulnerability, by which the only way to respond, in their opinion, is to be ambitious with the installations of renewable energy generators and be efficient in the consumption of electricity despite of its source. In addition, the bi-annual reports on the security of electricity supply in Luxembourg (MEAT, 2022), together with the risk prevention plan (PNOS) and risk-preparedness plans, make sure to monitor closely any risks associated with electricity supply. This is not to say that there will be no challenges related to the transition to green and renewable energy. The storage of this intermittent energy, alternatively to batteries, is still a concern. A possible solution could be provided via underground pumped-storage hydropower, but there are several topographic, societal and environmental limitations to be considered. A model analysis for an abandoned slate mine in Belgium as a potential lower reservoir solution has revealed that inconsistent underground water levels may reduce the efficiency and may undermine the reservoir stability, concluding that each location needs to be assessed before considering it as an energy storage reservoir (Kitsikoudis et al, 2020).

Mitigating the potential impacts of the physical threats would result in a growing competition for space, as visualised in Figure 7.2. The findings show that this problem will be aggravating due to the conflicting needs of a growing population with changing demands for the type and quality of cities, houses, work, products and foods consumed on one hand, and a variety of climate mitigation strategies such as green energy production, biomass for construction, bioenergy crops, and nature-based carbon sinks on the other. The Luxembourg in Transition project has suggested a number of ideas related to the planning and organisation of land use, which respect the fundamental principle of net zero land sealing and maintaining the agricultural land area size (Luxembourg in Transition, 2021). Taken together, the suggestions can give valuable guidance into the possible land use planning options with regard to agricultural land organisation, for example, , suitable areas for population expansion and transforming the existing building stock and sealed land into functional spaces for housing and shared social places. Many have raised the issue that overseas outsourcing of industries and operations has reached a critical level and much of the physical and know-how assets are not locally/regionally available anymore. Even if investments try to rebuild or bring back some of the industry to Europe, there is a growing concern for a lack of conditions to make this happen, because of environmental, social and political constraints and a lack of workforce willing to do this type of work anymore.

Even if food production (agriculture) is beyond the scope of this research, declining harvests and displacement of producers due to loss of pollinators and changes in growing degree days will affect regional actors in the processing sector as well. Research on Luxembourg's food system reveals that the dependency on imports of fruits and vegetables is a big weakness in the system (Reckinger, 2018). This weakness makes the food system vulnerable and thus exploitable by disruptions in the transport network, trade restrictions, supply shortfalls, and the proliferation of protectionist domestic supply policies (Davis et al., 2021; Godde et al., 2021). Nevertheless, this dependency can be overcome by domestic production without putting too much pressure on land use as one calculation suggests that following permaculture and organic growing techniques, one would only need 7 000 hectares out of the current 63 000 hectares of arable land in Luxembourg to produce vegetables for the country's future 700 000 inhabitants, while creating 14 000 jobs (Reckinger, 2018).

Future changes in land use will largely depend on integrative spatial planning policies, which need to allow for adjustment to land use changes, rather than resisting change. Such an approach would better succeed in sustaining livelihoods, ensuring food supplies, and preserving essential ecosystem services. The Common Agricultural Policy (CAP) program of the EU, currently a key factor for the agriculture economy in the EU, will need to be reshaped in such a way that encourages the provision of societal goods such as climate mitigation, biodiversity preservation and livelihood diversification over economic production. In the absence of such support, reactive adaptations to the impacts of socio-economic and climatic changes are likely to be detrimental at local and European scales (Holman et al, 2017).

The participants in the final stakeholder workshop were invited to reflect upon the aggregated findings from the empirical data. Overall, some participants were negatively surprised by what seemed to be a lack of awareness regarding physical risks, while others took this as a learning experience to find out about risks which have been unknown by then. The participants suggested that the reasons behind the seemingly underestimated environmental risks and the overestimated resource scarcity risks reflect their present vulnerability to threats which lay beyond their immediate responsibility, such as geopolitical (war in Ukraine) and health (Covid-19 pandemic) events. These continuing crisis modes have obstructed companies from allocating more time and resources to strategies for long-term physical risk mitigation. Furthermore, they question the extent to which market forces can deal with environmental risks if that entails a contradiction with their inherent profit imperative. Most participants have agreed that regulatory frameworks are more reliable tools to raise awareness, reduce vulnerability and steer business decision-making to mitigate risks and move towards more circular and resilient practices. Such regulations should be holistic, forward-looking in the long term, socially just, internationally aligned and based on redistribution of wealth, fair taxation (with a focus on big business taxation) and sufficiency (maintain desirability with less), in order to (re)gain the trust of economic actors.

Due to the large degree of interrelations between climate, resources and biodiversity crises, our feeling is that a tipping point for Luxembourg can be reached when global warming reaches more than 2.5 compared to pre-industrial levels (which can happen under very high emission scenarios around 2050 and beyond (IPCC, 2023)). Such high temperatures would not only pose significant risks for all economic activities studied, but will simultaneously affect the other threats of resource scarcity and biodiversity loss, exacerbating their impact as well. This may result in a situation where drought affects severely food production (food crisis) and availability and quality of drinking water (not able to replenish its sources and to naturally purify from parasitic organisms); demand for energy for cooling would be rocket high, but not everybody would be able to afford it.

Part III: Planning for Resilience

Chapter 9. Recommendations for Adaptation and Resilience

To tackle the identified threats and resulting risks, our team has conceived a list of recommendations for adaptation and resilience measures to be addressed according to three target stakeholder levels – companies, industries, and policymakers. A summary of the recommendations for single companies as well as entire industries (e.g. represented through their business associations) is given in Chapter 9.1 Actionable suggestions for practitioners, and those for policymakers in national and local governments are provided in Chapter 9.2 Recommendations for policymakers. Finally, all recommendations are comprehensively synthesised in Table 9.2, for which Table 9.1. serves as a model to familiarise the reader with the categorisation. The different areas of intervention are divided into four topical groups: technical, operational, governance and nature-based. These recommendations were conceived from a multitude of sources, listed below. The origin of each recommendation in the table is indicated by the letter corresponding to each source from the list below (to be found in brackets under the type of recommendation). In most cases, there is an overlap between various sources of recommendations, which strengthens their relevance.

A. Theories and good practices consulted in the literature;
B. Observations during empirical fieldwork;
C. Input from the final stakeholder workshop;
D. The joint workshop between the University of Luxembourg RISK2050 Consortium (UL) and Luxembourg Strategy;
E. Feedback (formal and informal) gathered during 3rd ECO2050 Conference (September 2023);
F. Brainstorming suggestions received from team Luxembourg Strategy;
G. Internally discussed and validated expert opinions by the RISK2050 Consortium members.

Furthermore, the link between our recommendations and the building blocks of the ECO2050 Strategy (Luxembourg Strategy, 2023) is indicated in a separate column. This helps to clearly see which building block can support specific adaptation measures as a response to identified threats. The "Vision 2050"[23] consists of the following ten strategic building bricks:

1. Strategic autonomy: stimulate national production
2. Circularity and sufficiency: save energy and raw materials
3. Focus on people, knowledge and well-being
4. Reconciliation of digital, ecological and social transitions: build a competitive and clean economy
5. Critical redundancy and strategic storage: duplicate solutions and build reserves for essential goods and services
6. Administrative simplification: improve the conditions for entrepreneurs and investors
7. Diversification of the economy: turn transitions into business opportunities
8. Sustainable economic diplomacy: strengthen global resource governance
9. Sustainable and solid public finances: finance sustainable transitions
10. Anticipation and celerity: plan for the long term, monitor and adapt to changes faster

[23] The final presentation is accessible here: https://luxstrategie.gouvernement.lu/fr/evenements/3e-conference.html

Figure 9.1 A model version of the fully fletched Table 9.2, with examples.

Type of Recommendation		Addressed threat	What does it mean for *companies*?	What does it mean at *industry level*?	What does it mean for *policymakers*?	Reference to Vision ECO2050	References and links
Technical	*Example: Efficient use of resources (F, G, B, A)*	*Energy scarcity, …*	*Consult best practices*	*Run awareness-raising campaigns*	*Run awareness-raising campaigns*	*Brick 2*	https://www.kopernikus-…
Operational	*Example: Flexible working hours (F, B)*	*Heat waves*	*Adapt business operations framework*	*Lobby for adaptations of the legal framework to changing industry needs*	*Adapt legal framework and create tax incentives*	*Brick 6*	
Governance	*Example: Asess-ment (G, F)*	*Climate*	*Implement a self-assessment mechanism*	*Develop industry-wide self-assessment tool*	*Run awareness-raising campaigns*	*Brick 10*	[https://encorenature.org/en …](https://encorenature.org/en)
Territorial	*Example: Green roofs (G, F. A)*	*Floods; Heat waves*	*Invest in green roofs and green facades*	*Lobby for subsidies*	*Consider implementing subsidies*	*Bricks 4, 9*	*EEA, 2021*

9.1. Actionable suggestions for practitioners

Governance

A preliminary action plan for reducing the vulnerability of individual companies may start at a governance and executive level. Adaptation planning begins with an assessment of current climate, resource and biodiversity-related risks and vulnerabilities to companies' assets and supply chains. Freely available tools, such as ENCORE[24], OCARA[25], RiskChanges[26] can be considered as a first step to exploring this process. Collaborating with external service providers such as consultancy firms can be pricier but will bring more tailor-made results, also allowing the implementation of double materiality and the combined effects of multiple threats. Employing an in-house (albeit small) R&D team to monitor and report on the exposure and vulnerability levels of the company can be another solution. This would allow businesses to create protocols for responding to potential disruptions in both their upstream supply, downstream consumption, and on-site management. These assessments can bring more substance to companies' sustainability reports. The new Corporate Sustainability Reporting Directive (CSRD) will require publicly listed companies meeting two of the following three conditions: 40 €million in net turnover, 20 €million in assets, or 250 or more employees, to disclose their climate and environmental impact. These conditions exclude SMEs from obligatory reporting, however, voluntary reporting mechanisms will be available for them. Assessment procedures, action plans and protocols should be regularly revisited, forming an integral part of the company's strategic governance. Engaging in foresight exercises based on simulations and speculative scenarios is also a valuable experience in forming anticipation and preparedness, which can involve engaging and creative techniques such as role-playing, fiction and backcasting (Kohler, 2021). Furthermore, expanding insurance policies with reliable service providers against physical risks should be considered. Industry representatives can support companies in various ways, such as by developing industry-wide self-assessment tools and offering consultation for their implementation. Impact chains for droughts can be consulted in the recently published European Drought Risk Atlas (Rossi et al, 2023).

[24] The ENCORE platform (https://encore.naturalcapital.finance/en/explore has been used in publicly commissioned studies to assess dependencies between economic activities and nature's contributions, and the impact of economic activities on ecosystems (Kan et al, 2021).
[25] OCARA's approach considers a three-phase process, starting with an analysis of current resilience, proceeding with generation of future climates and impact scenarios, and concluding with the creation of a resilience and adaptation plan. They distinguish between sites and processes that might be impacted by climate risks. This is a privately developed methodology by Carbon 4 and can be accessed on their website: https://www.carbone4.com/en/ocara-methodological-guide
[26] Risk Changes is an open-source spatial analysis tool for exposure assessment to multiple hazards, recommended by the UNDRR https://riskchanges.org/

Operational

These recommendations concern adapting business operations in response to high-risk threats such as heat waves and floods. For instance, companies are advised to adjust their operations to accommodate changing weather conditions, especially during heatwaves. We recommend putting in place protocols for adapting working hours to extreme weather conditions such as heat stress from heat waves. Support from industry representatives would entail advocating for changes in the legal framework to support industry adaptation. Addressing the raw materials scarcity threat, procurement policies need to be adapted to the supply of alternative products and practices regarding mobility and catering, to ensure the smooth operation of the company in case of shortages of specific supplies.

Technical

Companies could consult and implement best practices in energy efficiency and resource management, such as installing renewable energy systems for which a declining trend in costs is observed, for example, and decentralisation, diversification and nearshoring of supply chains.
Sufficiency as a business approach can be translated into moderating consumer demand by adding different values to the business model. These values can be based on the "reuse, reduce, avoid" principles, by transforming practices towards share, exchange, repair, cascading use of materials, and increasing efforts to avoid planned obsolescence and focus on product longevity and circularity instead (Kropfeld and Reichel, 2021; Bocken and Short, 2016).

Adaptation to the fluctuations of electricity is necessary for industrial actors when relying on renewable energy sources. The project SynErgie[27] has developed models for industrial actors, such as aluminium furnaces, chemical and gas manufacturing, and paper manufacturing, to secure industrial processes even when the currents fluctuate, making their use of electricity more efficient. These flexible solutions allow one of the largest industrial energy consumers in Germany to moderate its energy consumption daily, which corresponds to the output of around 25,000 three-person households. The project has determined that industrial energy consumers in Germany overall could increase their demand by up to 9 Gigawatt (GW), or decrease it by 10.7 GW, for 15 minutes, depending on the availability of electricity from renewable sources. This flexibility corresponds to the output of approximately 5,620 onshore wind turbines.

Additional resources for energy efficiency can be accessed through the Klima-Agence Toolbox[28].
Implementing rigorous building standards during the planning phase of new assets to ensure they are not only suitable for current conditions but also equipped to handle potential extreme events in the future. For existing infrastructure, retrofitting and climate defences, such as on-site power generation from renewable resources, are under consideration. Companies could also explore projects that offer additional environmental benefits, such as the restoration of mangrove forests and wetlands. Industry representatives are encouraged to promote policies and incentives that encourage businesses to adopt energy-efficient technologies.

Nature-based and Territorial

It is important to note that the availability and sustainable use of freshwater resources are critical considerations for industrial processes in Luxembourg, as water scarcity and environmental concerns related to water usage become increasingly important issues. Therefore, industries are encouraged to implement water-efficient technologies and practices to reduce their impact on freshwater resources and ensure their sustainable use. Companies are advised to invest in wastewater management technologies, especially for the recovery of rare and expensive chemicals used in the production process. Additional measures include developing cross-linkages between open green spaces and maintaining or creating green areas connected to surrounding regions. Further suggestions involve considering leaving as much area unsealed as possible to allow water infiltration and prevent runoff. Finally, investment in green roofs and green facades is encouraged as protection from floods and to support local animal and plant species, as mitigation of heavy rainfall events and for improving the micro-climate.

[27] https://www.kopernikus-projekte.de/projekte/synergie
[28] https://www.klima-agence.lu/en/toolbox

9.2. Recommendations for policymakers

Governance

Governance-related actions aimed at policymakers in Luxembourg to enhance adaptation to physical risks include:

- Raising awareness campaigns to educate businesses and the public about the significance of comprehending their exposure levels to physical risks. These campaigns can emphasize the potential impact on various sectors of the economy, encouraging proactive risk assessment and management.
- Allocating public research funding to improve the availability of assessment tools. This financial support can facilitate the development of more accurate and sophisticated methods for assessing and quantifying individual and compound physical risks.
- Policymakers could consider making it mandatory for larger firms to establish contingency plans that outline strategies for dealing with physical risks (already applicable for "Seveso" companies). For smaller companies, standardized procedures can be provided to help them address these challenges effectively. For example, the ISO 31000[29] on risk management provides a standardized framework, and training to obtain the certificate is available in Luxembourg by private providers.
- Creating incentives to motivate businesses to take action in assessing and managing their exposure to physical risks. This could include financial incentives or regulatory benefits. At the same time, there should be a mechanism to hold businesses accountable for their risk management efforts.
- Implementing exposure analysis as a standard practice in large infrastructural projects is essential not only to avoid high exposure but also to set an exemplary practice of ensuring that new developments are designed with all considerations of physical risks.
- To facilitate exposure analysis and self-assessments, publicly available tools such as the Geoportail may be expanded to include a broader range of physical risk exposure variables at the national level. This database can serve as a valuable resource for both the public and private sectors to access relevant data for risk assessment and decision-making. Variables like drought and the heat island effect can be particularly relevant in this context.
- Investing in continuous national-level foresight exercises to anticipate and prepare for future physical risks. These exercises can help identify emerging threats and inform proactive risk management strategies.
- Developing a drought management plan at a national level, similarly to the flood management plans, is crucial for this rising in importance threat (Rossi et al, 2023).

Operational

Policymakers are advised to be flexible and responsive to the evolving needs of businesses. Addressing the evolving nature of work, the legal framework should be adapted at the national level to accommodate flexible working solutions, accompanied by tax incentives to encourage their implementation. Furthermore, promoting sustainable practices, awareness campaigns for sustainable procurement policies, and incorporating selection criteria in public procurement standards can drive environmentally responsible decision-making. To enhance resilience against emerging threats, such as fires, a systemic approach to risk management plans should be implemented and continually adapted. This comprehensive strategy not only ensures legal and tax frameworks align with changing work dynamics but also promotes sustainability in procurement practices while fortifying resilience against unforeseen challenges through effective risk management planning.

Technical

Efforts to promote the efficient use of resources should include comprehensive awareness-raising campaigns emphasizing the significance of resource conservation. Informing the public about existing incentives and facilitating the smooth implementation of EU 'right to repair' regulations will contribute to fostering a culture of sustainability. Establishing relevant product standards, particularly those incentivizing 'simple' and less material-intensive solutions, especially in the building sector, can drive environmentally friendly practices. Additionally, providing regulatory flexibility allows for adaptive measures. Implementing a national vault to stock critical materials and resources ensures strategic reserves for unforeseen challenges. Developing public-private and cross-border partnerships strengthens collaborative approaches to sustainable resource management. Incentivizing domestic production and re-shoring initiatives boosts local economies and reduces reliance on resource-intensive global supply chains. It is essential to prioritize the maintenance of critical public

[29] https://www.iso.org/iso-31000-risk-management.html

infrastructures related to transportation, water management, and energy distribution to ensure resilience in the face of resource challenges. Last but not least, policymakers should run awareness campaigns highlighting the importance of efficient resource utilization, aiming for a balance between striving for self-sufficiency and international cooperation towards fair distribution of planetary resources.

Nature-based and Territorial

From a territorial perspective, implementing green belts around urban areas in development plans is advisable as a measure to reduce the risk from biodiversity loss and more specifically plant and animal species loss, climate regulation and water ecosystems. Transforming public sealed surfaces into green areas is proposed, especially in places like parking areas, parks, roads, and commercial zones. Building infrastructure for treating and reusing greywater through wetlands and canalization systems is also advocated, as is the use of treated wastewater for irrigating public green spaces. Research addressing the issue of droughts in the context of regional food production and agriculture in the context of Luxembourg can be used as a baseline for drought scenarios and impact on agriculture (Weichhold, 2021).

Figure 9.2. Recommendations for adaptation and resilience per target group: firms, industry representatives, policymakers.

Type of Recommendation		Addressed threat	What does it mean for *companies*?	What does it mean at *industry level*?	What does it mean for *policymakers*?	Reference to Vision ECO2050	References and tools
1. Technical	1.1 Efficient use of resources *(F, G, B)*	Energy scarcity; Raw materials scarcity	Consult and implement best practices regarding energy efficiency.	Run awareness-raising campaigns for the importance of efficient use of resources.	Lead by example, i.e. implement efficiency practices in all public institutional buildings and workflows	Brick 2	https://www.kopernikus-projekte.de/projekte/synergie https://www.klima-agence.lu/en/toolbox
	1.2 Efforts towards sufficiency and circularity *(F, G, E, C)*	Resource scarcity	Redesign business models towards sharing, exchanging, repairing, cascading use of materials, circularity, avoid planned obsolescence and focus on product longevity; Focus on essential vs non-essential products	Accompany and encourage firms in search for sufficiency oriented business models	Smooth implementation of EU 'right to repair' and related regulations; establish respective product standards; Create incentives for 'simple' (i.e. less material intensive) solutions, e.g. for the building sector; (see also recommendation 1.1)	Brick 2	Circular business models ebook (Jonker et al, 2022) https://circulareconomy.europa.eu/platform/sites/default/files/quick-scan-circular-business-models_ebook.pdf
	1.3 Switch to alternative fuels or products *(F, B, G)*	Raw materials scarcity	Consult best practices and implement new technologies (e.g. renewable energy resources) or substitute rare materials in product design/production process	Share best practices; further develop/adapt product norms	Provide regulatory flexibility	Bricks 2, 7	European Research Area (ERA) Industrial Technology Roadmaps (European Commission, 2023c)
	1.4 Redundancy *(G, F, B)*	Raw materials scarcity	Stockpiling of raw materials and spare parts; Make sure the volume and geographic concentration of existing stocks are distributed over several sites	Facilitate the optimal use of stocking spaces by sharing between companies	Implement a national vault of stocking critical materials and resources; Develop public-private and cross-border partnerships	Brick 5	OECD 4 keys to resilient supply chains https://www.oecd.org/trade/resilient-supply-chains/
	1.5 Diversification and nearshoring of supply chains *(G, B, F, D)*	Raw materials scarcity; Floods; Droughts	Make sure existing stocks are distributed over several sites; Consider the benefits of relocating production nearer or switching to nearer suppliers; Decentralise energy supply	Lobby for incentives	Implement incentives for domestic production and re-shoring, Regional and international cooperation towards fair distribution of planetary resources.	Bricks 7, 4, 1, 8	INTERREG Project: BRIDGES https://projects2014-2020.interregeurope.eu/bridges/

Type of Recommendation		Addressed threat	What does it mean for *companies*?	What does it mean at *industry level*?	What does it mean for *policymakers*?	Reference to Vision ECO2050	References and tools
1. Technical	1.6 Resilience of infrastruc-tures *(D, F, G)*	Floods; Windstorm; Wildfires	Maintain the integrity of buildings	Run awareness-raising campaigns and provide advice to firms	Maintain critical public infrastructures for transportation, water management, energy distribution. Disseminate communication on the Flood Risk Management Plan[30]	Brick 9	Climate Resilient Cities and Infrastructures HORIZON 2020 Project https://cordis.europa.eu/project/id/653522
2. Operational and behavioural	2.1 Flexible working hours *(B, F, A)*	Heat waves	Adapt business operations framework	Lobby for adaptations of the legal framework to changing industry needs	Adapt legal framework and create tax incentives	Brick 6	*Chapter 8.2 The role of governments* *Chapter 8.3 The role of employers* (International Labour Organization, 2019)
	2.2 Consumption changes: procurement policies *(B, F, G)*	Raw materials scarcity	Adapt procurement policies towards climate friendly products and practices (including mobility and catering); raise awareness among employees	Share best practices and raise awareness	Raise awareness for sustainable procurement policies; include selection criteria in public procurement standards. (see also recommendation 1.1)	Brick 2	Sustainable Procurement Platform https://sustainable-procurement.org/
	2.3 Behavioural adaptation to increased fire danger *(G)*	Heat waves	Implement on-site fire risk management plans	Raise awareness for the increasing need of fire risk management plans	Implement and adapt a systemic approach to fire risk management plans	Brick 10	*Towards a systemic approach to fire risk management* (Bacciu et al, 2022)
3. Governance	3.1 Assessment of exposure *(G, F, A)*	Climate, Resources, Biodiversity	Implement a self-assessment mechanism to understand exposure points to selected threats; Consult impact chains in the provided tools	Support companies with the development of (industry-wide) self-assessment tool and offer consultation for implementing it	Set up an independent statutory body with exclusive purpose to advise the government, assess progress on risk assessment and adaptation strategies, and perform own monitoring and research (e.g. UK Climate Change Committee)	Brick 10	ENCORE: https://encorenature.org/ OCARA: (Lepousez et al, 2021) RiskChanges: https://riskchanges.org/ Drought Risk Atlas: Rossi et al, 2023
	3.2 Assessment of double materiality *(A, F, G)*	Climate, Resources, Biodiversity	Integrate double materiality assessment in the firm's strategy, investment decisions, and reporting practices	Consult and support companies in their transparent assessment	Mobilise public research funding for improving assessment tools	Brick 9	*Q&A: CSRD* (Carbon Disclosure Project (CDP), 2021)

[30] MECDD (2023) PDG Inondations 2021 - 2027

Type of Recommendation		Addressed threat	What does it mean for *companies*?	What does it mean at *industry level*?	What does it mean for *policymakers*?	Reference to Vision ECO2050	References and tools
3. Governance	3.3 Mutli-risk assessment *(F, G, A)*	Climate, Resources, Biodiversity	Analyse and budget the combined effects of compounding disruptions	Offer toolkits and information sessions to keep awareness high and companies alert	Mobilise public research funding for compound assessments (see also recommendation 3.1)	Brick 4	ENCORE: https://encorenature.org/ OCARA: (Lepousez et al, 2021) RiskChanges: https://riskchanges.org/
	3.4 Contingency plans *(F, G)*	Climate, Resources, Biodiversity	Implement a business continuity plan for exposed and vulnerable processes (identified through the self-assessment process)	Facilitate companies in developing their contingency plans; develop transferable templates for small firms	Consider making contingency plans a requirement (individual plans for bigger firms; standardised procedures for small firms)	Brick 10	ISO 31000 on Risk Management https://www.iso.org/iso-31000-risk-management.html
	3.5 Strengthen ESG / CSRD reporting mechanisms *(B, F)*	Climate, Resources, Biodiversity	Give more value to climate and biodiversity reporting by integrating physical risk adaptation action plan and budget	Consult and support companies in their transparent reporting	Create incentives for SMEs to voluntarily report their double materiality exposure and strengthen accountability	Brick 6	*Q&A: CSRD* (Carbon Disclosure Project (CDP), 2021)
	3.6 Integrate physical risk exposure analysis in the pre-planning process *(F, G)*	Climate, Resources, Biodiversity	Analyse the exposure levels of new sites or locations for expansion, especially in the construction sector	Inform firms about existing tools and databases	Implement exposure analysis into large infrastructural projects; Expand the geoportail database with other physical risk exposure variables at national level, such as drought, heat island effect,	Brick 9	*Minimisation of risk exposure at the pre-production stage* (Whang and Flanagan, 2015)
	3.7 Insurance against physical risks *(F, G)*	Floods; Windstorms	Consider signing for insurance to cover operational losses linked to a disruption of supply, physical damage	Raise awareness for the necessity of risk insurance	Follow the ladder approach to catastrophe insurance for low risk/high impact events, including public-private partnerships	Brick 9	*Policy options to reduce the climate insurance protection gap* (ECB & EIOPA, 2023) *Enhancing the insurance sector's contribution to climate adaptation* (OECD, 2023)
	3.8 Invest in foresight exercises *(G, F, C)*	Climate, Resources, Biodiversity	Develop simulations, speculative scenarios, and stress tests on a company level	Develop and support foresight exercises at an industry level	Continuing practice of foresight exercises at national level	Brick 10	Risks and opportunities toolkit: 19 tool cards https://www.iriss.org.uk/sites/default/files/future_risk_and_opportunities_card_pack.pdf

Type of Recommendation		Addressed threat	What does it mean for *companies*?	What does it mean at *industry level*?	What does it mean for *policymakers*?	Reference to Vision ECO2050	References and tools
3. Governance	3.9 Invest in awareness raising measures *(D, G, B. E)*	Climate, Resources, Biodiversity	Bigger firms: In-house research and development teams for monitoring of risks SMEs: send executive member to dedicated trainings	Offer trainings, information sessions and best practice exchanges	Run awareness-raising campaigns on the importance of physical risks	Bricks 9, 10	Good practices for climate-related and environmental risk management (ECB, 2022)
4. Nature-based and territorial	4.1 Separation of wastewater fractions *(G, A)*	Freshwater scarcity	Invest in wastewater management technologies	Lobby for subsidies for wastewater management technologies on-site	Develop infrastructure for treatment and reuse of greywater via constructing wetlands and canalisation systems; Use of treated wastewater for irrigation of public green spaces	Bricks 4, 9	Wastewater as a resource (EIB, 2022): https://www.eib.org/attachments/publications/wastewater_as_a_resource_en.pdf
	4.2 Green corridors *(G, F, A)*	Animal/ plant species loss; Floods; Freshwater scarcity	Include into on-site planning to maintain or create green areas in connection with surrounding areas	Develop guidelines for firms; liaise firms with specialised planners/consultants	Implement green belts around urban areas into development plans	Brick 4	Urban Nature Atlas: 1000 nature-based solution examples https://una.city/ Stuttgart green corridors case study: https://networknature.eu/casestudy/21264
	4.3 Porous design of roads *(G, A)*	Floods	Implement new technologies for porous design of roads in private infrastructure projects	Develop guidelines for firms; liaise firms with specialised planners/consultants	Implement new technologies for porous design of roads in public infrastructural projects; where applicable, use PAP and Règlement des batisses to set standards for building design and on-site layout	Bricks 4, 9	Permeable surfaces as natural water retention measures: http://nwrm.eu/measure/permeable-surfaces Permeable pavements: http://www.paving.org.uk/documents/cppave.pdf
	4.4 Phosphorus recovery from sewage sludge ashes *(G, A)*	Raw materials scarcity	Invest in wastewater management technologies where applicable	Raise awareness for the direct/indirect benefits of the technology	Invest in wastewater management technologies in intermunicipal sewage syndicates	Bricks 4, 9	INTERREG Nereus Project: New energy and resources from urban sanitation https://www.nereus-project.eu/

Type of Recommendation		Addressed threat	What does it mean for *companies*?	What does it mean at *industry level*?	What does it mean for *policymakers*?	Reference to Vision ECO2050	References and tools
4. Nature-based and territorial	4.5 De-waterproof (unseal) surfaces *(G, F, A)*	Floods; Heat waves	Consider leaving as much area on-site as possible unsealed to allow water infiltration and avoid water run-off	Develop guidelines for firms; liaise firms with specialised planners/consultants	Transform public sealed surfaces into green areas where possible (e.g. parking, parks, roads, commercial zones) following the latest PDAT 2035[31]	Brick 4	A practical guide for accessing support from the EIB for conservation and nature-based solutions: https://www.eib.org/attachments/pj/ncff-invest-nature-report-en.pdf
	4.6 Green roofs and green facades *(G, A)*	Floods; Heat waves	Invest in green roofs and green facades	Lobby for subsidies	Consider implementing subsidies	Bricks 4, 9	Nature-based solutions in Europe (EEA, 2021) Green roofs in Hamburg: https://www.hamburg.de/information-in-english/

[31] Programme directeur d'aménagement du territoire, 2023.

Chapter 10. Limitations and suggestions for further research

The research design of this study was built on a categorical division between climate, resources, and biodiversity-related threats. Although categorisation was useful for a more systematic review of the risk drivers and impacts, at times it has been difficult not to transcend the introduced categories because all these ecosystem services are essentially interconnected. For example, water scarcity considered as a resource, is linked to a decline in precipitation and rising temperatures from the climate change category, which also affect the resulting changes in water ecosystems and their effect on the composition of species and provision of services. Furthermore, the research design relied on existing projections for the evolution of these threats. However, such projections were not available for every indicator, especially at high spatial resolution, which is important for Luxembourg. Eventually, we tried to overcome these limitations by triangulating between various projections at different spatial scales. Furthermore, not only projections of threats were insufficient for the context of Luxembourg. Overall, the literature consulted to devise a list of risks stems from a combination of national and international sources, which is not unusual in academic literature reviews. However, it should be noted that if there had been more Luxembourg-specific literature it would have contributed for more accurate conclusions on the Luxembourg situation.

Regarding the empirical data collection methodology, some limitations need to be considered as well. Besides time constraints, the study took place in a challenging political context marked by the war in Ukraine, rising energy prices, and logistical disruptions. These factors influenced the participants' focus, often emphasizing the energy issue at the foreground of other pertinent aspects. Collecting environmental risk-related data from companies in empirical studies has proved to be difficult both in this and similar studies (Betts & Brown, 2021). While the number of workshops and interviews aligns with the targeted sample size of the study, the response rate for the online survey remained below expectations. Despite these limitations, the collected dataset was sufficiently informative due to the sample varying approach used, comprising small, medium, and large enterprises.

Some of our discussions with stakeholders highlighted relevant and important risk topics for them, which however go beyond the scope of this project but can be considered for further exploration .An overwhelming majority of research participants have stressed that one of the biggest risks they anticipate in the mid- to long-term future is the scarcity of workforce, especially expert workforce, for electricians and applied engineers, but also for jobs in the retail and manufacturing sector. It is a risk not least fuelled by a demographic crisis of increasing elderly proportion of the population, but also by changing values and aspirations of young people entering the workforce. For further inquiries into the realms of physical risks and their relevance to Luxembourg's economy, we suggest the following avenues:

- Any future research steps would highly benefit from available developed and regularly updated climate change scenarios and projections. The Climate Data Factory, for example, is a service provider partnering with the Copernicus Climate Change Service, which offer climate projections for selected indicators with high-resolution data (at 10km). Elaboration of local projections for resource scarcity and biodiversity loss threats is highly advisable too.
- Instead of increasing the sample quantitatively, we would rather propose more in-depth research in selected industries or types of organisations (e.g. SME) by simultaneously focusing on specific (sub-)threats. As to the latter, the areas ranking high in our risk assessment might be prioritised (e.g. flash floods, heat waves).
- Such in-depth studies could more narrowly accompany single firms over a longer period of time and by that gain first-hand insights into challenges and dynamics in the respective sector.
- A systemic analysis of supply chain risks related to resource scarcity for both the manufacturing and the construction sector.
- Detailed mapping and database development for all logistics hubs, to have clarity on what is stocked where, e.g. nationally or in the Greater Region, by whom, etc.
- Policymakers' recommendations would profit from further cost-benefit analyses.
- An in-depth focus on biodiversity aspects and the role of nature, investigating into (indirect) repercussions of degrading environments with a context-adapted assessment taking into account both the specificities of the regional environment as well as the particularities of the country's socio-economic structure.
- An assessment of substitution scenarios (e.g. the regional sourcing of building materials vs. more long-distance supply chains) against their articulation with physical risks.
- Define specific research questions on the link between local and European situation/regulations.

All the above would profit from interdisciplinary as well as transdisciplinary research, that involves both different scientific disciplines as well as practitioners and stakeholders from the studied industries.

Chapter 11. Conclusion

This report offers a qualitative risk analysis that integrates a literature review with empirical fieldwork data to assess the vulnerability of Luxembourg's economy to climate change, resource scarcity, and biodiversity loss. A review of recent literature and scientific projections has identified several relevant threats to the area of Luxembourg. Vulnerabilities are identified across all sectors to a different degree and type. Contrasting those threats with the observed perceptions of research participants has allowed us to identify several threats which need more awareness-raising efforts to shape adaptation and preparedness measures, such as flash floods, soil erosion, changes in water ecosystems, heat waves and others.

In summary, ecosystem degradation is often underappreciated as an economic risk, and although climate change awareness is growing, climate scepticism can still be encountered. Decreasing affordability or availability of resources, "green energy" in particular, have outweighed all other threats in stakeholders' perceptions. The study's methodology combines aggregated perspectives from a standardized survey with in-depth expert interviews to gain a deeper understanding of individual business cases.

Addressing the combination of threats will place demands on land resources, necessitating high levels of inclusive, horizontal, and democratic coordination among stakeholders through multi-governance approaches and integrated spatial planning strategies. The final part of the report also charts a course for informed decision-making and proactive measures to ensure the resilience and sustainability of Luxembourg's economy in the face of environmental challenges. To comprehensively assess exposure to climate threats, businesses are encouraged to engage in individual risk self-assessment exercises, in order to boost their awareness of exposure and vulnerabilities.

The SOC2050 study, also commissioned by Luxembourg Strategy and running in parallel to the RISK2050 study, explores society's attitudes towards the green transition. It reveals that people tend to be more willing to change their behaviour towards more sustainable practices when they know that others are doing the same. One of the take-away messages, which correlates with the RISK2050 findings, is the appreciation of regulatory practices to guide sustainable transitions. Civil society and economic actors both perceive policy measures as a tool for putting everyone on a shared path for achieving a just transition. Both stakeholder groups seem to doubt the ability of economic free market principles alone to achieve the environmental and social objectives needed for a safe and just social foundation.

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Glossary

Threat: a hazard which can potentially exploit an existing vulnerability in its target.

Vulnerability: a known weakness in the system or workflow, a weak spot, which may be exploited by a threat. Vulnerability comes after **exposure**, which is the contact point between the threat and the target.

Risk: the probability and severity of damage from an exposed vulnerability exploited by a threat.

Resilience: refers to the ability to maintain stability after the damage, and/or to reduce the probability and severity of damage altogether.

Climate change: a change in the state of the climate observable over a long period of time. It is identified by changes in the mean and/or variability of climatological indicators; also referred to as climate crisis.

Biodiversity loss: The reduction of any aspect of biological diversity (at the genetic, species and ecosystem levels) lost in a particular area through death (including extinction), destruction or manual removal; also referred to as *ecosystem / biosphere integrity / ecosystem services / nature's contribution to people degradation.*

Resource scarcity: chemical, food, mineral, water, land or other natural resource crises at a global scale as a result of human overexploitation and/or mismanagement; also referred to as *natural resources crisis.*

Annex

A.1. Economic sectors and NACE 2 codes

Table 0.1. Correspondence between study scope economic sectors and STATEC aggregation of large employers in 2022 by NACE classes.

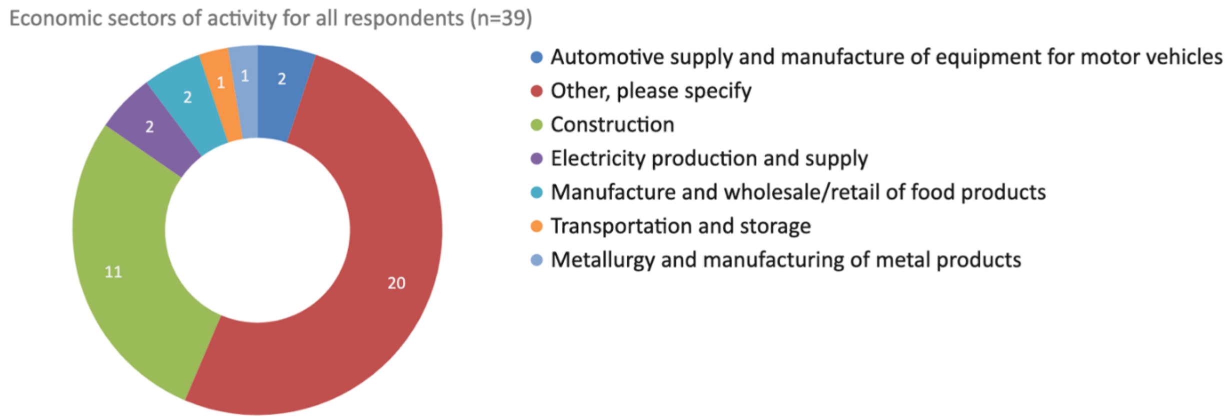
Study scope		STATEC aggregation per NACE 2 codes	N of employees in 2022, STATEC
Wood and forestry		OTHER MANUFACTURING, WOODWORKING, PAPER AND CARDBOARD INDUSTRY, PRINTING AND REPRODUCTION OF RECORDS, MANUFACTURE OF FURNITURE, COLLECTION, TREATMENT AND DISPOSAL OF WASTE, RECOVERY. NACE Rev.2 16, 17, 18, 31, 32, 38	1 570
Food		FOOD AND BEVERAGE MANUFACTURING, MANUFACTURING OF TOBACCO PRODUCTS NACE Rev.2 10, 11, 12	1 780
		46.3 Wholesale of food, beverages and tobacco	2 020
Construction		EXTRACTIVE INDUSTRIES NACE Rev.2 08, 09	100
		CONSTRUCTION NACE Rev.2 41, 42, 43	15 840
Manufacturing		MANUFACTURE OF TEXTILES, CHEMICAL INDUSTRY, MANUFACTURE OF RUBBER AND PLASTIC PRODUCTS, MANUFACTURE OF OTHER NON-METALLIC MINERAL PRODUCTS NACE Rev.2 13, 20, 22, 23	3 460
	Glass	23.1 Manufacture of glass and glassware	480
	Metal and steel	METALLURGY, MANUFACTURING OF METAL PRODUCTS NACE Rev.2 24, 25	4 440
	Automobile	MANUFACTURE OF COMPUTER, ELECTRONIC AND OPTICAL PRODUCTS, MANUFACTURE OF ELECTRICAL EQUIPMENT, AUTOMOTIVE INDUSTRY, MANUFACTURE OF MACHINERY AND EQUIPMENT N.E.C., REPAIR AND INSTALLATION OF MACHINERY AND EQUIPMENT NACE Rev.2 26, 27, 28, 29, 33	3 690
Energy		PRODUCTION AND DISTRIBUTION OF ELECTRICITY, GAS, STEAM AND AIR CONDITIONING NACE Rev.2 35	1 480
Logistics and Transportation		TRANSPORTATION AND WAREHOUSING NACE Rev.2 49, 50, 51, 52, 53	17 410

A.2. Sample of participants in the fieldwork per method of data collection workshops, survey, interviews.

Table A.2.1. Sample of participants in the workshops. N = 29

	Participants
Workshop 1	Luxinnovation Automobility Cluster, Luxinnovation CleanTech Cluster, IBLA, Luxinnovation Wood Cluster, Luxinnovation Materials & Manufacturing Cluster,ILEA), MECO, FEDIL
Workshop 2	BorgWarner, Leaseplan, SES, Vodafone, Amazon, ArcelorMittal, Shipsta
Workshop 3	Ministry of Energy and Spatial Planning
Workshop 4	Encevo
Workshop 5	Wijngaard Natie, ArcelorMittal, Tata Steel Europe, Liberty Steel Group, +7
Follow-up workshop	IBLA, IMS, Ministry of Economy, CFL Multimodal, City of Esch / Sudstrom, IEE, Raval / ILEA, Eurometal, Luxinnovation, Hein Dechets

Figure A.2.1. Sample composition of online survey participants, per economic sector. Above: represented sectors of interest as per NACE classification; below: specification of "other" sectors beyond the scope of study.



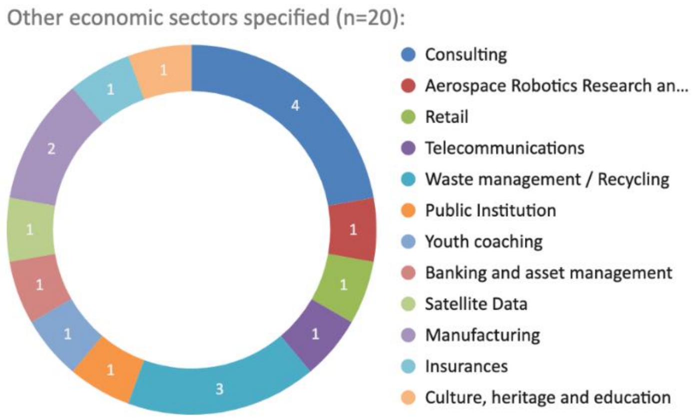


Table A.2.2. Interview sample composition per type of organisation and economic sector. N = 21.

Economic sector / Type of organisation	Number of participants
Energy	3
Logistics	2
Food	2
Forestry	1
Automobility	2
Construction	2
Metal and steel	1
Glass	1
Waste, Recycling	1
Municipalities / National authorities	3
Associations	3

A.3. A summary of studies/reports/presentations for 1) Securing proper water supply, 2) Flash floods and heavy rainfall events, and 3) Droughts in Luxembourg

Table A.3.1. National strategies regarding securing water supply.

Title	Authors	Main content	Comments
Strategie zur langfristigen Absicherung der Trinkwasserversorgung (Strategy for a long-term protection of water supply) 2021	Tom Schaul Ministere de l`Evironment, du Climat et du Developpement durable (MECDD)	▪ Impacts of Climate change on groundwater ▪ Impact of demographic development ▪ Strategy for long-term protection of water supply ▪ Forecast of drinking water consumption in Luxembourg	Presentation
Dritter Bewirtschaftungsplan zur Umsetzung der Wasserrahmenrichtlinie (3th Plan for realisation of Water framework Directive, 2022	MECDD	▪ Deficit in water supply in LU in long-term due to demographic development and growth of economy ▪ Measures for reduction of water consumption are necessary ▪ Critical situation from year 20240 on ▪ Also wastewater treatment has to be adapted (size of WWTP)	Hint to `Programme directeur d` amenagement du territoire` (in progress)
Water Management in the Twenties, 2020	Luc Zwank, Administration de la gestion de l`eau	▪ Evolution of national drinking water needs ▪ Challenges: climate change, demographic development ▪ Strategic approaches (reduction, protection of resources, new resources)	Presentation
"Le Grand-Duché de Luxembourg et ses besoins futurs en eau potable", 2016	Management Consultants Luxembourg		unpublished

Table A.3.2. National strategies regarding Flash floods and heavy rainfall events.

Title	Authors	Main content	Comments
Starkregen-Risikomanagement in Luxembourg (Risk management of heavy rainfall events in Luxembourg) 2021	Ministry for Environment, Climate and Sustainable Development / Administration de la gestion de l`eau	▪ Definition and description of problem ▪ Starkregenatlas (maps with areas at risk) ▪ Risk assessment ▪ Concrete measures	Report
Starkregengefahrenkarten Luxembourg 2022	Claude Meisch, MECDD / Administration de la gestion de l`eau	▪ Description of historical events ▪ Adaption strategies on Climate Change ▪ Management of heavy rainfall events on local level	Presentation
Starkregengefahrenkarten on Geoportail		▪ Maps with risk assessment measures can be downloaded on local level	
Allgemeine Informationen zur kommunalen Starkregenvorsorge	MECDD / Administration de la gestion de l`eau	Projects regarding flood-protection can be funded up to 100% by Fonds de la gestion de l'eau [Artikel 65 §1 (k) de la loi modifiée du 19 décembre 2008 relative à l'eau].	Additional information
Hochwasserrisikomanagement-Richtlinie 2007/60/CE			

Table A.3.3. National strategies regarding Droughts.

Title	Authors	Main content	Comments
Geoportail		▪ Maps with assessment of a) phase yellow – prevention b) phase orange – shortage of drinking water supply c) phase red – increasing shortage	

A.4. References for climate change economic impacts.

Indicator	References
Industrial Manufacturing	Gambhir et al, 2022; Pogačar, 2018; Dasgupta et al, 2022; UNEP FI, 2023; International Labour Organization, 2019; IEA, 2018; Cachon et al, 2012; ArcelorMittal, 2021;
Construction	WBCSD, 2020; German Environment Agency, 2019; MECDD, 2018; Smith, 2013
Forestry	Forzieri et al, 2020; Romeiro et al, 2022; Martinez del Castillo et al, 2022; Hanewinkel et al, 2013; EEA, 2017; Jonsson et al, 2021
Food processing	Molitor and Junk, 2019; Fan et al, 2021; Godde et al., 2021; Guerin, 2022; Reardon & Zilberman, 2018; Duchenne-Moutien and Neetoo, 2021
Energy	Després and Adamovic, 2020; Kapica et al, 2023; Spinoni et al, 2018;
Logistics	Lepousez and Derouet, 2022; Mantin et al, 2021; McKinnon and Kreie, 2010; Pappis, 2010

A.5. References for resource scarcity economic impacts

Indicator	References
Industrial Manufacturing	Kan et al, 2021; European Commission, 2020c;
Construction	Göswein et al, 2021; UNEP FI, 2023; European Commission, 2021; Science for Environment Policy, 2016
Forestry	Beck-O'Brien et al, 2022; Mishra et al, 2021; O'Brien & Bringezu, 2017
Food processing	Molitor and Junk, 2019; Fan et al, 2021; Godde et al., 2021; Guerin, 2022; Reardon & Zilberman, 2018; Duchenne-Moutien and Neetoo, 2021
Energy	Gregoir and Van Acker, 2022; European Commission, 2020a
Logistics	Charles et al, 2009; European Water Association, 2018; UNEP FI, 2023; Research Luxembourg, 2020

A. 6. References for the biodiversity loss economic impacts

Indicator	References
Industrial Manufacturing	ten Have et al, 2012; ENCORE; DNB & PBL, 2020
Construction	Herweijer et al, 2020; ENCORE
Forestry	Herweijer et al, 2020, Forzieri et al, 202
Food processing	IPBES, 2019; Molitor and Junk, 2019; Fan et al, 2021; Copernicus Climate Change Service, 2021
Energy	Herweijer et al, 2020; ENCORE
Logistics	ENCORE

A. 7. Projections for the probability and severity of threat indicators, on which the risk matrix is based.

Indicator	References
extreme wind	Seneviratne et al, 2021; Ranasinghe, 2021; Fischer and Knutti, 2015; Sousa et al., 2018
wildfires	*Climate-ADAPT > Indicators > High Fire Danger Days*
cold waves	Smid et al, 2019; *Climate-ADAPT > Indicators > Frost days*
heat waves	Russo et al., 2015; Smid et al, 2019; Junk et al, 2019; *Climate-ADAPT > Indicators > Climatological heatwave days* Szewczyk et al, 2020
t > 35°C	*Climate-ADAPT > Indicators > Maximum temperature*
drought	Lin et al, 2022; *EEA > Indicators > Drought impact on ecosystems in Europe*
riverine floods	MECDD (2023) PDG Inondations 2021 – 2027 Geoportail.lu *Climate-ADAPT > Indicators > Total precipitation* *Climate-ADAPT > Indicators > River flood* Kleeschulte et al, 2020
flash floods	MECDD (2023) PDG Inondations 2021 – 2027 Geoportail.lu *Climate-ADAPT > Indicators > Total precipitation* *Climate-ADAPT > Indicators > River flood*
blackout	Ministère de l'Énergie et de l'Aménagement du territoire, 2022
brownout	Creos Luxembourg, 2020; Creos Luxembourg, 2021
energy price/use	Way et al, 2022; PNEC; IEA, 2022a; Zappa et al, 2019; Bogdanov et al, 2019; Breyer et al, 2022
raw materials	European Commission, 2023b; European Commission, 2020a; Gregoir and Van Acker, 2022; Mantin et al, 2021; Beck-O'Brien et al, 2022
industrial land	ESPON, 2020; European Commission, 2021; Science for Environment Policy, 2016; PDAT, 2023
water navigation	European Commission, 2020c; CCNR, 2023; BDV, 2023; Phillips & Green, 2022
fresh water	MECDD, 2021; MECDD, 2022; *Climate-ADAPT > Indicators > Total precipitation*
soil erosion	Panagos et al, 2021
pests	Eickermann et al, 2023
air pollution	Guzmán et al, 2022; San José, 2016 *Copernicus Atmosphere Monitoring Service*
grasslands	Observatoire de l'environnement naturel, 2022 ; IPBES, 2019
water ecosystems	MECDD, 2021; MECDD, 2022; Pörtner et al, 2021; IPBES, 2019; IPCC, 2023 *EEA > Indicators > Drought impact on ecosystems in Europe*
plant species	Observatoire de l'environnement naturel, 2022; IPBES, 2019; Observatoire de l'environnement naturel, 2022; IPBES, 2019; Pörtner et al, 2021
lifecycle plants	Copernicus Climate Change Service, 2021; Observatoire de l'environnnement naturel, 2022; IPBES, 2019
animal species	Observatoire de l'environnement naturel, 2022; IPBES, 2019; Eickermann et al, 2023; Pörtner et al, 2021

A. 8. Risk analysis

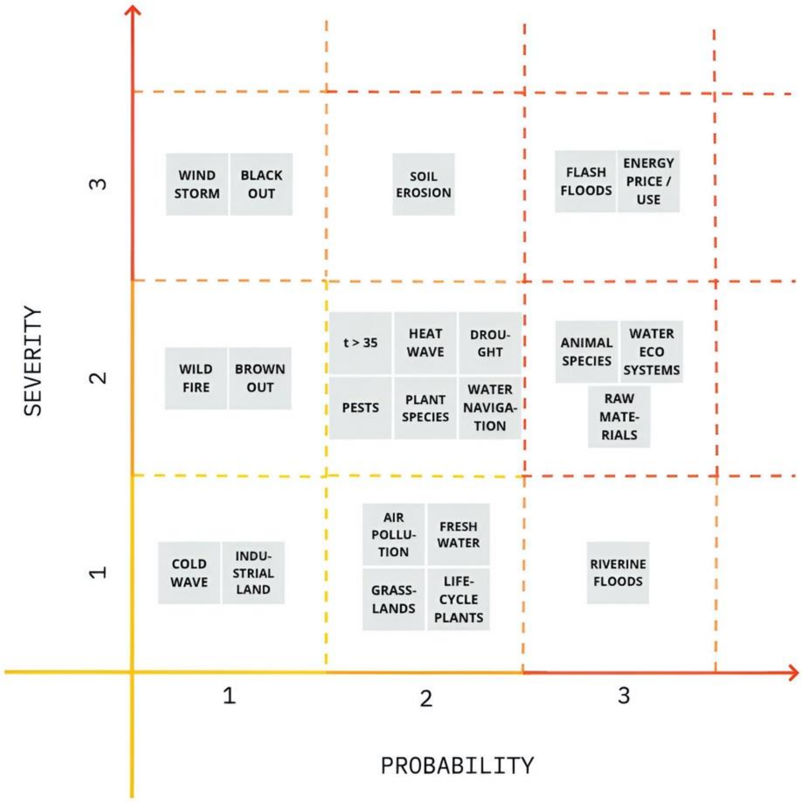


Figure A.8.1. Risk matrix based on scientific projections consulted in the literature review.

Figure A.8.2. Risk categorisation based on empirical data of stakeholders' risk perception (the medium category was not introduced in most of the data collection for reasons of time and simplicity).