The technological issues involved in adapting to climate change

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Energy Transition Working Group

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Introduction

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1.1. Background and objectives

Faced with accelerating climate change, societies must imperatively adapt to the new environmental realities. France has established a National Plan for Climate Adaptation (PNACC) to respond to the complex issues involved in these changes. In 2024, the National Association of Research and Technology (ANRT) asked its Energy Transition Working Group to carry out a detailed investigation into the technological issues involved in adapting to climate change.

Since 2017, the Energy Transition WG has assisted public authorities in drawing up the National Energy Research Strategy (SNRE), which sets out the country's energy policy goals, consistent with the National Low-carbon Strategy (SNBC) and the Multi-annual Energy Plan (PPE).

In 2024, under the chairmanship of Olivier Appert, the group closely examined available technologies and innovations with the potential to address climate-related challenges, taking a systemic approach to adaptation covering a range of fields including water, energy, industry, agriculture and urban planning. This integrated approach aims to identify and promote technological innovations capable of strengthening the resilience of different economic sectors while considering their complex interactions. The objective is to put forward concrete strategies that will help France to adapt its economy and infrastructures to the new climate conditions.

This report, entitled *"The Technological Issues Involved in Adapting to Climate Change"*, has a two-fold objective: to identify key technological solutions for adapting sectors to deal with climate change; and to provide public and private decision-makers with strategic recommendations to effectively integrate these technologies into their policies and action plans.

1.2. Why look at the technological issues involved in adapting to climate change?

Like the rest of the international community, France must adapt to the inevitable, already observable consequences of climate change, which are expected to feature more intense extreme phenomena like floods, droughts, and heatwaves, with major impacts on our economy.

Historically, international climate discussions, like Conferences of the Parties (COP), put the emphasis on taking mitigation measures, in other words, reducing greenhouse gas emissions. In the early days, adaptation was sometimes seen as an alternative to emissions mitigation, but it has since become an absolute necessity, given the global incapacity to effectively reduce emissions. However, faced with the intensification of extreme weather events, it is imperative that we adapt our way of living, which involves making deep-seated changes to our behaviour and societies.

This challenge, while different from mitigation, is of major strategic importance if we are to preserve the economy and guarantee sustainable development. Although the target of carbon neutrality by 2050 remains central to climate policies, adapting to the increasing impacts of global heating will require conceiving and implementing innovative, resilient technological solutions. This requires both improving the resilience of existing technologies and coming up with innovations specifically adapted to deal with future climate conditions.

Integrating these technologies is indispensable if we are to build a resilient society that is capable not only of meeting the challenges of climate change, but of exploiting the opportunities of long-term sustainable development, while protecting people and optimizing key resources.

1.3. Method

Our method involves gathering, analysing and summarizing the contributions of a large range of industrial and academic experts covering various themes, but with a concern for systemic aspects.

1.3.1. ORGANIZATION OF THEME-BASED INTERVIEWS

Theme-based interviews with experts and the resulting exchanges with partners proved invaluable to identify the specific challenges facing France and propose concrete technological solutions.

1.3.2. SELECTION AND ANALYSIS OF THE CONTRIBUTIONS

These contributions were meticulously transcribed and analysed. Some of them were supplemented by complementary sources in order to go deeper into the technical aspects.

1.3.3. SYSTEMIC, TRANSVERSAL APPROACH

The method adopted by the Energy Transition WG is different from traditional sectoral approaches, which are often limited to a specific analysis of the technological issues by domain. In this case, the group adopted a systemic approach by considering the interconnections between sectors and technologies with the aim of identifying potential intersectoral synergies.

1.3.4. SUMMARY AND REPORT WRITING

Based on the minutes of plenary meetings and the subsequent exchanges, the WP produced a summary of the information collected. This work was organized to reflect the priorities identified and integrate the specific recommendations made by the experts. The final report was therefore written based on a rigorous analysis of the data and testimonials, ensuring that each recommendation relies on solid scientific and practical foundations.

The WG identified several adaptation strategy areas, highlighting key technologies that will be crucial to ensure the resilience of energy systems, the sustainable management of water, the evolution of agricultural practices, the adaptation of urban infrastructures, and the strengthening of the public health system in the face of climate change. These technologies are not only tools for responding to climate impacts, they are also levers for sustainable transition, since they benefit from French technology and industry.

Under the chairmanship of Olivier Appert, Denis Randet and Richard Lavergne, the summary and writing process was coordinated by Antoine Belleguie, who acted as the group's rapporteur during 2024.

1.4. Structure of the report

To reflect this systemic approach, this report is organized into nine different themes:

- Water
- Energy
- Agriculture
- Cities & Buildings
- Industry
- Transport
- Health
- Defence
- Space

For each theme, the report analyses the challenges related to climate change, the existing technological solutions, their readiness level, their application potential, and the issues involved in deploying them. The interactions between these sectors are looked at in detail taking a systemic approach, which is indispensable to guarantee effective, consistent adaptation.

The report concludes with a series of strategic recommendations, including concrete proposals for developing adaptation technologies, improving the resilience of infrastructures, and coordinating the efforts of different public and private stakeholders.

1.5. Acknowledgements

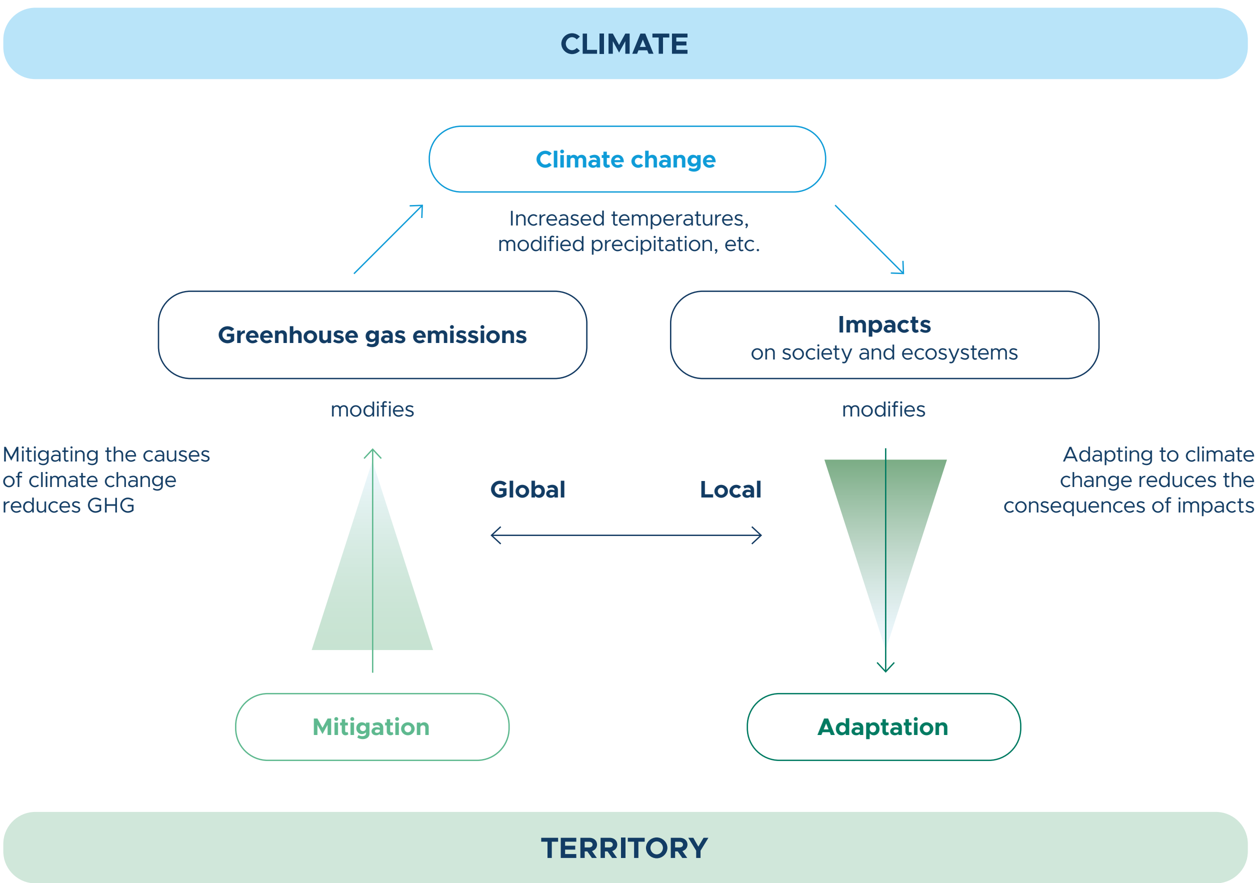
The coordinators of the working group warmly thank the numerous participants, both internal and external to the group, who helped make this such a rich, high-quality report. Their expertise and commitment were essential to identify the technological issues involved in adapting to climate change and put forward concrete solutions. The list of participants is provided in the annex.

General framework for climate change adaptation

02

2.1. Defining adaptation: the issues and the dividing line with mitigation

Climate change adaption to is central to national and international strategies to manage climate risks. It aims to reduce the vulnerability of human and natural systems to the inevitable impacts of climate change, while strengthening the resilience of infrastructures and ecosystems (MTECT, 2023). Unlike mitigation, which focuses on reducing greenhouse gas (GHG) emissions, adaptation is concerned with the impacts of warming, including local effects and multiple indicators. However, the dividing line between adaptation and mitigation is sometimes unclear because some technologies, procedures and strategies can meet both objectives simultaneously.



Source: Adapted from MTECT/ONERC (2023)

2.1.1. ISSUES INVOLVED IN ADAPTATION

Adapting to climate change is now a necessity. The impacts of this change are already visible and will become more intense in the coming decades. Global climate models do not always concur, local-scale forecasts are particularly difficult, and France occupies a pivotal geographic position at the crossroads of several influences. This calls for a great deal of data and modelling work. In the mid to long term, Météo-France forecasts a rise in average temperatures, more frequent heatwaves, reduced summer rainfall, more droughts and more intense winter precipitation, increasing the risk of flooding. The third National Plan for Climate Adaptation (PNACC) aims to prepare France to deal with a temperature rise of +4°C by 2100. The adaptation issues identified by the PNACC 3 include public health, territorial resistance, the protection of key infrastructures, and preservation of biodiversity, in addition to the protection of inhabitants in the face of extreme climate events, prevention of technological risks, resilience of the economy, and protection of the cultural heritage.

2.1.2. ADAPTATION AND MITIGATION

Although often treated separately, adaptation and mitigation are closely related. Numerous technologies designed to mitigate climate change also contribute to adaptation. For example, the development of electric networks, smart grids and energy storage can result in both better management of energy resources and improved resilience of infrastructures in the face of extreme weather events. These technologies facilitate the integration of intermittent renewable energy and make it easier to manage local disturbances, thus reinforcing adaptation at the same time as reducing GHG emissions.

Adaptation and mitigation are complementary strategies that are indispensable to deal with climate challenges. Investments made in infrastructure, buildings, agriculture and networks must be coordinated to simultaneously respond to these two objectives. This systemic approach requires greater cooperation, such as through reinforcing observation capacities, improving data management tools and climate models, and better governance and coordination between stakeholders.

It is difficult to clearly dissociate mitigation and adaptation investments since both approaches are often interconnected. Some investments made to reduce greenhouse gas emissions (mitigation) also contribute to adaptation by strengthening the resilience of infrastructures and systems to climate change. Any rebound affects also need to be monitored, although these appear to be rare in the examples observed.

While the connections between climate scenarios and their precise impacts on energy infrastructures are sometimes difficult to establish, it is crucial that they be integrated into planning to anticipate future climate risks. This step is essential to ensure the resilience of all energy infrastructures, including renewable energy systems, storage systems, and other systems. For example, concerning energy, EDF uses climate forecasts to direct its investment decisions, which include identifying the most suitable areas for establishing new energy facilities, like wind farms.

A systemic approach is often put forward as necessary, but sometimes inadequately defined. An effective systemic approach needs to consider not only interactions between the different adaptation technologies and sectors, but also the interrelations between the targets of mitigation and adaptation. This approach requires a rigorous evaluation of the costs and benefits of each technological solution, integrating both gains in resilience and potential savings in terms of GHG emissions.

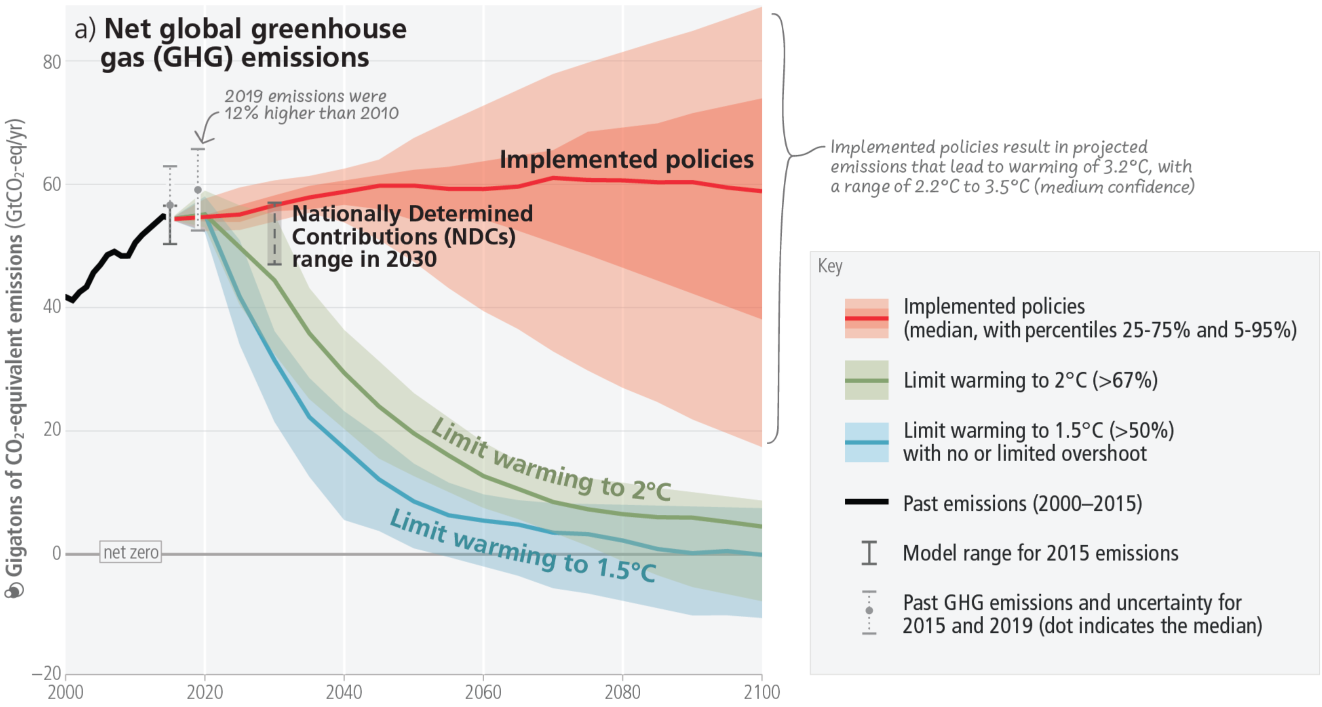
2.2. National and international policy: PNACC and beyond

Climate change adaptation policy, at both national and international scales, is part of a strategic framework aimed at responding to the increasing challenges of climate change impacts. The National Plan for Climate Adaptation (PNACC) is a key policy in France to organize and coordinate the country's adaptation efforts. The plan is broken down into several priority focus areas, integrating specific measures to improve the country's resilience to deal with future climate hazards. At international scale, these efforts are part of a bigger framework of commitments made by France and other countries under the United Nations Framework on Climate Change (UNFCC) and its associated agreements.

Source: IPCC AR6 Synthesis Report: Climate Change (2023)

2.2.1. STRATEGIC FOCUS AREAS OF THE PNACC

The third National Plan for Climate Adaptation (PNACC 3), currently being finalized, is designed to prepare France to deal with a potential temperature rise of +4°C by 2100. The latest version is organized into five main focus areas broken down into 51 measures to guide climate change adaptation efforts:



1. **Protect inhabitants:** The first area focuses on reducing the impacts of climate change on public health and the security of inhabitants. It comprises measures like reinforcing early warning systems for heatwaves, installing air conditioning units in sensitive buildings, and preventing psychosocial and health risks related to extreme conditions.
2. **Ensure the resilience of territories, infrastructures and key services:** This focus area involves improving the capacity of territories and critical infrastructures (energy, water, transport) to stand up to extreme weather events such as floods and droughts. For example, it includes building dykes, improving protection infrastructures and creating maps forecasting risks at 30 and 100 years to guide territorial planning.
3. **Adapt human activities:** The objective is to ensure economic resilience and guarantee food, energy and economic sovereignty in the face of climate hazards. This includes adapting production sectors, adopting sustainable agricultural and industrial practices, and anticipating the impacts of climate on production and supply chains.
4. **Protect our natural and cultural heritage:** This area focuses on preserving ecosystems and natural resources and the cultural heritage. It comprises actions like adopting agroecology practices, using drought-resistant crops, managing forests to limit the risks of fire, and conserving the architectural heritage threatened by climate hazards.
5. **Mobilize civil society:** This last focus area highlights the importance of collective mobilization to successfully adapt to climate change. It involves raising awareness and training citizens, local communities and economic actors on the importance of adaptation, while strengthening governance and the coordination of actions at all levels.

2.2.2. INTERNATIONAL COMMITMENTS AND COOPERATION

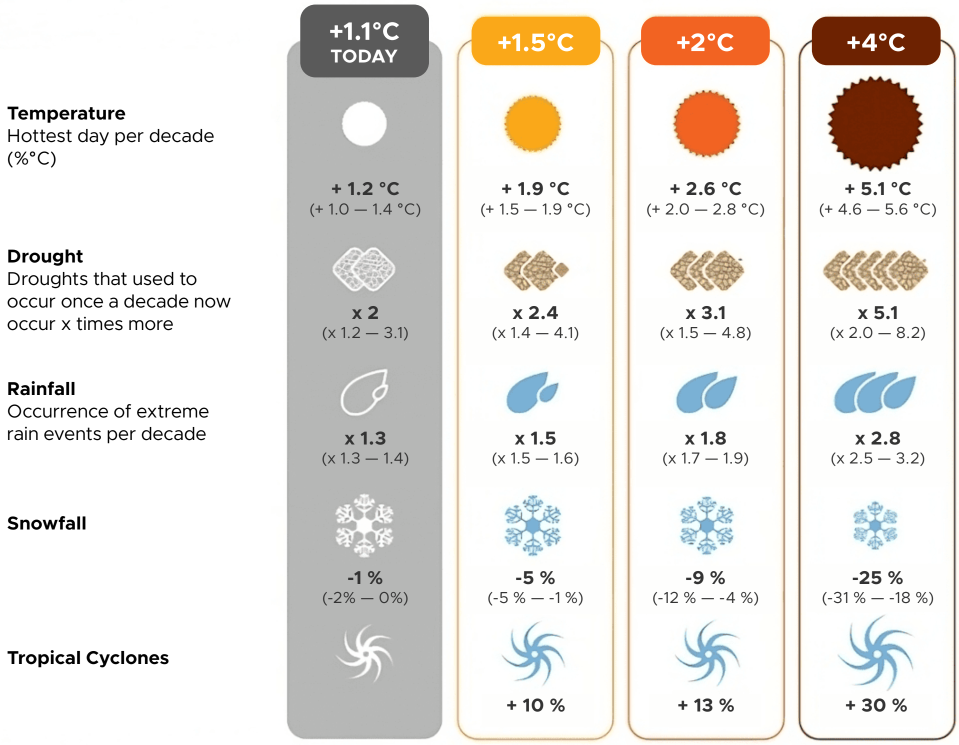
On the international scene, France is committed through its support for development, which largely includes adaptation to climate change. As part of its international commitments, this support aims to reinforce cooperation with developing countries by sharing technological expertise, participating in joint research projects, and aligning actions with global targets to reduce climate risks. For many developing countries, adaptation is perceived as a more urgent and accessible priority than mitigation, which underlines the importance of development support that targets adaptation strategies.

2.3. Economic and social issues involved in adaptation

Adapting to climate change involves major economic and social challenges that touch on all sectors of the economy and society. The impacts of climate change, such as increased extreme weather events, variations in precipitation, and higher temperatures, require adapted responses to protect inhabitants, preserve social cohesion, and ensure the resilience of economic infrastructures. The costs of these adaptations, although considerable, are justified by the damage avoided and the short- and long-term benefits.

EVERY DEGREE COUNTS: WHAT CAN WE EXPECT?

Each fraction of a degree of increased heat around the globe has a strong impact on climate extremes.



Source: Translation of an infographic produced by Météo-France based on the work of the IPCC (2023)

2.3.1. ECONOMIC AND FINANCIAL IMPACTS OF ADAPTATION

Climate change has a direct impact on several key economic sectors, requiring specific adaptations to guarantee their viability:

— **Agriculture:** The agricultural sector must adapt to more varied rainfall and more frequent droughts. Measures include optimized irrigation, reuse of treated wastewater, and development of drought-resistant crops, which are essential to ensure food security.

— **Industry & transport:** Industry must strengthen the resilience of supply chains and adopt technologies that are less vulnerable to extreme climate conditions. In transport, adaptation concerns both infrastructures (railways, roads) to resist heatwaves and floods, and services, in order to guarantee thermal comfort in vehicles and the continuity of travel during crisis periods. The PNACC 3 puts the accent on an integrated approach that combines adapting mobility infrastructures and services.

— **Buildings & cities:** Buildings and urban infrastructures must implement adaptation measures like improved thermal insulation, rainwater management, and the reduction of urban heat islands thanks to better use of vegetation.

— **Employment & work organization:** Adaptation will generate financial opportunities, such as the creation of jobs in sectors like technology, sustainable construction, and climate risk management. However, adjustments will be needed in the way work is organized, in particular for sensitive sectors like agriculture and construction. Remote working and work hours adapted to weather conditions will play a key role in reducing risks and protecting workers.

2.3.2. EVALUATING THE COSTS AND BENEFITS OF ADAPTATION

Evaluating the cost of adaptation projects remains a challenge due to the lack of measurement systems to quantify the short-term benefits. Yet this analysis is essential to guide political choices and justify investments. It should include prospective scenarios based on climate forecasts for 2050-2100, taking uncertainties into account.

The benefits of adaptation include the reduction of material damage, the preservation of infrastructures, and the maintenance of economic productivity. For example, evaluating the amount of damage avoided makes it possible to rank actions in order of priority, like reducing mortality rates or improving the resilience of transport networks.

2.3.3. FINANCING ADAPTATION

Adapting to climate change involves considerable investments in infrastructures, R&D and stakeholder training. A report by the Institute for Climate Economics (I4CE) estimates investment needs of several billion euros per year, split between the following sectors:

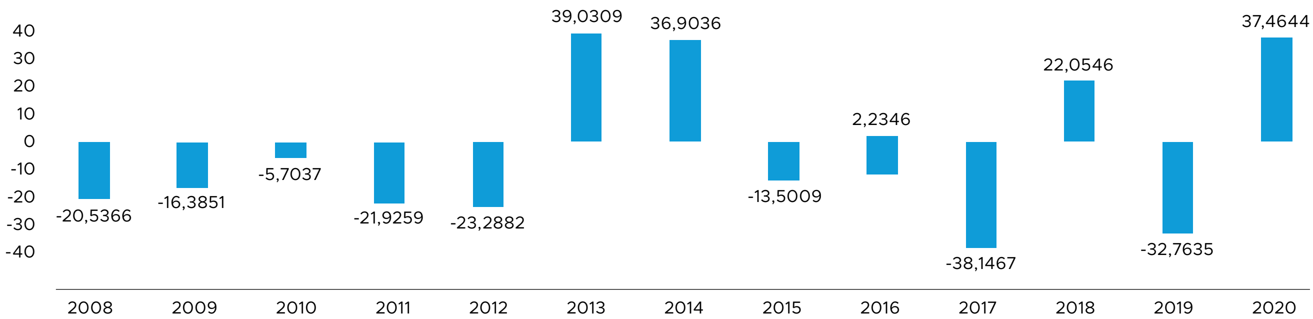
- **Buildings:** From 1 to 2.5 billion euros a year for new builds, and up to several billion to renovate the existing park once the energy renovation efforts have reached maturity.
- **Transport:** Several hundred million to several billion euros per year to modernize roads and railways.
- **Agriculture:** Up to 1.5 billion euros per year to maintain yields in the face of climate change.

These figures do not take into account the indirect but significant efforts already made. For example, EDF is modernizing its electric networks to make them more resistant to climate hazards, and SNCF Réseau is adapting its rail infrastructures in planned regeneration cycles. These initiatives, although not explicitly classed as ‘adaptation’, play a key role in resilience.

Adaptation technologies by sector

3.1. Water

Water is essential to the life of both humans and ecosystems. Climate change is putting more and more pressure on freshwater resources, impacting both their availability and their quality. In France, variations in precipitation, higher temperatures, increased evaporation, and the variability of water regimes aggravate drought, flooding and water stress[1]. These problems require adapted technological solutions to preserve resources and secure the water supply in a future where extreme phenomena are set to become more frequent. This chapter looks at the issues, challenges and technological solutions for adapting the water sector in France to the new climate conditions.



Source: SDES - Evolution of renewable water resources in France compared to average (water year).
The 0 line represents the 1990-2020 average of 211 billion m^3 (2021)

1 Situation in which, in a given geographic area, water demand exceeds available water resources

3.1.1. ISSUES RELATED TO WATER MANAGEMENT AND WATER STRESS

Challenges concerning water management: Water is vulnerable to the consequences of climate change.

In France:

- **32% of drinking water comes from surface water** (2022) but **90% of catchment points draw from groundwater.** However, in some large cities like Paris, the supply is equally divided in volume between ground and surface water.
- Leaks in the water supply network, which covers **900,000 km**, total an **average loss of 18.7%** of the water injected into the network, corresponding to an average cost of **520 euros** per household per year. Note that this figure of 18.7% hides wide disparities between one city and the next.

Degradation of water quality and quantity: The impact of climate change on water quality and quantity is a major concern. Several aggravating factors have been identified, including:

- **Proliferation of cyanobacteria:** When temperatures rise above 17°C, cyanobacteria and other bacteria proliferate in water supply networks, posing a threat to drinking water.
- **Eutrophication**[2] **and deoxygenation:** These rising phenomena require technologies to reoxygenate water bodies and reconstitute natural reserves.
- **Chemical pollution:** Low-water periods see a rise in the concentration of pollutants, such as from pesticides and farming products, calling for the development of new methods for processing wastewater.
- **Water stress:** France regularly experiences long periods of drought, which may be meteorological, edaphic or hydrological[3]. In 2024, about 20% of French farmland was affected by water stress making it necessary to adopt more effective agricultural and irrigation practices.

3.1.2. WATER MANAGEMENT AND TREATMENT TECHNOLOGIES

A range of mature and innovating technologies have been identified to improve the effectiveness and sustainability of water resource management. These solutions require detailed life cycle assessments to evaluate their net energy impacts, in particular given that most energy is still not carbon-free:

- **Micro-irrigation and smart irrigation:** Optimizing irrigation is a priority to reduce water consumption and optimize water use, while maintaining agricultural yields. Automated water systems, supported by advanced technologies like IoT[4] sensors, artificial intelligence (AI), and satellite imagery, can be used to adjust the amount of water needed to meet crop needs, and thus reduce water consumption by 30% to 40% while ensuring similar yields. These technologies are employed to monitor soil humidity in real time and only activate irrigation when needed, to avoid wasting resources.
- **Reuse of treated wastewater:** The reuse of treated wastewater is a promising solution to compensate water shortages. Following the EU regulation of 2020, the French regulations on the reuse of treated wastewater (REUT) were harmonized at EU level. In France, the regulatory framework has recently been supplemented by decrees and orders that implement the 'Varenne' agricultural plan on water and climate change adaptation of 2022. However, challenges remain, such as the geographic distance between the urban areas that produce this non-conventional water and the rural areas that need it, which sometimes makes transportation unviable. Currently, about 30% of French rivers are fed by water treatment plants, underlining the importance of this practice to maintain river flows, in particular during times of drought. In France, the reuse of water is strictly regulated to avoid conflicts between users (authorization from the regional prefect) and to preserve the natural environment (water and soil) and human health (plants and aerosols).
- **Water desalination:** Desalination is considered to be a potential solution for coastal regions suffering from water shortages. Although rarely used in France, this technology could be envisaged in the long term, in particular if climate change exacerbates freshwater shortages. However, although seawater desalination is crucial to respond to shortages, it does present challenges. For example, inverse osmosis produces water that is too pure; unless it is remineralized, it attacks metal pipelines, as observed in Barcelona. It is therefore imperative to include these technologies in a global strategy.
- **Groundwater recharge:** Faced with reduced levels of available water, artificial recharging of the water table is another adaptation solution. Techniques like directly injecting treated water or creating infiltration basins are now widely used, such as in the USA, Australia, and Israel. These methods can be used to maintain sustainable water levels even during prolonged droughts.
- **Water management tools:** It is essential to devise management tools to anticipate water conflict issues, in particular with the end of glacier reservoirs, which will affect summertime river

2 Excessive nutrients (nitrates and phosphates) leading to a proliferation of algae, a drop in oxygen, and the degradation of the aquatic ecosystem.

3 Meteorological drought: lack of precipitation; edaphic drought: dried-out soil; hydrological drought: decreased flow in waterways, water tables or reservoirs.

4 Internet of Things : network of physical objects connected to the internet and capable of exchanging and transmitting data.

flows. The sustainable management of groundwater is a major political priority.

3.1.3. TECHNOLOGIES FOR WATER STORAGE AND TRANSPORT SYSTEMS

Climate change not only involves drought. Extreme weather events, like flooding, flash floods and wildfires, require specific adaptations in the way water infrastructures are managed.

- **Modelling of precipitation and network sizing:** Precise modelling of future precipitation is crucial to adapt water infrastructures to new climate situations. In France, modelling tools are being developed to simulate extreme events like torrential rain in order to correctly size pipes for managing rainwater and ensure that they are effective in the long term.
- **Reduction of leaks in the water system:** Improving infrastructures and implementing leak-detection technologies are essential to reduce leaks, in particular in rural areas where networks cover greater distances and are therefore more difficult to maintain.
- **Rainwater storage and groundwater recharge:** Storage on the surface or in the water table is now crucial to guarantee the constant availability of water during drought periods. Surface reservoirs are used to capture and store rainwater, while artificial recharge of the water table maintains the hydrological balance. To recharge groundwater, techniques like direct injection and infiltration basins must also be included in adaptation strategies, while monitoring water quality.
- **Adaptation of infrastructures to wildfires:** Forest fires directly threaten water infrastructures, in particular in areas where drinking water is pumped from underground reservoirs. Infrastructures need to be adapted to guarantee a constant supply of drinking water, even during crisis periods.

3.1.4. INNOVATIVE SOLUTIONS AND ALTERNATIVES

- **Management of water quality:** Climate change has a negative impact on water quality, partly due to the rise in pollutants and wastewater discharge. Research on the microbial ecology of supply networks and the proliferation of bacteria due to rising temperatures is currently being carried out to anticipate public health problems and protect water infrastructures against bacterial biofilm blockage[5]. Efforts to adapt to climate change must imperatively include more research on how water quality, as well as air and soil quality, impact human health.
- **Crisis management action catalogue:** A catalogue of crisis management action, including energy sufficiency measures (e.g. restricting watering of gardens or banning private swimming pools) is currently being developed to respond to emergency situations resulting from water shortages.
- **Water desalination:** Desalination of seawater is a solution for the future to deal with rising freshwater shortages in France, although it is currently not widely employed in the country. This option is a serious solution for the future, in particular given the increasingly dry, hot summers. Nevertheless, this solution requires considerable investments and technological progress to make it economically viable and less energy-intensive. Another challenge concerns the treatment and recovery of brine resulting from desalination. Discharging this brine back into the sea can have negative impacts on the environment, particularly if quantities increase as desalination develops.

3.1.5. SYSTEMIC ISSUES AND GOVERNANCE

- **Fragmented governance and stakeholder coordination:** Water governance in France is fragmented, with over 12,000 sanitation facilities dispersed around the country operating independently. This fragmentation makes it more complex to coordinate and implement consistent policies at national level for climate change adaptation. Measures already in place in France include water agencies, local water committees, and local water management projects (PTGE). Increased investments in R&D, infrastructures, and coordination are necessary to improve this governance, although the France 2030 programme has provided financial support. In addition, a reflection on more sober usage of water is crucial to maintain economic sovereignty and protect the environment, with water being listed as in the general interest under French law. Regulations can therefore act as both a lever and a constraint for sustainable water management. A significant effort is required to strengthen cooperation between the different actors to guarantee consistent, effective management of water. Interconnecting potable water facilities would improve resilience in the case of accidents or perturbations. A national prevention and awareness campaign on water management is essential, highlighting the specific local features of water crises and encouraging responsible behaviour.
- **Adoption and reform of the value chain:** In addition to technological innovations, adaptation requires a complete revision of the water value chain, including better spatial distribution of crops and a re-evaluation of water usage. Adoption by stakeholders, especially farmers and local authorities, is essential to ensure the success of adaptation initiatives.

5 A layer of bacteria or other microbes that stick to a surface and each other.

Climate change brings considerable challenges for water resource management, in terms of both quality and quantity. Adapting the water sector requires a number of technologies and strategies aimed at more sustainable management of an increasingly valuable resource in the face of climate change. Technological solutions, which may involve improving the efficiency of irrigation networks, water storage, or desalination, will be essential to ensure the sustainable management of this vital resource.

3.2. Energy

Energy is a critical sector for adapting to climate change. The need to maintain production of energy that is adequate, affordable and sustainable, while minimizing its environmental impact, calls for technological innovation. The main challenges include increased temperatures, extreme weather events, and the management and availability of natural resources like water. Adapting the energy sector is crucial to guarantee the continuity of energy production and supply, and to maintain the resilience of energy infrastructures. This chapter explores these issues through an analysis of the technological solutions in place to reinforce the energy sector's resilience to climate change.

3.2.1. INFRASTRUCTURE ADAPTATION AND TECHNOLOGICAL SOLUTIONS

Climate change has significant repercussions on the entire energy sector, including:

— **Resistance and safety of infrastructures:** The resilience of energy infrastructures to extreme climate events, like storms, floods and heatwaves, constitutes a major challenge. Nuclear power plants, for example, are reviewed every ten years to evaluate their capacity to resist these weather hazards, update protection measures, and integrate specific devices to manage flash floods. Safety measures, such as raising dykes, are implemented to protect installations against increased risks due to climate variations. Electricity supply systems, like high-voltage lines, are also vulnerable, partly due to the thermal expansion of cables during heatwaves, which can reduce their efficiency and increase the risk of failure. These challenges require developing suitable technologies to reinforce the robustness of infrastructures, improve the resistance of equipment to extreme events, and extend safety criteria to anticipate future climate conditions.

— **Water resources management:** As water resources become rarer, ensuring water supply is crucial, in particular for inland thermal and nuclear power plants, which can require large quantities of water for cooling. The decrease in precipitation and increase in evaporation affect the levels of rivers and reservoirs used for this purpose. As well as improving cooling systems and thermal discharge, EDF is working on optimizing water management and availability. In the long term, emerging technologies like Small Modular Reactors (SMR) could reduce water consumption thanks to their lower power levels.

— **Electricity production:** Variations in the climate, such as changes in seasonal rainfall patterns and lower stocks of snow, directly influence hydraulic electricity production. In some regions, these changes can be accompanied by an increase or decrease in overall precipitation, depending on local dynamics. Drought periods also directly impact electricity production in thermal power plants, where losses connected with the Carnot cycle are exacerbated by high external temperatures. It is important to differentiate internal energy consumption related to the actual systems (e.g., energy losses in cooling systems or pumped storage hydro plants) and the final energy demand of users, in order to correctly evaluate the overall energy needs and the necessary adaptation measures. Some measures have been established to limit the environmental impact of production on rivers and aquatic ecosystems, which can result in lower production levels during some periods. Solutions also include revising standards concerning the discharge of heat into rivers to avoid ecological perturbations. Overall, a sufficient production capacity needs to be anticipated to deal with the new climate conditions, considering all the impacts of meteorological variables, such as changes in temperature, precipitation, cloud cover and wind, which influence how the balance between production and consumption is managed.

3.2.2. RESILIENCE OF THE SUPPLY NETWORK

Energy storage and the resilience of networks are both essential to ensure the continuity of energy supplies in the face of unpredictable weather events. Modernizing electricity networks is one way of better anticipating and managing incidents caused by extreme climate events:

— **Underground power lines:** Burying medium voltage lines underground is a key strategy to improve the network's resilience to extreme weather events. The French power grid operator, Enedis, plans to bury 100,000 km of medium voltage lines underground by 2050. Underground lines are less vulnerable to extreme climate events, such as storms and high temperatures, while ensuring continuous electricity supply.

— **Resilience of gas networks:** Gas supply networks are more resilient since they are underground, which makes them less sensitive to bad weather. However, they are still vulnerable to flooding, in particular sudden rises in the water level. France's leading gas operator, GRDF, has started works to anticipate and mitigate the impacts of climate change on its infrastructures, such as by evaluating the potential impacts of a rise in temperatures and flooding on network operations. Like for electricity, significant efforts are required to adapt gas infrastructures, LNG terminals, and carbon capture and storage (CCS) technologies, which represent strategic levers for a resilient, low-carbon energy transition.

— **Development of smart grids:** The digitization of the electric grid using technologies like smart grids, which use digital communications technology to detect and react to local changes in usage, makes it easier to efficiently manage energy flows and integrate renewable energy and new uses, like electric mobility and energy storage. These smart grids also contribute to the optimization of loads and reinforce the resilience of infrastructures to deal with perturbations. Their development nevertheless requires greater intersectoral coordination to maximize their effectiveness and impact. In addition, methods employing artificial intelligence and exploiting geospatial data, independently from smart grids, can play a key role in anticipating extreme climate events and managing crises, coupled with smart grid functions.

— **Innovative solutions to improve network resilience:** The use of microgrids can improve the resilience of the network in some conditions, by ensuring constant local supply in the case of major perturbations on the main network. However, these solutions alone cannot provide a direct response to the issues involved in climate change adaptation. In addition, the development of renewable energy sources requires reinforcing transportation and supply networks, which often have greater benefits than local storage solutions. Microgrids and local energy storage should be seen as complementary to central infrastructures, with an emphasis on taking a mixed approach to meet the challenges of resilience and energy optimization. However, the increase in self-consumption, using smart grids, microgrids and pumped storage hydro plants, results in a drop in the yield of energy assets, and optimization strategies should take this into account.

— **Pumped storage hydro plants (PSHPs):** PSHPs play a key role in managing fluctuating renewable energy by storing the excess energy produced. They operate by pumping water into elevated reservoirs during low demand periods, then releasing the water to produce electricity during consumption peaks. Although their development is not directly related to climate change adaptation, PSHPs contribute to the stability of the power system and the integration of renewable energy in the energy mix. In France, their storage capacity of up to 100 GWh makes them useful for balancing transport networks.

— **Intersectoral coordination:** Better coordination between the different infrastructure networks (electricity, gas, telecommunications, internet) is essential to improve the overall resilience of national infrastructures and minimize supply interruptions, while providing a fast response during major climate crises. Electricity in particular plays a key role as a means of controlling energy and commodity flows, including in gas networks and other critical infrastructures. This cross-cutting capacity underlines the importance of investing in interconnected systems like smart grids, which are capable of optimizing energy flows and reinforcing the capacity of networks to deal with extreme climate events.

3.2.3. RENEWABLE ENERGY ADAPTATION

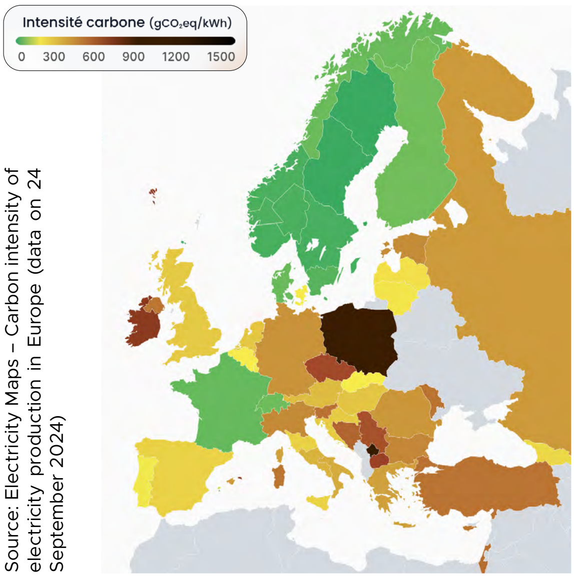
— **Hydropower:** Climate change modifies water regimes, affecting river flows and, consequently, hydropower production. Technological solutions are implemented to anticipate future flows and optimize the management of dams, in order to balance the production and consumption of electricity subject to seasonal variations. Pumped storage hydro plants (PSHPs), which recycle water between two reservoirs, also play a key role in making optimum use of existing dams. They store excess power produced from other sources, like wind or solar, and release it during peak demand periods. Although they are not directly affected by prolonged droughts like run-of-river power stations, their yield of around 80% means that in the absence of additional gravitational inflow, they consume more energy than they produce. For these systems to operate effectively and contribute to the energy transition, they must be efficiently managed and used with dams.

— **Wind power:** Current wind patterns, which determine the location of wind turbines, are considered to determine the lifespan of installations (about 30 years). However, beyond that period, the long-term evolution of wind conditions remains uncertain. In terms of adaptation, the main issue is to make turbines resilient to extreme weather conditions, like storms and exceptional wind speeds, rather than to guarantee stable production despite climate change. In addition, the increase in self-consumption, facilitated by technologies like smart grids, microgrids and PSHP, brings a drop in energy yields. These operational challenges must be taken into account to optimize the integration of wind power while maintaining the robustness and overall efficiency of the energy system.

— **Solar power:** The effectiveness of photovoltaic panels is affected by increased temperatures and cloud cover variations. Extreme climate events like hail also constitute a significant threat for solar installations, requiring improvements in local forecasting models.

— **Renewable gas production:** Climate change also affects the production of renewable gas from methanation and biomass. In particular, changes in sunlight, precipitation and temperature may influence the growth of crops used to produce biomass. Crop rotation needs to be adjusted to optimize this production.

- **Smart energy management systems:** Smart energy management systems play a key role in adapting energy networks to the development of renewable energies and to integrate new uses. These technologies optimize the use of renewables and thus contribute to reducing GHG emissions and improving the flexibility of electricity systems to manage the variations in climate. In the case of extreme weather events, these decentralized systems facilitate proactive management of power cuts and efficient distribution of the energy load, thus improving the resilience of infrastructures to climate change impacts. However, although their load-shedding capacity makes them more resilient, decentralized systems are less reliable than centralized systems (higher LOLE). In addition, their self-consumption is much higher due to more complex on-grid/off-grid decisions, the coexistence of AC/DC, and real-time management requiring more technological resources. These operational and energy constraints must be considered to maximize the benefits while limiting the impacts on the overall efficiency of networks.



Source: Electricity Maps – Carbon intensity of electricity production in Europe (data on 24 September 2024)

3.2.4. ENERGY STORAGE

Energy storage technologies constitute future solutions to improve the flexibility of the network and reduce greenhouse gas emissions.

- **Storage batteries:** Although stationary batteries can store surplus electricity produced by wind and solar farms during excess production periods, their role in the context of climate change adaptation mainly resides in their capacity to operate in extreme conditions. Technical issues include their performance and durability in high external temperatures of up to 50°C, which requires developing resilient technologies adapted to these new climate constraints.
- **Thermal storage:** Thermal storage is used to capture and store surplus heat or cold produced from renewable or industrial sources. This method is used in district heating networks and industrial applications to store energy during low demand periods and release it at peak times.

3.2.5. ECONOMIC AND GOVERNANCE ISSUES

- **Investment costs:** Investments in adapting energy infrastructures are essential to limit the costs generated by supply interruptions and repairs following climate catastrophes. Modernizing these infrastructures and improving their climate resilience is a key strategy to avoid major financial losses in the long term. The electricity grid, in particular, needs to be adapted to the new climate conditions and the increased integration of renewable energy. The French transmission system operator, RTE, has announced an ambitious plan to invest 100 billion euros by 2040. This plan involves modernizing the grid, making it more robust to climate hazards, and facilitating the energy transition by supporting the optimal management of renewable energy.
- **Governance and coordination:** Close coordination between energy sector stakeholders (network managers, energy producers, regulators, and governments) is essential to guarantee that adaptation strategies are implemented effectively. Partnerships between actors in the energy sector and research laboratories are increasingly common, with an objective to develop innovative solutions in the domains of energy storage, water resource management, and carbon footprint reduction.
- **Security of critical material supply chains:** It is crucial to monitor supply chains of critical materials like copper, while encouraging the use of recycled materials to reinforce the resilience of the electricity network. Supply chain management increasingly relies on advanced technological solutions, like integrating blockchain-enabled tracking systems. Although these technologies improve transparency and trust in materials flows, they also require more energy and IT infrastructures, underlining the importance of striking a balance between these advances and sustainable energy solutions.

3.2.6. INNOVATION AND R&D

- **Pursue research and development:** Technological innovation is at the heart of energy sector adaptation. R&D programmes concentrate on developing new technologies to improve the resilience of existing infrastructures and create new-generation energy solutions capable of resisting future climate impacts. Priority research avenues include:

a. **Develop resilient batteries:** As well as increasing their capacity and durability for long-term storage of renewable energy, it is crucial to make these technologies resistant to extreme climate conditions like high temperatures and rapid temperature shifts.

b. **Adapt smart grids:** Smart grids are essential for real-time management of energy flows and their resilience to climate change, such as storms and floods, needs to be reinforced to guarantee constant supply.

c. **Incorporate innovative materials in infrastructures:** Energy infrastructure construction should integrate more resistant materials to stand up to extreme weather events, like heatwaves, storms and flooding.

d. **Reduce water consumption in cooling systems:** Air-cooled or hybrid technologies constitute a sustainable alternative to limit water withdrawals by thermal and nuclear power plants, which is vital in a context of increased water shortages.

— Partnerships and collaborations: Partnerships between energy sector stakeholders, start-ups, research laboratories, and climate experts are essential to accelerate the adoption of adaptation technologies. These partnerships make it easier to share best practices and contribute to the fast implementation of innovative solutions at national and international scales.

3.2.7. LIQUID AND WOOD FUELS

— **Liquid and wood fuels:** Although this report mainly focuses on electricity and gas networks, liquid fuels (like fuel oil) and wood fuel also constitute important energy sources in France, in particular in rural areas. Their share of the energy mix is currently declining, but they remain indispensable for numerous domestic and industrial applications. Future research could usefully carry out a detailed evaluation of their resilience to climate change, in particular concerning the supply and regeneration of wood resources.

The energy sector in France is taking a proactive approach to adapt to the challenges raised by climate change. Actors in the sector are combining the modernization of infrastructures, technological innovation, and strategic coordination to guarantee reliable energy production and supply that is resilient to increasing changes in the climate. The improved resilience of infrastructures, development of renewable energies, and innovation in energy storage technologies are essential to guarantee a sustainable future for energy. Current investments in these adaptation technologies are vital to preserve the country's energy security while minimizing long-term financial costs.

3.3. Agriculture

Agriculture, which is directly linked to food security, is strongly impacted by climate change, in particular in terms of water management. Changes in precipitation, increased temperatures and the frequency of extreme weather events like droughts and floods, combined with scarcer availability of freshwater, constitute considerable challenges for agricultural production. In France, about 20% of farmland is already affected by drought, making it urgent to develop technologies and adaptation strategies to ensure food security and the sustainability of agricultural systems. However, global supply chains, particularly for livestock products and strategic crops, increase the challenges of climate change and call for coordinated international approaches. This chapter looks at the climate issues involved in agriculture, and at the adaptation technologies to optimize the management of resources.

3.3.1. CLIMATE CHANGE CHALLENGES FACING AGRICULTURE

Agriculture is one of the most vulnerable sectors to climate change. The main impacts are as follows:

— **Increasing water stress:** More frequent, intense droughts, due to changes in precipitation patterns, put greater pressure on water resources.

— **Soil degradation:** The lack of water exacerbates soil degradation, leading to a drop in fertility and a greater risk of erosion, thus compromising long-term agricultural production and calling for the development of sustainable management practices.

3.3.2. TECHNOLOGICAL SOLUTIONS FOR ADAPTATION IN AGRICULTURE

3.3.2.1. Optimized water management

Water management is crucial to adapt agriculture to the new climate conditions. Irrigation is essential to compensate for drought periods, but it must be optimized to avoid water waste. Automated management systems, using IoT sensors, artificial intelligence and satellite imagery, can be used to monitor soil humidity levels and adjust irrigation in real time.

— **Micro-irrigation:** This system employs pipes and drip systems to deliver small quantities of water directly at the root of plants, leading to a 30 to 40% drop in water consumption, without reducing yields.

— **Reuse of treated wastewater:** Reusing treated wastewater for irrigation is a promising solution to make up for water shortages in farming areas. In France, about 30% of rivers are fed by water from water treatment plants. However, this practice needs to be carefully managed to avoid conflicts between water users and to protect natural ecosystems. Particular attention should be paid to the quality of reused water to avoid contaminating crops.

— **Sensors and decision-making aids:** The use of soil humidity sensors combined with automatic irrigation systems facilitates precise water management. These sensors measure the water requirements of crops in real time and adjust irrigation in accordance, thus avoiding under- or over-watering.

— **Managed irrigation:** Irrigation must be used carefully to avoid a rebound effect, whereby an increase in the availability of water leads to a non-sustainable intensification of agricultural production. The objective is to maintain current production levels while minimizing water consumption in order to preserve this valuable resource in a context of greater climate variability.

3.3.2.2. Plant selection, agroecology and soil management

Selecting plants that are resistant to water stress is an essential adaptation solution:

— **Variety selection:** The development and dissemination of crop varieties that are resistant to drought, salinity and other climate stresses, are essential to ensure that the agricultural sector can adapt to climate change. Varieties with deep roots can access water more easily, reducing their dependence on regular rainfall. Selecting varieties allows farmers to maintain high yields despite unfavourable climate conditions.

— **Agroecology and agroforestry:** Agroecology, which is based on diversifying crops and using natural processes to improve the resilience of agricultural systems, is key to adaptation. This practice reduces crops' vulnerability to extreme climate conditions and makes soil healthier, which is crucial to maintain long-term productivity. Agroforestry is a sustainable solution that involves combining farm crops with trees, thus protecting crops against climate hazards. These practices lead to more diverse production and improve the resistance of farms.

— **Smart agricultural equipment:** Watering robots and drones are used to optimize irrigation and monitor the health of crops on a large scale. This kind of equipment allows for very precise, more effective management of water and agricultural inputs[6].

— **Agrivoltaics:** The installation of solar panels above crops generates electricity at the same time as protecting crops against direct sunlight, thus reducing the water requirements of some plants. R&D projects on this subject, such as those developed by the public research institute INRAE, aim to combine energy production and the resilience of farming practices to deal with climate change.

— **Robotics:** Combined with precision technologies like IoT sensors, robotics offers promising solutions to optimize agroecological practices in a changing climate.

3.3.2.3. Microorganisms and soil management

— **Managing microorganisms:** The management of microorganisms in the soil is a promising approach to deal with the environmental challenges ensuing from climate change. The continuous occupation of soil thanks to intercropping and relay cropping maximizes the soil's capacity to provide ecosystem services and stimulates increased microbial biodiversity. This approach also maintains more fertile soils, by increasing their carbon content and reducing GHG emissions.

— **Role of livestock in soil management:** Livestock, in particular ranching, plays a key role in soil management. The animals help to enrich the organic matter in the soil thanks to their excrement, which improves the soil's structure and fertility. Moreover, well-managed grazing can limit erosion, increase water retention, and stimulate biodiversity in grassland ecosystems. However, excessive grazing and bad management can lead to the degradation of soil, which underlines the importance of sustainable, regulated livestock rearing.

— **Soil management and action to combat erosion:** Soil management, especially using techniques like vegetation cover and minimal labouring, is essential to prevent erosion and maintain soil fertility. In addition, note that adding biochar to fields can be harmful to growth for numerous shallow-rooted plants, for example main crops like sunflowers and soy. Biochar appears to be less effective on plant growth than glucose, for example, which contains soluble carbon. These practices foster water retention in the soil, thus reducing dependence on irrigation and increasing crops' resilience to drought.

— **Maintenance of vegetation cover on soil surfaces:** It is essential to maintain continuous soil cover to reinforce resilience and protect biodiversity. Leaving soil bare, as on some large areas of farmland, can create 'biological deserts'. Hot bare soil accelerates the respiration of microorganisms, which rapidly consumes the remaining organic matter and threatens long-term fertility.

— **Optimization of carbon and nitrogen storage in soil:** The availability of nitrogen plays a central role in agriculture, and maintaining the carbon content of soil is essential. The C/N (carbon/nitrogen) ratio is a key indicator for evaluating the evolution of organic matter in soils. A ratio of 10 is often considered as stable. Unfortunately, as a result of inappropriate farming practices, soil stores too little carbon, often with excessive emissions of N_2O (nitrous oxide), a powerful greenhouse gas. It is therefore essential to adopt farming practices focusing on balanced management of carbon and nitrogen in soils.

6 All of the products and resources employed in the agricultural production process to improve yields or protect corps.

3.3.3. RISK MANAGEMENT AND MONITORING TECHNOLOGIES

— **Climate modelling and agricultural forecasts:** Advanced climate models can be used to anticipate short- and long-term meteorological conditions, so that farmers can take informed decisions about planting, irrigation and crop management. These forecasts can be used to optimize crop calendars and adapt practices according to climate condition forecasts.

— **Climate crisis management tools:** Agricultural adaptation also requires early warning systems and crisis management tools to deal with extreme climate events like droughts, heat waves, and floods. These systems help minimize farm losses by providing real-time information and tips on how to protect crops.

— **Cropping practices to improve soil management and GHG emissions:** Intercropping and relay cropping are accessible, effective solutions to improve agricultural practices. Planting several crops on the same parcel increases biodiversity, reduces GHG and captures more carbon in the earth. The practice also means that soil is constantly covered, which increases its carbon content and decreases erosion.

3.3.4. REFORM OF THE AGRICULTURAL VALUE CHAIN

Climate and food issues require taking a global approach that includes farming and food systems.

— **Spatial distribution of crops:** Climate change requires rethinking the spatial distribution of crops in France. Some regions traditionally suited to particular crops will need to alter their planting habits due to new climate conditions. New agricultural production areas will need to be defined corresponding to the new climate situations in order to optimize the use of resources and maximize yields.

— **Agrifood production systems:** Industrial and specialized farming systems are particularly vulnerable to climate change. Maintaining long-term food security requires shifting towards more resilient production systems involving a wider range of crops and sustainable use of natural resources. The large volume of imports to meet livestock and human food needs calls for greater efforts to secure global food chains to deal with climate risks. Increasing dependence on foreign markets could accentuate food vulnerabilities in the case of major climate perturbations.

3.3.5. ECONOMIC AND SOCIAL ISSUES

— **Investment costs:** Adapting the agricultural sector to climate change requires substantial investments in technologies and infrastructures. These investments in modernizing irrigation systems and adopting agroecological practices can be substantial for small farms, yet the costs are justified by the long-term benefits for food security and economic resilience. Investments in smart irrigation and early warning systems can, for example, reduce farm losses and stabilize farmers' income despite changing climate conditions.

— **Impact on farm employment:** The transition towards more resilient farming practices could lead to changes in the structure of farm employment. New skills will be required to manage advanced technologies and adapt agricultural practices to the new climate conditions. This will call for training and professional retraining to ensure that farm workers are prepared for the challenges of adaptation.

— **Governance and stakeholder coordination:** Successful adaptation requires efficient coordination between the different agricultural stakeholders, including farmers, cooperatives, research institutes and governments. This involves developing agricultural practices that support the innovation and adoption of resilient practices, and guaranteeing that farmers have access to the resources and information needed to implement these practices.

— **Public support and pooling:** To deal with these economic challenges requires setting up financial support measures. Pooling farm technologies and equipment is one solution being developed, so that small farmers can access advanced technological tools.

— **Role of public policies:** Agricultural policies need to integrate climate change issues by promoting sustainable solutions adapted to local situations. Collaboration between research actors, agricultural sectors and local authorities is crucial to ensure an effective transition to more resilient agriculture.

Adapting agriculture to climate change, in particular in terms of water management, is a key challenge for the coming decades. Technologies like micro-irrigation and drought-resistant crops are indispensable, but it is also essential to think about how parcels are managed. Instead of uniform parcels, it is preferable to encourage practices like intercropping, in which different crops are planted on the same parcel. The result is increased biodiversity, more resilient soil, and fewer greenhouse gas emissions, contributing to a more sustainable future for agriculture. In addition, it is essential to improve farming methods, combined with strategic reorganization of the value chain. The future of agriculture in France will depend on the sector's capacity to integrate these technological innovations while respecting ecological imperatives.

3.4. Cities and buildings

Cities and buildings are central to climate change adaptation issues. Cities, which are home to over half of the world's population, are particularly exposed to climate risks and face considerable challenges: managing heat, reducing flood risks, dealing with rising sea levels, and optimizing resources. Urban infrastructures and buildings need to be adapted to resist forthcoming climate changes while integrating durable solutions to protect people and the environment. In France, most expenditure on adaptation concerns infrastructures. While they are in a good state nationally, it is crucial to pursue efforts to guarantee their resilience to handle future climate crises. This chapter explores the issues and technological solutions to improve the resilience of the building sector to deal with climate change. In addition, the way that cities are organized, such as scattered peri-urban areas and urban sprawl, exacerbates vulnerability to climate change impacts. When urbanization is spread out, the distances to travel are longer, increasing the use of private vehicles, and amplifying infrastructure requirements, which pushes up the energy footprint and the costs of adaptation. Denser, better integrated urban planning is therefore indispensable to reduce these vulnerabilities and make cities more resilient.

3.4.1. CLIMATE ISSUES FACING CITIES AND BUILDINGS

The impacts of climate change on cities and buildings take different forms, such as:

— **Urban heat islands:** The increase in temperatures and uncontrolled urbanization make cities particularly vulnerable to the formation of heat islands, where heat is trapped by impermeable surfaces like concrete and asphalt. Cities can endure temperatures up to 10°C higher than surrounding rural areas.

— **Urban flooding:** Rapid urbanization, combined with often under-sized drainage systems, exposes cities to more frequent, intense flooding caused by sudden heavy rain. Coastal cities are particularly vulnerable to rising sea levels and storms.

— **Water resources management:** Access to drinking water and rainwater management are major challenges. Prolonged droughts can affect water supply in cities, while heavy rain increases flood risks.

— **Swelling and shrinking soils:** Clay-rich soils are subject to natural swelling and shrinkage provoked by changes in humidity, creating a major challenge for buildings and infrastructures, in particular in areas with clay-rich soils. This risk, which is part of the national catastrophe plan following the efforts of insurers and the Langreney Report, is increasingly part of discussions on climate change adaptation. Reports by the national Court of Auditors and inter-ministerial inspections have also highlighted the extent and financial implications of this problem. Along with the technical challenges of detecting, preventing and repairing cracks, swelling and shrinking soils are a significant issue for the insurance sector. Insurers are confronted with a rise in compensation claims, which raises questions concerning the financial sustainability and means of covering these risks. The creation of a climate risk observatory by insurers represents a major advance for monitoring these phenomena and adapting insurance strategies. Lastly, technological research should put more priority on real-time monitoring tools, innovative repairs, and preventative approaches such as improving soil surveys and developing resilient materials. These initiatives will be essential to reduce costs, limit impacts on infrastructures, and guarantee the stability of the insurance system to deal with the increasing challenges of soil swelling and shrinkage.

3.4.2. TECHNOLOGICAL ADAPTATION SOLUTIONS

3.4.2.1. Management of rainwater and adaptation of infrastructures

— **Rainwater management infrastructures:** Cities are particularly vulnerable to flooding caused by extreme rain events. To meet this challenge, rainwater management infrastructures, like retention basins, infiltration systems, and improved drainage are being developed to absorb and divert excess water. These infrastructures need to be sized in accordance with future climate projections to guarantee their long-term efficiency.

— **Sustainable urban drainage systems (SUDS):** These systems include infrastructures like retention basins, planned flood zones, and trench drains, designed to absorb and retain rainwater and thus prevent sudden floods. SUDS can also be used for groundwater recharging purposes.

— **Permeable infrastructures:** Permeable materials can be used for pavements, carparks and roads to allow rainwater to directly filter into the earth. This reduces the amount of water that needs to be evacuated through drains and thus limits the risk of flooding.

— **Warning systems and crisis management:** Early warning systems and crisis management plans are essential to anticipate flood risks and act fast. These systems employ real-time data on precipitation and river levels to trigger warnings and implement emergency measures, thus reducing the impacts of flooding for urban populations.

3.4.2.2. Adaptation of buildings to deal with heat and drought

— **Thermo-resilience and insulation:** The thermo-resilience of buildings and a profound understanding of the science of current materials are crucial to make constructions more resistant to heatwaves and extreme phenomena. Two essential characteristics to consider in this context are thermal inertia (heat capacity of materials) and thermal conduction. These properties influence a material's capacity to store and release heat and thus allow effective natural storage. Materials with high thermal inertia, like concrete, stone and bricks, have significant advantages in regulating indoor temperatures. Improving the thermal insulation of buildings is essential to reduce the energy required for heating in winter and cooling in summer. It is crucial to adapt choices according to the characteristics in order to maximize thermo-resilience and deal with climate change. However, note that many materials currently available, like those containing clinker [7], are dual emitters: during the conversion of clinker into lime, and due to the energy required to produce them, which often comes from non-electrified sources. The use of materials with high thermal inertia, capable of storing up heat and then releasing it slowly (like concrete, stone and brick), limits the accumulation of heat in buildings during the day. It is essential not to focus solely on strategies to protect from the cold, but to also consider the increasing length of intensely not periods. These materials can be used to improve the energy efficiency of buildings, reducing their carbon footprint while improving their resilience to extreme climate conditions. In addition, biosourced and recycled materials offer low-carbon solutions that are also adapted to deal with changing climate conditions.

— **Air conditioning and advanced ventilation systems:** Given the increase in heat waves, effective air cooling is essential to protect human health. However these cooling systems must be designed to minimize their energy consumption. Managing ventilation is key to guarantee a balance between energy performance and air quality in buildings faced with extreme temperatures. Innovative solutions, like natural ventilation systems and heat pumps, are being explored to offer a sustainable alternative to traditional air conditioning. Natural ventilation and sunscreens can also be used to cool buildings and avoid using energy-intensive cooling systems.

— **Urban vegetation:** Urban vegetation, involving planting trees and creating green spaces in cities, in particular when combined with suitable insulation practices, can reduce the need for air conditioning. Trees provide shade, reduce evaporation, and increase biodiversity. Some cities have established ambitious programmes to plant up to 30% of their urban surface area.

— **Integrated approach based on sciences related to buildings (building physics, materials and geology):** Several experts pointed out that the construction sector lacks a kind of 'general building science' in order to act holistically without damaging the entire system. Rather than simply developing new materials, the solution begins with making better use of existing materials, considering their properties and behaviour in different climate conditions, both hot and cold. Adaptation and mitigation efforts also require large quantities of material, which shows how important it is to redesign infrastructures in order to minimize their environmental impact with an emphasis on recycling the materials used. This integrated scientific approach could considerably improve the effectiveness of adaptation solutions. IMT engineering school is also developing research into new material properties, such as self-repair and increased durability, with the aim of lengthening lifespan and reducing waste.

3.4.2.3. Solution for managing risks and floods

— **Dykes and coastal protections:** To protect coastal cities from rising sea levels and storms, dykes, anti-flood barriers and natural solutions like mangroves and coastal marshes are put into place.

— **Smart networks to manage infrastructures:** Smart cities develop smart networks to monitor water and energy flows in real time, facilitating fast, effective responses to floods and shortages.

3.4.3. RESILIENT CITIES AND SUSTAINABLE PLANNING

— **Development of resilient urban areas:** To minimize climate risks, urban development needs to integrate the principle of resilience. This includes planning new urban areas in regions that are less vulnerable to flooding, creating ecological corridors to improve the resilience of urban ecosystems, and integrating nature-based solutions to improve the capacity of cities to absorb climate shocks. In addition, it involves smart densification of urban areas to limit motorized journeys, reduce the energy footprint, and optimize existing infrastructures.

— **Revision of building regulations and standards:** Building regulations and standards need to be updated to adapt them to the new climate situation. This includes stricter requirements concerning flood resilience, resistance to extreme wind, and urban heat management. These norms should also encourage the use of sustainable materials and construction techniques that reduce the carbon footprint of buildings while improving their durability in the face of climate change.

— **Renovation of existing infrastructures:** The renovation of existing urban infrastructures is a priority to improve their resilience to climate change impacts. This includes strengthening old buildings to resist storms and floods, modernizing drainage systems to anticipate urban floods, and improving the accessibility of green areas to reduce the effects of heat islands.

7 Component of cement produced by heating a mix of 80% limestone and 20% aluminosilicate to a very high temperature.

— **Reduction of urban sprawl:** The outward spread of cities, often linked to uncontrolled urbanization, increases climate vulnerability and energy consumption. Better urban organization that encourages local services and infrastructures in inhabited areas is essential to limit these impacts.

3.4.4. TECHNOLOGIES AND INNOVATIONS FOR URBAN MOBILITY

— **Resilient urban transport:** Adapting transport infrastructures to the impacts of climate change is crucial to maintain urban mobility. This comprises reinforcing rail and road infrastructures to resist extreme temperatures and flooding, and developing sustainable mobility solutions, like electricity-powered public transport and cycle lanes, which reduce dependency on fossil fuels and improve cities' resilience.

— **Adaptation for soft mobility:** The development of soft mobility, like walking and cycling, calls for adapting urban infrastructures to stand up to climate change impacts. Special routes should be devised to include shaded areas, trees, and passages alongside waterways, with the aim of mitigating heat wave impacts and making these modes of transport more attractive, even in extreme climate conditions. These initiatives would not only reduce the average distance travelled by inhabitants thanks to denser, more mixed urbanization, they would also contribute to making cities more resilient while encouraging sustainable alternatives to motorized transport.

3.4.5. SOCIAL AND GOVERNANCE ISSUES

— **Protection of vulnerable inhabitants:** Vulnerable inhabitants, like old people, children, and people with reduced mobility, are the most exposed to climate change in urban environments. Urban planning policies should include specific measures to protect these groups, in particular by improving accessibility to essential services, creating air-conditioned refuges, and setting up awareness-raising programmes to prepare communities to deal with climate risks.

— **Urban governance and intersectoral coordination:** Urban adaptation calls for efficient governance and coordination between the different government levels, private and public sectors, and civil society. Urban adaptation efforts are still scattered and lack effective governance. This calls for establishing governance structures capable of managing the complex challenges involved in adaptation, ensuring coherent urban planning, and mobilizing the resources needed to implement the adaptation solutions identified.

Adapting cities and buildings is indispensable to guarantee the resilience of cities to the impacts of climate change. Technological solutions like sustainable management of rainwater, green roofs, and the use of materials with high thermal inertia, are concrete responses to deal with the challenges of heat, flooding and water shortages. These technologies, combined with effective governance and significant investments, will help cities more effectively manage the impacts of climate change and ensure resilient urban environments capable of protecting inhabitants and preserving quality of life, despite challenging future climate conditions.

3.5. Industry

The industrial sector is particularly exposed to the consequences of climate change, due to its dependence on natural resources like water and energy, and the vulnerability of its infrastructures. Extreme climate phenomena, like heat waves, storms and drought, directly perturb industrial production, increase the costs of maintenance, and affect the competitiveness of businesses.

3.5.1. CLIMATE CHANGE ISSUES FOR THE INDUSTRIAL SECTOR

Extreme climate events have significant impacts on the industrial sector, ranging from the interruption of supply chains to the degradation of infrastructures, and increased production costs. These perturbations compromise the continuity of industrial operations, cause product delivery delays, and impact the competitiveness of companies on national and international markets.

— **Water consumption and water stress:** Industry uses large quantities of water for cooling purposes, in particular in thermal and nuclear power plants. Faced with the increase in heat waves and the drop in precipitation, the availability of water is a major concern. Water stress affects production capacity, especially in sectors consuming large quantities of water, like the chemical and agrifood industries.

— **Vulnerability of infrastructures:** Industrial infrastructures, which are often located in coastal areas or on sites vulnerable to flooding, face high risks. Storms and flooding damage installations, disrupting operations and leading to high repair costs. Extreme climate events can also interrupt the supply of raw materials and energy, with repercussions on production chains.

— **Energy dependence:** Industry is highly dependent on energy networks to ensure constant production. Climate events perturb these networks, provoking electricity cuts that affect production chains. The integration of renewable energies and storage systems can improve energy resilience, although their capacity to reliably deal with interruptions remains to be evaluated.

— **Decarbonization of industrial processes:** Industry also faces the challenge of decarbonization to meet targets to reduce greenhouse gas (GHG) emissions. This involves adopting less carbon-intensive technologies and modernizing infrastructures to reduce the sector's carbon footprint. However, note that industrial processes are subject to intrinsic output losses due to thermodynamic limitations. These output losses, exacerbated by the adaptations required to manage climate change and reduce emissions, can affect the profitability of industrial investments.

3.5.2. KEY TECHNOLOGIES FOR ADAPTING THE INDUSTRIAL SECTOR

Adapting the industrial sector to climate change involves adopting resilient technologies, modernizing infrastructures, and effectively managing natural resources. Innovations made to cooling systems, the reuse of wastewater, and real-time monitoring of infrastructures will together reinforce the sector's resilience to climate change.

— **Advanced cooling systems:** Closed-circuit cooling systems constitute a major technological priority since they considerably reduce withdrawals of natural resources by recycling used water. Air-based cooling systems reduce the consumption of water in industrial processes. Some industries are developing dry cooling systems to limit their dependence on water during droughts, in particular in extreme climate conditions.

— **Reuse of industrial wastewater:** The reuse of treated wastewater is a key solution to limit water consumption in industrial sectors. Innovative treatment systems are deployed, in particular in the chemical industry, in order to better manage water resources.

— **Connected sensors and predictive management of infrastructures:** IoT sensors can be used in buildings to monitor installations in real time and anticipate any failures caused by extreme weather events. These smart management systems guarantee preventative maintenance and reduce downtime, even when climate conditions are difficult.

— **Supply chain optimization:** Supply chain adaptation involves using weather simulation models to anticipate the impacts of short- and mid-term climate hazards and adjust supply strategies in accordance. This helps to ensure constant flows of critical raw materials, in particular for sectors that depend on international transport and ports.

— **Resilient energy solutions:** To deal with electricity cuts, which are likely to increase due to climate hazards, industries generally use back-up solutions like diesel-powered generators. Investments are being made in energy storage solutions like high-capacity batteries to reduce the carbon footprint of these systems, although this concerns mitigation more than adaptation.

— **Resilient and recyclable materials:** Industry is adapting to climate conditions by adopting materials that resist extreme temperatures and erosion. These materials improve the durability of infrastructures and reduce long-term maintenance needs. Some future industrial activity will involve supplying recyclable materials and products to other sectors.

— **Advanced thermal insulation:** Innovative insulation materials are used to better regulate temperature in factories, and thus reduce air-cooling and heating needs. This measure contributes to limiting energy consumption and improving the resilience of installations to increasingly frequent heat waves.

— **Organizational and procedural solutions:** In addition to technological innovations, organizational approaches can improve the resilience of industrial infrastructures to extreme climate conditions. This includes adjusting working hours to limit the exposure of workers and equipment to the hottest periods, and adapting industrial processes to reduce their sensitivity to temperature variations. These 'soft' measures can be rapidly and cheaply implemented alongside technological efforts.

3.6. Transports

Transport is one of the main economic sectors in France, and is particularly vulnerable to climate change. Extreme events like heat waves, floods and storms perturb infrastructures and transport services, increase maintenance and repair costs, and affect the continuous movement of people and goods. A precise mapping of climate risks affecting transport infrastructures and services makes it easier to anticipate and manage the vulnerabilities of this critical sector. Other new needs are also emerging due to climate change, requiring a proactive response from industry. This includes developing innovative materials like 'cooling glass', and reflecting coatings devised to improve the thermal resistance of infrastructure and equipment. These innovations provide a response to the increasing requirement for sustainability and adaptation to future climate events. A modal shift towards less polluting forms of transport like trains instead of planes or cars is also essential to reduce climate impacts and improve the sector's resistance. This chapter looks at the main issues facing the transport sector and the adaptation solutions implemented to improve its resilience to climate hazards.

3.6.1. IMPACTS OF CLIMATE CHANGE ON THE TRANSPORT SECTOR

All transport infrastructures, including road, rail, ports and airports, undergo serious deterioration due to the multiplication of extreme climate events like heat waves, flooding and storms. These impacts affect maintenance and repair costs, which rise significantly, and the continuity of voyager and freight transport services. Consequently, transport delays and interruptions have direct repercussions on the economy.

- **Heat waves and dilation of infrastructures:** Extreme temperatures cause rails and catenary lines to dilate, which can increase the risk of derailing, obliging trains to slow down and impacting the quality of the transport service. Significant temperature variations can also affect roads, making them less durable and harder to use. In 2022, for example, heat waves meant that trains had to travel considerably slower, disturbing the transport network and user journeys.
- **Floods and storms:** Floods, whether caused by runoff, rising groundwater, or overflowing rivers due to torrential rain, seriously damage infrastructures and transport. These events can lead to the prolonged closure of roads, tunnels and bridges, as observed during Storm Alex in 2020. These disruptions directly affect the mobility of people and goods, with significant consequences on the continuity of transport services.
- **Subsidence and landslides:** Transport infrastructures, in particular in mountainous regions, are exposed to landslides, in particular following excessive rainfall. These phenomena can block roads and railway tracks, leading to considerable delays and prolonged transport service interruptions.
- **Aviation and maritime transport:** Air and sea transport, although addressed peripherally, represent nearly 10% of global primary energy and are almost totally reliant on fossil fuels. These sectors need to anticipate specific adaptations: air transport could be obliged to avoid wetlands to reduce the greenhouse effect caused by vapour trails, while maritime transport could explore new routes, like the Northern route, as the Arctic becomes easier to navigate. The adoption of new propellants, like sustainable aviation fuel (SAF), and even nuclear power for large ships, is a technological priority for these industries.

3.6.2. KEY TECHNOLOGIES FOR ADAPTING TRANSPORT INFRASTRUCTURES

- **Modelling of hazards and vulnerabilities:** Risk analyses detect long-term climate vulnerabilities, and guide and prioritize actions.
- **Early warning and meteorological management systems:** Advanced meteorological warning systems are used to anticipate extreme climate phenomena and quickly inform authorities and transport operators to secure infrastructures and anticipate accidents.
- **Connected sensors to monitor infrastructures:** IoT sensors installed on transport infrastructures like railways and roads are used for real-time monitoring of critical parameters, like rail temperature, cracks in the road, and early signs of landslides. These surveillance systems contribute to anticipating the interventions required and minimizing service interruptions.
- **Resilient public transport:** Public transport services must adapt to climate change to ensure operations and passenger comfort, even during extreme climate events. A particularly crucial issue is the adaptation of rolling stock to extreme heat and water penetration caused by intense rainfall. This includes measures like improving air-cooling systems, using resilient materials, and improving the waterproofing of vehicles. A working group has been set up by the French Directorate-General for Infrastructure, Transport and the Sea, gathering authorities responsible for mobility, passenger transport companies, and federations to exchange good practices on thermal comfort in vehicles. The aim is to guarantee reliable, comfortable services for users, even in extreme climate conditions.
- **Reinforcement of transport infrastructures:** Transport infrastructures, including bridges, tunnels, roads and railways, need to be reinforced to deal with increasingly frequent and intense climate hazards, like floods, storms and landslides. Drainage systems must be modernized to stop water from accumulating on roads and rail tracks, and so guarantee the security of users while minimizing service interruptions. In particularly exposed areas, effective drainage systems can be used to rapidly evacuate rainwater. The state and the public urban planning agency Cerema are already working on this issue for roads, and are currently updating a technical guide to sanitation, resulting from a working group gathering public and private experts. This approach aims to integrate climate change issues in the design and maintenance of sanitation systems. In addition, the evolution of technical references for the design, operation and maintenance of infrastructures pursued by the state, infrastructure managers and organizations like Cerema, constitutes a response to these challenges. The updating of national technical references to take climate change into account could also drive standardization at European and international levels, such as CEN and ISO standards, thus encouraging global adaptation. In addition, early warning systems play a key role in anticipating climate risks, in particular in the case of floods, storms and heat waves, thus making it possible to reduce disturbances and improve user security. Moreover, the use of innovative materials resistant to extreme temperatures is a priority to make infrastructures more sustainable. This includes developing road surfaces capable of withstanding high temperatures without deforming, and using more effective metal alloys for rails and overhead lines in order to resist thermal dilation. Lastly, adapting rolling stock to extreme climate conditions is essential. This includes installing advanced cooling systems to prevent vehicles from overheating and guarantee a reliable, comfortable transport service, even during intense heat waves. These

combined efforts will significantly improve the resilience and sustainability of infrastructures and transport services to the growing impacts of climate change.

— **Adaptation of means of propulsion:** In aviation, the development of alternative fuels like SAF (sustainable aviation fuel) is a priority. In maritime transport, research on nuclear propulsion or hybrid systems, combined with the innovative design of hulls to reduce drag, is essential to adapt to future climate-related requirements and regulations.

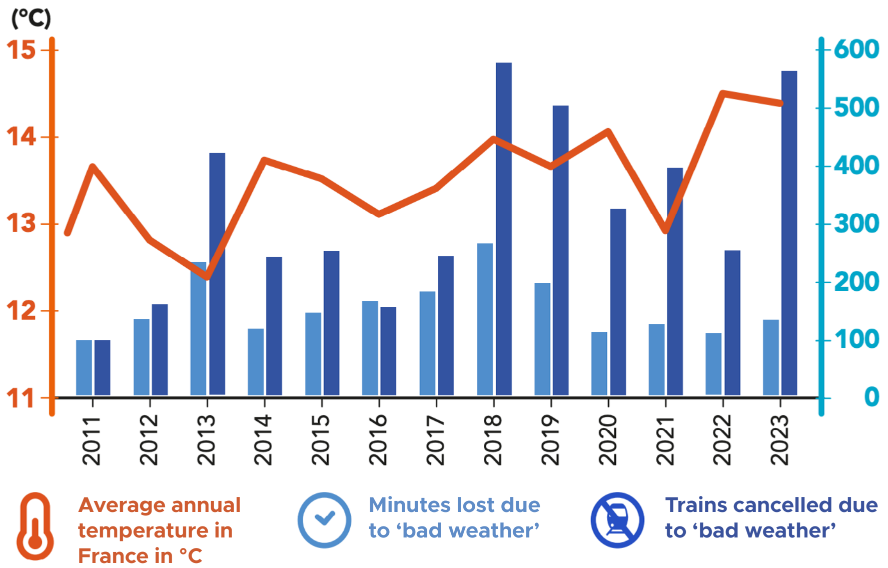
— **Resilient charging infrastructure:** The development of electric mobility requires robust charging stations that can resist extreme climate events like storms, heat waves and heavy rain. These infrastructures must guarantee continuous service even in the case of climate perturbations. Charging stations must be designed to anticipate not only floods and power cuts, but also the risk of overheating affecting their operation. In addition, electric vehicles should integrate advanced thermal management technologies to prevent batteries from overheating in extreme conditions. Nevertheless, this adaptation of charging infrastructures could take place in the mid term, given that they only have an estimated average lifespan of 10-15 yeas. This perspective brings an opportunity for progressive planning to integrate resilient solutions when renewing facilities.

— **Flow management systems and smart transportation grids:** Smart grids can improve the resilience of transport infrastructures by optimizing flow management in real time. These technologies allow operators to redirect transport flows, adjust the timetables of trains and buses, and temporarily close parts of the road or railway according to weather conditions, thus minimizing perturbations for users.

— **Improved drainage systems:** In areas particularly exposed to flooding, transport infrastructures must be equipped with effective drainage systems. These systems rapidly evacuate rain water to avoid dangerous accumulations on roads and rail tracks, guaranteeing the safety of users and minimizing service interruptions.

— **White paint on rails and road infrastructures:** Inspired by practices in South Korea and Japan, painting rails and roads white can absorb heat and thus limit the risk of dilation and cracking in infrastructures during summer heat waves. However, the long-term effectiveness of this method remains to be proved and requires additional experimentation to confirm its benefits over time.

— **Rail-cooling systems:** To deal with heat waves, rail-cooling systems like sprinklers are used to avoid excessive dilation. This technology, which is already used in several countries, is being evaluated in France for application in the most exposed areas.



Source : SNCF Réseau – Augmentation des températures et impact sur les services ferroviaires (2024)

The transport sector faces major challenges due to climate change, in particular in terms of the resilience and adaptation of infrastructures. Technological innovations like connected sensors, smart management systems, and resilient materials, play a central role in improving the capacity of infrastructures to resist extreme climate events. The strategic priorities are the transition to lower-carbon modes of transport, like trains, and the integration of sustainable solutions to adapt aviation and maritime infrastructures to the new climate and energy situations. Adopting alternative fuels like SAF, and exploring nuclear propulsion for large ships, offer promising perspectives for reducing the carbon footprint of these sectors while making them more resilient. However, this transformation calls for massive investments, consistent regulatory support, and close cooperation between private and public actors to guarantee the sustainability of the transport network, respond to climate expectations, and ensure the continuity of services for the decades to come.

3.7. Health

Health is one of the most vulnerable sectors to climate change, with profound short- and long-term repercussions that affect both people and health infrastructures. The increase in heat waves, changes in the geographic spread of vector-borne diseases, and greater risks related to extreme weather are all factors that put more pressure on health systems, calling for rapid, effective adaptation to protect vulnerable populations, maintain health quality, reinforce the resilience of infrastructures, and anticipate health crises. The third French National Climate Change Adaptation Plan (PNACC) puts a particular emphasis on the challenges of heat waves, vector-borne diseases and psychosocial risks for France in the future. Faced with these critical issues, it is now imperative to explore technological solutions and understand the strategic issues related to adapting the health sector. This chapter focuses on a detailed analysis of these technological solutions and the principal challenges to overcome in order to guarantee the sustainable adaptation of the health sector in the face of climate change.

3.7.1. HEALTH ISSUES

The health sector is strongly impacted by climate change. The health issues involved are diverse and affect various levels:

— **Heat waves and extreme weather events:** As illustrated by the infographic in section 2.3 produced by Météo-France based on the work of the IPCC (2023), extreme heat episodes are increasingly common and prolonged, with exceptionally hot temperatures rising by 1.9°C and a global average increase of +1.5°C. These heat waves exacerbate death rates, in particular among the vulnerable (old people, children, people with chronic diseases). Heat stress aggravates existing medical conditions and increases the rate of hospitalization. In France, the heat wave of 2003 caused almost 15,000 additional deaths, illustrating the urgent need to improve the resilience of health systems. Moreover, the impact of extreme climate events is not restricted to heat: in Pakistan, the floods of 2022 caused 1,500 deaths and 12,000 injuries, underlining the need to adapt health infrastructures and systems to deal with increasingly frequent and serious crises. As global temperatures rise (+2°C or +4°C), these phenomena will become more intense, bringing increasing challenges to manage infrastructures and protect people. The role played by transport, in particular long-haul flights, in the proliferation of illnesses and vector-borne diseases should also be highlighted since it facilitates the rapid expansion of epidemics around the world.

— **Vector-borne diseases:** Climate change creates the conditions for some vector-borne diseases such as dengue fever, chikungunya and malaria to propagate in previously unaffected regions, including France. Higher temperatures encourage the proliferation of vectors like mosquitoes, bringing greater risks for public health. Studies show that climate change could extend the spread of vector mosquitoes and diseases to new regions in Europe, raising the risk of epidemics.

— **Proliferation of bacteria:** Climate change encourages the proliferation of bacteria and cyanobacteria in waters above 17°C, bringing considerable risks for public health. Detailed microbial ecology studies are required to guarantee the quality of drinking water.

— **Psychosocial risks:** Extreme climate events like floods and storms, coupled with the forced displacement of people, lead to greater psychosocial problems, in particular post-traumatic stress, depression and anxiety.

— **Impact of pesticides:** Rising temperatures and droughts intensify the concentration of pollutants in water, including from pesticides. These chemical products, which are widely used in agriculture, can have serious repercussion on human health, in particular when consuming contaminated water during low-water periods.

3.7.2. TECHNOLOGICAL ISSUES

Adapting the health sector to the new climate situation brings a number of technological and organizational challenges:

— **Ageing infrastructures:** Numerous hospitals in France are old and were not designed to resist extreme heat or other climate events. Modernizing them while maintaining everyday operations is a significant technical and financial challenge.

— **Energy dependence:** The operation of healthcare systems relies strongly on a stable energy supply, both for air conditioning and medical systems. Back-up solutions, like generators, remain essential to guarantee the resilience of hospitals in crisis periods. The progressive adoption of low-carbon energy storage solutions like batteries aims to reduce the carbon footprint of these systems, although this concerns mitigation more than adaptation.

— **Intersectoral collaboration:** Combatting vector-borne diseases and managing climate-related health crises require close collaboration between health authorities, scientists, engineers and local governments. To strengthen this cooperation, it is vital to develop efficient coordination platforms to share information, implement common strategies, and manage resources in real time. On an international level, collaboration in the health field calls for a more subtle approach that takes into account the realities and priorities of the BRICS, which represent more than half of the world's population and two-thirds of the land surface. The joint development of solutions adapted to local contexts is essential, involving transferring technologies as well as sharing best practices and pooling research efforts to meet global climate change challenges.

3.7.3. TECHNOLOGICAL SOLUTIONS FOR ADAPTATION

— **Resilience of healthcare establishments:** Faced with the increased number of heat waves, healthcare establishments must be equipped with effective air-conditioning systems to guarantee optimal care conditions. However, these systems need to be designed to minimize their energy consumption and environment impact. Heat pumps combined with natural ventilation systems are the best solutions to provide thermal comfort while reducing energy demand. Hospitals and other healthcare facilities must also be made stronger to resist extreme climate events like floods, storms and earthquakes. This includes establishing backup systems for the electricity supply, protecting against flooding, and creating secure zones in hospitals to shelter parents and staff in case of crisis.

— **Early warning system for heat waves:** The development of predictive technologies and early warning systems based on meteorological models is essential to forecast and anticipate the impacts of heat waves on public health. Warnings allow preventative measures to be taken, like activating emergency plans in hospitals and organizing care for people at risk (setting up centres for cooling and distributing resources to the most vulnerable).

— **Management of water and sanitation facilities:** Wastewater management and water quality are key for public health, in particular during heat waves, which increase the risk of the proliferation of bacteria and cyanobacteria in water. Using advanced sensors to monitor water quality and setting up systems for more effective wastewater treatment can limit these risks.

— **Surveillance and prevention of vector-borne diseases:** Climate change fosters the geographic spread of disease vectors, like mosquitoes that transmit dengue fever, chikungunya and malaria. To respond to this threat, it is crucial to reinforce epidemiological surveillance systems using technologies such as environmental sensors, and drones to map zones at risk. These automated surveillance systems integrating artificial intelligence can be used to monitor the propagation of disease vectors like mosquitoes so that health authorities can take fast measures to limit epidemics, including targeted vaccination campaigns and preventative treatment.

— **Development of vaccines and adapted treatment:** Adapting the healthcare sector also includes research and development on new vaccines and treatments for vector-borne diseases likely to become more common due to climate change. This requires close collaboration between research institutions, pharmaceutical companies, and health authorities to accelerate the development and distribution of these solutions.

— **Remote consultations and telemedecine:** Integrating digital technologies into the management of care is essential to improve the resilience of healthcare facilities. Electronic systems for managing medical records, telemedicine platforms, and crisis management tools can result in more effective coordination of care and faster response to climate emergencies. When floods, storms or heat waves make travel difficult, remote consultations are essential to ensure the continuity of care. In addition to telemedicine, guaranteeing access to healthcare in all parts of the country, especially during climate crises (e.g. heat waves) is essential. New digital and governance tools can play a key role in this greater accessibility. Digital tools and telemedicine systems, while necessary to respond to climate challenges, also require efficient energy management to avoid greater dependence on fossil fuels.

— **Access to healthcare during crisis situations:** It is essential to guarantee that vulnerable people can quickly access care during climate crises. This might involve setting up mobile clinics, distributing emergency medical kits, and using telemedicine to give remote consultations when access to healthcare facilities is limited.

3.7.4. SOCIAL AND GOVERNANCE ISSUES INVOLVING HEALTH

— **Intersectoral coordination and international collaboration:** Adapting the healthcare sector requires efficient coordination between the different sectors, including social services, local authorities, and national health agencies. This coordination is crucial to implement consistent adaptation plans and to mobilize the resources needed in times of crisis. Sharing knowledge and best practices at international scale is essential to reinforce the capacity of health systems to adapt to climate challenges. Collaborations with international organizations like the World Health Organization (WHO), and participating in global research networks are key to improving the resilience of the healthcare sector.

— **Public health policies adapted to climate:** Public health policies should be revised to integrate climate risks. This includes establishing national health monitoring programmes linked to climate change, reinforcing the response capacities of health systems, and allocating specific resources for climate adaptation in the public health budget.

— **Research on how climate impacts health:** Research on the connections between climate change and health should be intensified to improve understanding of the underlying mechanisms and develop effective responses. This includes producing studies on how heat waves, vector-borne diseases, and atmospheric pollution impact public health, and developing innovative prevention and treatment technologies.

Adapting the health sector to climate change is a complex challenge that requires a multidimensional approach integrating technological solutions, institutional reforms, and intersectoral coordination. Investments in these domains are essential to protect people, maintain healthcare quality, and anticipate health crises resulting from future climate impacts. The successful adaptation of the healthcare sector requires a proactive approach involving immediate action to reinforce existing systems and long-term strategies.

3.8. Defence

Climate change brings significant strategic challenges for national defence. Extreme weather events like floods, storms and heat waves affect the security of military infrastructures, the mobility of troops, and the capacity to react fast in times of crisis. In addition, these changes increase geopolitical tensions, in particular concerning natural resources like water and habitable land, which intensifies the need for adapted defence technologies.

3.8.1. CLIMATE CHANGE ISSUES FOR MILITARY OPERATIONS

Climate change has direct consequences on the operational capacities of the French armed forces. The impacts of extreme climate events (high temperatures, intense rainfall, hurricanes, etc.) change the environments in which soldiers need to operate, meaning that military infrastructures and equipment need to be adapted. Geopolitical tensions related to the scarcity of natural resources compound these challenges, forcing armed forces to anticipate and integrate climate adaptation strategies.

— **Extreme temperatures:** Deployment areas like the Sahel and the Middle East regularly endure temperatures above 40°C, which exposes soldiers to the risk of heat stroke and reduces the effectiveness of military equipment (e.g. helicopters, armoured vehicles, etc.). Military equipment needs to be adapted to these extreme temperatures to maintain the operational capacity of armed forces in these regions.

— **Precipitation and flooding:** More frequent, intense rainfall, in particular in Africa, perturbs military and humanitarian operations, rendering roads and logistical infrastructures impossible to use. In areas like the Sahel, flooding exacerbates tensions arising from climate instability and makes it harder to coordinate military interventions.

— **Hurricanes and winter storms:** French military infrastructures, in particular naval bases located on the Atlantic coast and in tropical regions, are regularly damaged by winter storms and hurricanes. This disturbs both operations and the maintenance of strategic equipment like military ships.

— **Higher sea levels and temperatures:** Coastal naval and army bases are confronted by erosion and rising sea levels. This calls for structural reinforcements to protect critical infrastructures.

3.8.2. GEOPOLITICAL ISSUES AMPLIFIED BY CLIMATE

Climate change also catalyses geopolitical tensions, in particular in fragile regions where competition for natural resources is intensifying.

— **Climate-related conflicts:** Food insecurity and forced migrations, made worse by climate change, are likely to provoke conflicts in already-unstable areas like West Africa. Armed forces must not only adapt to extreme climate conditions, they must also prepare responses to humanitarian crises and the mass displacement of people caused by the degradation of the environment.

— **International cooperation on climate security:** Climate security calls for closer cooperation between international armed forces to share intelligence, technologies and rapid response capacities to deal with climate threats. France plays an active role in joint exercises and in the development of climate defence technologies to better anticipate global climate risks.

3.8.3. KEY TECHNOLOGIES FOR ADAPTING MILITARY INFRASTRUCTURES AND EQUIPMENT

— **Attack helicopters:** Simulations show that in environments where temperatures can reach 40°C, like the Middle East, the carrying capacity of helicopters is considerably reduced. This affects their mission effectiveness. Solutions include adapting engines and cooling systems to improve their performance in extreme heat conditions.

— **Electronic systems and modern weapons:** Rising temperatures increase the risk of failure in electronic systems and modern weapons, which need constant cooling to function properly. The development of improved cooling systems, like hybrid systems, is a priority to maintain operations of military equipment in high temperatures.

— **Resilient military bases:** Reinforcing coastal and inland military bases to make them more resilient to climate events is indispensable. Coastal infrastructures require protection against erosion and rising sea levels, while inland bases need to be equipped with drainage systems to deal with floods.

— **Connected sensors and surveillance systems:** IoT sensors installed in military infrastructures can detect deterioration caused by climate phenomena in real time, including dilation of material and cracks in structures, thus guaranteeing rapid intervention and preventative maintenance.

— **Uniforms and equipment adapted to extreme climate conditions:** Soldiers' uniforms must be designed to guarantee better ventilation and thermal insulation corresponding to the environments they operate in. New technologies result in lighter, waterproof uniforms that can maintain an adequate body temperature.

— **Autonomous energy management systems:** Microgrids can be used in military bases to ensure constant energy supply in the case of climate perturbations. These autonomous systems guarantee that bases located in remote regions or areas subject to climate risks can maintain their operations even during power outages.

3.8.4. IMPACTS AND ADAPTATION OF ARMED FORCES

Climate change profoundly alters the conditions in which armed forces operate, calling for constant adaptation of infrastructures, equipment, and strategies. Military infrastructures must be strengthened to stand up to flooding and coastal erosion, while soldiers need to be trained to operate in increasingly hostile environments. Resilient logistical strategies must also be set up to maintain the flexibility of military operations.

The defence sector must adapt to the realities of climate change by integrating advanced technologies to reinforce infrastructures, improve military equipment, and guarantee fast response capacity to deal with humanitarian crises and geopolitical tensions made worse by climate conditions. Investments in these technologies and international cooperation are essential to maintain national and international security.

3.9. Space

The space industry is a key player in our understanding of climate change thanks to space technologies. Observation satellites can closely monitor climate phenomena, although space infrastructures need to adapt to the new atmospheric and climate conditions.

3.9.1. HOW THE SPACE SECTOR CONTRIBUTES TO ADAPTATION

The space sector plays a central role in monitoring and understanding climate change on a global scale. Space technologies, like observation satellites, collect essential data on extreme climate phenomena and changes in ecosystems. In addition, satellites help maintain telecommunications when bad weather affects the network on Earth. However, the space sector itself is impacted by climate change, in particular space infrastructures and launching operations.

— **Observation of climate change:** Observation satellites can monitor phenomena like melting glaciers, rising sea levels and desertification. These data are crucial for managing geopolitical risks and anticipating climate impacts on critical infrastructures.

— **Climate observation satellites:** Observation satellites, like the TRISHNA programme, play a key role in collecting thermal and climate data to monitor water resources management and extreme climate phenomena. These satellites provide valuable data for planning climate responses.

— **Communication systems using resilient satellites:** Communication satellites help to maintain transmissions during crises, guaranteeing efficient coordination at such times. Most innovations concern reinforcing satellite networks.

— **Smart satellites and advanced sensors:** New satellites equipped with more effective sensors can detect phenomena like atmospheric pollution, storms and heat waves in real time. This information is essential to manage climate crises and means that governments and armies can react faster and more effectively. Thanks to smart satellites, major climate phenomena can be more readily anticipated, making it easier to plan interventions in areas affected by natural catastrophes.

— **Sustainable propulsion technologies:** Research on propulsion engines aims to reduce the carbon footprint of space launching while ensuring optimal performance in changing climate conditions. These technologies are crucial to minimize the environmental impact of the space sector while maintaining an effective capacity for exploration and observation.

3.9.2. SPACE PROGRAMMES AND TECHNOLOGICAL INNOVATIONS

Several space programmes in collaboration with agencies like the CNES and ESA directly contribute to climate change adaptation. These projects monitor and collect precise data on extreme climate phenomena, and develop technologies to improve the resilience of space infrastructures.

- **TRISHNA (Thermal infraRed Imaging Satellite for High-resolution Natural resource Assessment):** This French-Indian programme centres on managing water resources using thermal infrared imagery of the Earth. The data collected are crucial for regions vulnerable to drought, and can also be used to reinforce the resilience of military bases located in arid areas.
- **SWOT (Surface Water and Ocean Topography) Satellite:** This programme, involving a partnership between NASA and the CNES, measures the water level of rivers, streams and reservoirs at global scale. These data are essential to anticipate water shortages and strategically manage resources in areas subject to conflict and humanitarian crisis exacerbated by the effects of climate change.
- **Galileo:** This European satellite navigation system, which is crucial for defence and humanitarian missions, allows for precise coordination of military and civil operations. Galileo is also a valuable tool for mapping climate impacts and ensuring effective response to natural catastrophes.
- **Smart satellites:** New-generation satellites are equipped with advanced sensors and supply information in real time on phenomena like atmospheric pollution, heat waves, and storms. These data make it easier to manage military and humanitarian responses in areas impacted by climate change.
- **Sustainable propulsion technologies:** Innovations on propulsion engines reduce the carbon footprint of space launching and increase the efficiency of exploration and surveillance missions. These technologies are essential to adapt the space sector to the current climate realities.
- **Real-time observation:** Technological improvements in imagery and remote detection mean that major natural catastrophes like wildfires, floods and hurricanes can be constantly observed in real time. This facilitates military and humanitarian interventions in areas affected by climate catastrophes.

The space sector is at the forefront of climate change action thanks to its surveillance and observation capacities. Technological innovations in satellite communication systems, advanced sensors, and sustainable propulsion technologies are essential to guarantee the resilience of space infrastructures. In parallel, the reinforcement of the airport infrastructure and international collaboration on space projects like Copernicus make it easier to anticipate and respond to climate crises around the world.

Overview of adaptation technologies

04

The acceleration of technological adaptation to climate change largely relies on the emergence of new technologies and innovative solutions. These innovations are crucial to meet the specific challenges raised by climate impacts, involving resource management, the protection of infrastructures, and the resilience of ecosystems. In France, several promising innovations stand out in diverse sectors, supported by research programmes and public and private initiatives. These R&D innovations, expected in key domains like building science, the improvement of climate models, the development of satellite technologies and the associated metrology, in addition to advances in microbiology, are essential to improve resilience to climate change. Moreover, these studies draw from previous progress, including in the areas of smart grids and so-called game-changing technologies. It is important to continue exploiting these advances to accelerate adaptation efforts.

4.1. Water resources management technologies

— **Smart irrigation systems:** Optimizing irrigation using these advanced systems is a priority to reduce water consumption while maintaining agricultural production. Automated water management systems, which include IoT sensors, artificial intelligence (AI) algorithms, and satellite imagery, enable precise irrigation corresponding to the real needs of crops.

— **Micro-irrigation:** This system, which delivers small quantities of water directly to the root of plants, reduces water consumption by 30 to 40% without compromising agricultural yields.

— **Reuse of treated wastewater:** This technology consists in reusing treated water for irrigation purposes, which contributes to alleviating water shortages. Water treatment stations feed into about 30% of French rivers. However, the use of wastewater needs to be regulated to avoid contaminating the soil and conflicts of use.

— **Water storage:** Underground and surface reservoirs are planned to conserve water during stress periods and avoid conflicts of use. This method is a response to temporal and geographic fluctuations in water availability.

— **Groundwater recharge:** Faced with the increasing scarcity of water, artificial groundwater recharging techniques, like injecting treated water or creating infiltration basins, are being experimented to maintain sustainable water supplies, even during prolonged droughts.

— **Modelling precipitation and sizing pipelines:** Precise modelling of future precipitation is crucial to adapt hydraulic infrastructures to the new climate realities. In France, modelling tools are being developed to simulate extreme events like torrential rain, and therefore correctly size rainwater management systems and ensure their long-term effectiveness.

— **Rainwater retention and management systems:** To deal with extreme rain episodes, retention basins and wastewater recycling systems are being developed to ensure that urban infrastructures are less vulnerable.

— **Leak detection system:** Improved infrastructures and the establishment of leak detection technologies are essential to reduce leaks, in particular in rural areas, where more extensive networks make maintenance more difficult.

— **Environmental sensors and water resources surveillance:** The development of environmental sensors to survey the quality and quantity of water in real time is essential to proactively manage crises related to drought or pollution. These sensors are employed in rivers, lakes and water tables to provide crucial data to anticipate water shortages and optimize management strategies.

— **Water desalination:** Although expensive and energy intensive, desalination of seawater is seen as a potential solution for coastal regions suffering from water shortages. Current research focuses on developing more effective desalination technologies that consume less energy, and on managing saline residues produced by the process.

— **Reoxygenation and innovative treatment:** The reoxygenation of water bodies to combat eutrophication and deoxygenation is essential to deal with the consequences of climate change. Specific technologies are being developed to restore aquatic ecosystems while respecting biodiversity.

— **Development of advanced treatments:** Tertiary and quaternary treatment of wastewater eliminates micropollutants and guarantees quality drinking water.

4.2. Energy resilience technologies

— **Electricity network modernization:** This involves accelerating the burying of electricity lines, modernizing transformer substations, and developing smart grids to anticipate and manage climate incidents.

— **Smart grids:** Smart grids represent a key innovation to improve the resilience of electricity networks to extreme climate events. These grids integrate technologies for communication and real-time energy management, resulting in better management of energy flows and rapid responses to disturbances. Enedis, for example, is investing in developing smart grids to improve the resilience of its supply network, including the integration of renewable energy sources and storage solutions.

— **Advanced energy storage:** Energy storage is crucial to ensure stable electricity supply, such as when the climate is perturbed. In order to guarantee energy resilience, it is essential to step up the development of storage technologies, like high-density batteries and pumped storage hydroelectricity. High-density batteries, flywheels and pumped storage hydroelectricity systems are promising solutions to guarantee constant availability of energy, even when renewable power sources are intermittent.

— **Autonomous microgrids:** Microgrids are autonomous systems that are capable of operating independently from the main network. They are particularly useful in rural and isolated areas to ensure constant, resilient supply in the case of climate crises. These microgrids can integrate renewable energy sources, like sun and wind power, and storage systems, thus offering a resilient solution for critical infrastructures.

— **Renewable energy and climate forecasting technologies:** EDF, Enedis and ENGIE are investing in improving climate models and forecasting technologies to identify the best areas to establish solar and wind farms. These models can also anticipate risks related to extreme weather conditions and optimize the management of existing farms.

— **Optimization of grid management:** Enedis is setting up preventative management solutions to limit the impact of climate events. This includes using remote sensing technologies to diagnose and anticipate breakdowns, and developing microgrid demonstrators to explore local solutions.

— **Resilient photovoltaics:** Photovoltaic infrastructures, like agrivoltaic systems, need to be designed to resist extreme temperatures and more frequent hail episodes. Climate models are used to evaluate these risks and adapt equipment in accordance.

— **Adaptation of nuclear power stations:** This involves reenforcing the resistance of nuclear power plants to climate variations, deploying alternative cooling technologies and reducing water withdrawals. In response to the challenges raised by scarcer water resources, EDF is working on alternative cooling systems that use less water for its nuclear plants. Less water-intensive technologies are also used to ensure the constant production of electricity during heat waves.

4.3. Agriculture resilience technologies

— **Variety selection:** Developing plant varieties that can resist drought, water stress and salinity is crucial to maintain agricultural production. The characteristics targeted include deep roots, improved water efficiency, and precocity. Selection techniques like hybridization, mutagenesis, transgenesis and genome editing can be used to create varieties more adapted to the new climate conditions.

— **Agroecology and agroforestry:** Agroecology encourages the diversification of crops by using natural processes to improve the resilience of agricultural systems, thus reducing the vulnerability of crops to extreme climates. Agroforestry, which integrates trees and crops, protects against climate hazards and improves the long-term resistance of farms.

— **Micro-irrigation and smart irrigation technologies:** Micro-irrigation systems deliver small quantities of water directly at the root of plants, thus reducing water consumption by up to 40% while preserving agricultural yields. These systems are often combined with IoT sensors, probes and decision-making aids to monitor humidity levels and optimize irrigation in real time.

— **Climate modelling and agricultural forecasting:** Advanced modelling and climate forecasting technologies help farmers make informed decisions on planting schedules, irrigation, and crop management. These tools help farmers optimize their calendars and adapt their practices to short- and long-term climate forecasts.

- **Smart agricultural equipment:** Watering robots, hoeing robots and drones can be used to monitor crops on a large scale and optimize the use of water and agricultural inputs. This automated equipment provides more precise, effective management of resources, thus improving productivity while reducing environmental impacts.
- **Early warning systems and climate crisis management:** Agriculture also needs to integrate early warning systems for extreme climate events like droughts, heat waves and floods. These tools provide real-time information and practical advice to minimize farm losses.
- **Soil management and action against erosion:** Preserving the quality of soil is essential to guarantee the resilience of crops in the face of changing climate conditions. Practices like plant coverage and minimum labouring help to prevent erosion, maintain soil fertility and retain water in the soil.
- **Agrivoltaics:** Installing solar panels above crops is a way of generating power while protecting plants from direct sunlight. This technology reduces water requirements and protects some crops from extreme climate conditions like heat waves.

4.4. Resilient urban planning technologies

- **Thermal insulation and energy efficiency:** It is essential to improve the thermal insulation of buildings to reduce energy consumption, whether for heating in winter or cooling in summer. Materials with thermal inertia, like bricks and stone, can regulate indoor temperatures by storing then releasing heat slowly, thereby increasing buildings' resilience to heat waves.
- **Resilient construction materials:** The development of innovative building materials that can resist extreme climate conditions is essential to improve the resilience of buildings. Research in building science must be accelerated to better understand the thermo-resilience of current materials, and adapt building practices to optimize insulation and ventilation. New materials like high-performing concrete, advanced thermal insulation, and flood-resistant coatings result in more durable buildings in the face of heat waves, storms and floods.
- **Urban vegetation and green infrastructures:** Nature-based solutions, like green roofs and walls, and the integration of green infrastructures in cities, play a key role in mitigating the impacts of urban heat islands and improving the thermal resistance of buildings. These innovations also make it easier to manage rainwater more sustainably, since they reduce the risk of flooding and improve air quality in urban environments.
- **Heat pumps and advanced ventilation systems:** In a global warming context, it is indispensable to install energy-saving air-cooling systems to guarantee the comfort and security of inhabitants, in particular during heat waves. These systems must be designed to minimize energy consumption, along with alternatives like natural ventilation systems and sunshades.
- **Adaptation and renovation of infrastructures:** Infrastructures should be reinforced, such as by modernizing drainage systems and strengthening old buildings to make them more resistant to storms and heat waves, with the aim of adapting urban areas to the new climate realities. Investments in systems to manage and retain rainwater is key to limit the impacts of flooding and extreme precipitation.
- **Planting of trees and creation of green spaces:** Green areas created in urban areas reduce the ambient temperature, encourage rainwater infiltration, and contribute to regulating urban ecosystems. Some cities have set a target of greening up to 30% of their urban surface area.
- **Resilient urban transport:** Transport infrastructures must be adapted to extreme climate events like floods and heat waves. This includes reinforcing roads, bridges and railways. Developing electricity-powered public transport and soft mobility solutions (cycle lanes and pedestrianized areas) is encouraged to reduce dependence on fossil fuels and improve the resilience of urban systems.
- **Resilient coastal solutions:** In coastal cities, dykes, anti-flood barriers and nature-based solutions (like mangroves and marshes) are deployed to combat rising sea levels.

4.5. Technologies for industry

- **Advanced cooling systems:** Faced with increasingly frequent heat waves, industrial factories and installations are under great demand for cooling solutions. Advanced cooling systems, like air-coolers and hybrid systems, not only maintain stable production, they also considerably reduce water consumption, which is crucial during prolonged droughts. These technologies are capable of managing heat peaks while minimizing the carbon footprint of industries, contributing to the adaptation of industrial processes to deal with climate challenges.
- **Digitization of logistics chains:** Digitization, associated with artificial intelligence and data analysis, transforms logistics chains by making them more resilient to climate perturbations. These technologies provide improved forecasts of interruptions in the supply chain, optimize routes in the case of extreme weather conditions, and diversify suppliers to reduce vulnerability to hazards. Industries can thus anticipate delays and

adjust their strategies in real time, reducing losses and maximizing the efficiency of logistics.

— **Technologies for forecasting and adapting industrial processes:** The integration of IoT sensors and analysis systems in real time allows for optimized management of industrial processes to deal with climate hazards. These sensors monitor crucial parameters of industrial infrastructures, like temperature, humidity and pressure, to adapt processes in accordance with environmental conditions. The data collected are then used to adjust machines and anticipate interruptions, guaranteeing constant production, even during extreme weather episodes.

— **Energy efficiency in factories:** Energy efficiency has become vital for industries, in particular in a context of climate change. The optimization of energy management systems in factories means that industrial production can be kept stable while reducing overall energy consumption. Technologies like smart energy management systems and high-efficiency appliances are deployed to minimize waste and guarantee optimal management of resources during energy stress periods.

— **Microgrids for industrial sites:** Microgrids are increasingly popular solutions to ensure the continuity of industrial operations, in particular when the main network fails due to extreme climate events. These systems, which integrate renewable energy sources like sun and wind power, can operate independently from the central network, thus ensuring constant power supply for strategic industrial sites. They offer a local solution that is resilient to climate perturbations.

— **Resilient materials:** To ensure that industrial infrastructures can remain operational during extreme climate events, it is essential to employ materials that can resist these variations. More robust materials, like high-performing concrete, advanced thermal insulation, and flood-resistant coatings, result in more durable infrastructures. These materials are designed to resist very high or low temperatures, while reducing the impacts of storms, flooding and other climate events on industrial buildings.

— **Recycling and critical materials:** Industries' dependence on some critical materials like copper, combined with the risks raised by interruptions in the supply chain, make it necessary to closely monitor the use of these resources. Integrating recycled materials into industrial processes is a key lever to reinforce the resilience of industries in the face of perturbations. It is a way of reducing dependence on imports and guaranteeing continuous operations, even during times of global climate crisis.

— **Robotization of industrial processes:** The automation and robotization of factories play a central role in optimizing industrial processes when climate conditions are difficult. Smart robots can precisely adjust operations in real time, while reducing energy consumption and increasing productivity, even during extreme temperatures. This rapid adaptation of manufacturing processes makes it possible to manage interruptions and ensure constant industrial activity.

— **Connected sensors to manage risks:** Connected sensors installed on industrial infrastructures can monitor installations in real time and rapidly identify risks related to extreme climate events. These sensors measure critical parameters like dilating materials, cracks in structures, and variations in temperature, facilitating rapid intervention to avoid breakdowns and major accidents.

— **Technologies for nuclear cooling systems:** EDF and other energy actors are working on alternative cooling systems for nuclear power plants that are less dependent on water. These technologies are essential to deal with water shortages during heat waves so that plants can maintain stable power production while respecting environmental regulations.

4.6. Technologies for transport

— **Reinforcement of transport infrastructures:** Transport infrastructures, like roads, bridges, ports, tunnels, airports and railways, need to be reinforced to cope with increasingly frequent climate hazards such as floods, storms, heat waves and landslides. This involves making major investments in modernizing existing infrastructures to make them more resilient. For example, it is essential to update drainage systems for rapid evacuation of rainwater in case of extreme precipitation. The French state and the public urban planning agency Cerema are actively working on updating national technical references, including a technical guide to sanitation currently being revised. Their efforts are also aimed at driving an evolution of European and international norms like the CEN and ISO standards.

— **Innovative materials for infrastructures:** Adapting infrastructures requires using materials capable of resisting extreme temperatures and the constraints of climate change. This includes road surfaces that can resist high temperatures and freeze/thaw cycles, and metal alloys that can reduce the risks of thermal dilation for rails and catenary lines. These advances make infrastructures more long-lasting and improve safety for users.

— **Connected sensors and smart management of infrastructures:** Integrating IoT sensors on roads and railways means that they can be monitored in real time to detect anomalies like cracks, deformations and overheating. The data collected facilitate rapid intervention and preventative maintenance, and reduce the risks of interrupted service. On railways, these sensors can also monitor the temperature of rails and overhead lines to anticipate the impacts of heat waves.

- **Electricity-powered mobility and resilient charging infrastructures:** The increasing development of electric mobility makes it crucial to design charging stations to resist extreme climate hazards like storms, floods and heat waves. To ensure that they can operate in difficult conditions, charging stations must be adapted thanks to advanced thermal management technologies. Although these adaptations are a priority in the medium term, they can be gradually integrated as charging stations are renewed (average lifespan 10-15 years).
- **Resilient public transport and passenger comfort:** Public transport networks like trams, subways and electric buses must be reinforced, not just at infrastructure level, but also in the way services are designed to guarantee continuity during extreme climate conditions. Vehicles must be adapted by integrating effective, less energy-intensive cooling systems adapted to heat waves. In addition, the use of insulating materials with high energy efficiency can ensure the thermal comfort of passengers.
- **Storage and product distribution strategies:** In the logistics sector, the development of strategically located distribution centres, in particular close to risk zones, can secure supplies and limit interruptions caused by climate events. These centres can employ smart management technologies to adjust their stocks to correspond to climate forecasts and rapidly respond to perturbations.
- **Systems to forecast and manage logistics flows:** Advanced climate models and forecasting systems can be used to optimize supply itineraries and strategies in the transport and logistics sectors. These tools help anticipate interruptions caused by extreme events, adjust logistics flows, and guarantee the continuity of essential services.
- **Advanced drainage technologies:** Developing innovative drainage systems that are adapted to torrential rain is crucial to limit the risk of floods and the degradation of infrastructures. These technologies play a key role in ensuring the continuity of services, in particular in areas exposed to climate hazards.
- **Digitization and maintenance in real time:** Digitization of transport infrastructures enables proactive, intelligent management of resources allocated to maintenance. Connected systems detect anomalies fast, facilitating effective planning of interventions. This approach reduces costs, improves user safety, and guarantees the reliability of services.
- **Stakeholder mobilization to adapt transportation:** Adapting transport services and infrastructures requires coordination between the state, local authorities, infrastructure managers and producers of technical references like Cerema. Working groups have been set up to exchange on good practices, such as thermal comfort in vehicles, and to promote a collaborative approach to integrating climate issues.

4.7. Technologies for health

- **Warning systems for extreme climate events:** Early warning systems use advanced climate models and real-time data to forecast and anticipate extreme climate events that directly impact health, like heat waves, and trigger emergency plans. These systems can be used to set up preventative measures like opening cooling centres, distributing drinking water, and protecting vulnerable people such as children and the elderly.
- **Surveillance of vector-borne diseases:** Climate change fosters the geographic spread of disease vectors like mosquitoes that transmit dengue fever and malaria. Innovative technologies like environmental sensors, drones to map risk areas, and artificial intelligence to analyse epidemiological data, are being developed to proactively monitor and control these vectors.
- **Reinforcement of hospital infrastructures:** Hospitals and other healthcare facilities need to be modernized to resist extreme climate events, like floods and storms. This includes establishing backup systems for the power supply, protecting against floods, and creating secure zones within the hospitals.
- **Effective air-cooling systems:** Faced with the increase in heat waves, healthcare establishments must be equipped with highly energy-efficient air conditioning systems. Solutions like heat pumps, combined with natural ventilation systems, make it possible to guarantee optimal healthcare while minimizing energy consumption.
- **Development of vaccines and suitable treatments:** Research into vaccines and treatments for emerging diseases linked to climate change is crucial. Biotechnology and pharmacology innovations are developing medical solutions adapted to the new health risks raised by climate change.
- **Microbial ecology:** Reinforcing research into microbial ecology can anticipate the proliferation of cyanobacteria and guarantee the quality of drinking water.
- **Remote consultations and telemedecine:** Telemedicine can ensure healthcare when floods and storms make travel difficult. Digital platforms facilitate remote consultations and the electronic management of medical records for better coordination of healthcare during crisis situations.
- **Emergency medical kits and mobile clinics:** In times of crisis, it is crucial to guarantee rapid access to healthcare for vulnerable people. This includes distributing emergency medical kits and setting up mobile clinics to provide local healthcare.
- **Interoperability of healthcare management systems:** Interoperable information system, like geographic information systems (GIS), are essential to monitor climate vulnerabilities in real time and anticipate public health responses.

4.8. Technologies for defence

- **Surveillance of climate and geostrategic threats by satellite:** Surveillance systems based on Earth observations can monitor geopolitical movements and climate impacts. These technologies can anticipate tensions arising from natural catastrophes by detecting environmental changes before they affect military operations.
- **Reinforcement of coastal and inland military bases:** Military infrastructures must be reinforced to resist rising sea levels, floods and storms. This includes installing advanced drainage systems and using building materials that can stand up to extreme climate conditions.
- **Cooling systems for military equipment:** Rising temperatures make it necessary to adapt cooling systems for military equipment like armoured vehicles and embedded electronic systems, which require constant operating temperatures.
- **Protection of critical infrastructures during extreme weather:** Military infrastructures, like munitions stores and communication centres, need to be strengthened to resist storms and other extreme climate phenomena. This includes using thermal and physical protection technologies.
- **Equipment adapted to climate conditions:** Military uniforms and individual equipment must be adapted to ensure that soldiers can maintain their operational efficiency in extreme temperatures. New technologies focus on improving ventilation, thermal insulation, and protection against humidity.
- **Autonomous energy systems for military bases:** Microgrids and energy storage systems can ensure constant power supply in remote military bases or those affected by extreme climate events.
- **Drone technologies for surveillance in extreme environments:** Drones are being developed equipped with sensors capable of real-time monitoring of areas affected by natural catastrophes and conflict zones in hostile climate environments.
- **Climate forecasting for military operations:** Climate models and forecasting technologies mean that armed forces can anticipate extreme weather in zones of conflict and adapt their operational strategies. The data collected by the satellites can be used to monitor the movements of troops in tense geopolitical situations exacerbated by climate change.
- **Reduction of the carbon footprint of military operations:** Technologies are being adopted that aim to minimize the carbon footprint of armed forces, including the use of alternative fuels and the establishment of sustainable military bases that are autonomous in terms of energy.
- **Military transportation resilient to extreme conditions:** Development of armoured vehicles and other means of transport capable of standing up to extreme conditions like high temperatures, sand storms and floods.

4.9. Technologies for space

- **Geostrategic surveillance and climate observation by satellite:** Space technologies, in particular Earth observation satellites, are essential to monitor the impacts of climate change on global scale. These satellites provide precise data in real time on extreme climate phenomena, changes to ecosystems, and deforestation, which is crucial to plan climate responses. The CNES, in collaboration with the ESA, is developing new-generation satellite missions to improve the precision of climate data and facilitate decisions for adaptation.
- **Resilient satellite communication systems:** Satellites must be reinforced to resist climate perturbations and guarantee stable, secure communication when natural catastrophes occur. Innovations are centred on reducing risks of failure.
- **Development of smart satellites equipped with advanced sensors:** New satellites are equipped with sensors that can measure in real time climate data like atmospheric pollution, surface temperatures, and storm intensity. This information is crucial to anticipate climate change impacts.
- **Resilient space propulsion technologies:** Space propulsion innovations are concentrated on producing systems that are more resistant to climate variations and more energy efficient. These technologies increase the lifespan and efficiency of space missions.
- **Mapping of climate risks based on satellite data:** Satellites provide a global view of climate risks, so that governments and industries can be better prepared for natural catastrophes. These mapping systems help identify vulnerable areas.
- **Artificial intelligence applications for satellites:** AI is integrated into satellites to improve their capacity to process data and optimize missions. These smart satellites can anticipate and react rapidly to climate and geopolitical changes.

Technologies play a crucial role in climate change adaptation. These technologies, supported by intensive research and development in France, provide concrete solutions to strengthen the resilience of infrastructures, improve the management of natural resources, and protect public health in the face of growing climate challenges. To maximize the impact of these innovations, it is essential to promote their wide-scale adoption, support partnerships between private and public actors, and reinforce financing mechanisms for R&D on climate adaptation.

Systemic approach and governance

05

Numerous interactions take place between sectors. This is particularly the case for energy and water, which occupy a central position. Climate change adaptation can only be effective by taking a systemic approach that integrates complex interactions between different sectors and governance levels. Other interactions include agriculture and health: climate change influences food security and public health, making it essential to integrate these sectors. The information systems and forms of organization that manage systemic interactions are also central to this transversality. They require an approach focused on reducing their carbon emissions and optimizing their use of energy. Adopting resilient agricultural practices, like agroecology and the selection of drought-resistant crops, helps to secure food supplies while reducing the use of pesticides, thus limiting water contamination. In parallel, the spread of vector-borne diseases like dengue fever and chikungunya calls for closer coordination between the agricultural and health sectors to proactively manage vectors. Also noteworthy are the interactions between urban planning and transportation, where infrastructures need to be adapted to better resist climate impacts like floods and heat waves. In addition, integrating urban densification and public transport policies into urban planning can reduce the dependence on private vehicles and limit greenhouse gas emissions. Investments, like by Vinci into resilient roads and the development of public transport infrastructures, reinforce urban mobility and cities' resilience. Detailed local models are indispensable to predict the climate risks specifically affecting infrastructures and optimize adaptation plans. Lastly, information systems, fed by advanced digital technologies like artificial intelligence and communication networks, play a key role in the coordination of systemic efforts. Nevertheless, these systems also have a significant energy footprint and efforts need to be made to reduce it. Detailed local models are also indispensable to anticipate climate risks specific to infrastructures and optimize adaptation plans.

5.1. Interconnections between sectors

Energy and Water

The energy and water sectors are closely interconnected. For example, nuclear and thermal power plants rely on water for cooling purposes. The intensification of droughts and the increasing scarcity of water make it imperative to develop cooling systems that use less water. EDF is actively working on optimizing cooling systems to reduce water consumption, in particular in regions vulnerable to drought. Hydropower, another example, depends on the availability of water to produce electricity.

Energy and Information Systems

Information systems, which play a coordination role in all sectors, require a stable, decarbonized supply of energy. The interconnection between energy and information systems is crucial to manage systemic interactions. Smart grids, supplied by advanced digital solutions, can be used to improve the resilience of energy networks and to support the electrification of transport and the integration of renewable energy, while reducing greenhouse gas emissions.

Water and Agriculture

Agriculture consumes a great deal of water. Irrigation of farmland must be managed taking into account the resources available to avoid competition between uses. More effective irrigation techniques and water management systems are crucial to ensure that agriculture does not disrupt the water supply. At the same time, sustainable agriculture can play a role in the protection of water resources through practices like agroecology.

Water and Health

Water plays an essential role in public health, both as an essential resource, and as a vector of diseases if it is contaminated. Climate change increases the frequency of drought and drinking water shortages, exacerbating health challenges. Efficient water management is crucial to avoid the propagation of diseases and guarantee access to quality water.

Water and Urban Planning

Urban infrastructures are reliant on water resources management. Rainwater management, resistance to flooding, and the water supply pose increasing challenges as cities grow and the climate gets hotter. Solutions like rainwater retention and urban greening to limit heat islands can contribute to improving water management in urban environments.

In addition to the central position played by water, other interactions include the following:

Agriculture and Health

Climate change influences food security and public health, making it essential to integrate these sectors. The public research institute INRAE underlines the importance of developing resilient farming practices like agroecology and the selection of drought-resistant crops to secure food supplies and limit the impacts on health, in particular by reducing the use of pesticides. In addition, the increasing spread of vector-borne diseases like dengue fever and chikungunya calls for close collaboration between the agricultural and health sectors to proactively manage the vectors.

Urban Planning and Transport

Urban planning and transport are also interdependent. Transport infrastructures must be adapted to resist climate impacts like floods and heat waves. In parallel, urban densification and public transport development policies need to be integrated into urban planning to reduce the reliance on private vehicles and minimize greenhouse gas emissions.

5.2. Synergies and optimization of resources

— **Optimization of investments:** Investments can by optimized by taking a systemic approach that involves identifying synergies between the different sectors. For example, smart grids not only improve the resilience of the electricity network, they also make it easier to integrate renewable energy, manage electricity demand, and electrify transportation. These technologies reduce greenhouse gas emissions while improving energy resilience, which makes them a key solution for several sectors at once.

— **Reduction of costs and negative impacts:** A systemic approach can also lead to lower costs and avoid rebound effects or non-intentional negative impacts. For example, the introduction of water-saving irrigation technologies into agriculture must be coordinated with energy needs to avoid an increase in electricity demand, which counteracts efforts to reduce GHG emissions in the energy sector.

— **Integrated risk management:** The integrated management of climate risks, which takes into account interactions between the different sectors, is essential to guarantee the resilience of critical infrastructures. For example, Enedis is working on integrating electricity networks with transport infrastructures and water management systems to minimize service interruptions and guarantee an effective response in the case of natural catastrophes. This integration means that responses to climate crises can be more effectively coordinated, by optimizing the use of available resources and minimizing collateral damage.

5.3. Coordination and governance

— **Intersectoral coordination:** Coordination between the different sectors is essential for the effective implementation of a systemic approach. This coordination must be facilitated by adapted governance structures, which encourage collaboration between ministries, companies, local authorities and research institutions. This coordination also relies on robust information systems capable of centralizing data and facilitating decisions. The French Ministry of Ecological Transition, which works with other ministries and agencies like ADEME, plays a key role in coordinating adaptation efforts in France.

— **International cooperation:** Anticipating climate phenomena at local level is particularly difficult due to the current limitations of models. To overcome these obstacles, it is essential to develop and improve modelling tools, such as by using technologies like satellites and artificial intelligence. Closer international cooperation in this domain is necessary to ensure more precise forecasting. In addition, technological advances rely on collaboration with major players in the digital sector, which raises issues related to the global governance of these tools.

— **Standards and platforms for sharing intersectoral data:** A successful systemic approach requires setting up platforms to share information and facilitate sharing data and best practices between sectors. These platforms make it easier to understand the interconnections between the different sectors and develop integrated solutions for climate adaptation. Initiatives like intersectoral conferences and cross-cutting working groups contribute to this collaboration and to the standardization of adaptation strategies. Sectors and territories increasingly share data , but obstacles remain, such as the lack of consensus on standards and exchange protocols. It is important to define international standards to regulate data sharing and guarantee smooth communication. Without a common standards framework, such as those that exist in the digital sector, it will be difficult to carry out effective widescale exchanges.

A systemic approach to climate change adaptation is clearly necessary to coordinate efforts between the water, energy, agriculture, urban planning, health, industry, transport, space and defence sectors. The transversality of energy and information systems also appears to be a central axis of systemic adaptation to climate change. A coordinated, low-carbon approach is essential to maximize adaptation strategies and synergies between sectors, optimize investments by bringing down costs, and reduce risks while ensuring sustainable resilience.

Conclusion

06

The following overview sums up the main issues identified and the technological solutions envisaged, with an accent on the importance of taking a systemic approach and underlining positive synergies between adaptation and mitigation.

6.1. Issues and solutions, sector by sector

Water:
Issue: On the one hand, water stress, made worse by periods of drought and prolonged heat, is threatening water resources in numerous regions of France, including its quality, bringing health risks. On the other hand, floods caused by more intense, concentrated rainfall put homes, infrastructures and soils in danger.

Solution: It is indispensable to establish a national strategy on water management and supply. This includes action like storage, continuing research into water desalination, recharging groundwater using correctly treated wastewater, maintaining the vast supply network and reducing leaks, and optimizing irrigation systems. It is also crucial to improve water uses, by eliminating unnecessary consumption and avoiding demand peaks, such as through awareness-raising campaigns targeting more responsible behaviour.

Action to combat flooding comprises the constant reinforcement of critical infrastructures, which should be equipped with sensors to monitor their state, better climate forecasting at local scale, more frequent satellite imagery, and the development of scenarios and warning and assistance plans in the case of extreme events.

Energy and Telecommunications:
Issue: These sectors are particularly vulnerable to climate change impacts. Heat waves, storms and floods can seriously perturb production, and in particular electricity supply and the dissemination of information.

Solution: Mechanically reinforcing power cables or placing them underground considerably reduces their vulnerability. Another solution for the electricity network is to decentralize control using smart grids, and to create local storage capacities.

Agriculture:
Issue: Agriculture faces huge challenges due to droughts, flooding and extreme temperatures, threatening both food security and the economic viability of farms.

Solution: Part of the solution is to manage water more effectively. Another approach combines agroecological water usage with the adaptation of farming practices: development of new crop varieties and establishment of rotations to continually exploit the soil, while maintaining and improving its quality.

Some of these changes could be rapidly perceived as win-win solutions for agricultural value chains, although they are currently still held back by structural inaction and constraining regulations.

INRAE plays a key role in researching these solutions, and scientific advances in microbiology play an increasingly large part.

Cities and Buildings:
Issue: Urban infrastructures and buildings are increasingly exposed to heat waves and floods, which threatens the health and safety of inhabitants and risks damaging infrastructures.

Solution: Part of the response is thermal renovation. In addition to protecting against the cold, rising temperatures represent a danger for health and require protection. Ventilation is another key factor. Buildings operate like systems, and the main difficulty lies in carefully putting together technical elements while coordinating the numerous levels of decision-making and execution.

Prescriptions, standards and support should also be more based on building physics and materials sciences. In addition, it would be pertinent to improve information to help make decisions and adjust behaviour. Technological innovations, like thermal insulation, heat pumps, high-performance concrete, and materials recycling can play an important part. Urban planning also plays a central role: making cities more habitable and sustainable is a major objective.

Urban greening can help reduce heat islands, although its impact on the indoor temperature of housing is limited. Urban sprawl into risk zones should also be closely monitored.

Industry:
Issue: Industry is vulnerable to extreme climate events, which can interrupt production, damage installations, disrupt supply and dispatch chains, and increase maintenance costs. In parallel, industry can play a key role in developing more resilient, recyclable products.

Solution: This requires investments into protecting installations and innovations in processes and product design.

Transport:
Issue: Transport infrastructures are vulnerable to extreme weather events, which can perturb mobility, safety and service quality, with considerable economic consequences.

Solution: French infrastructures, including roads, railways, and airports, are of high quality. The main issue involves increasing their maintenance to take into account the rise in climate risks.

In parallel, intermodality, which is one of the main evolutions – in particular the rise of electric vehicles – will require better coordination and smoother information transmission. The development of digital and smart grids will play a key role in this transition.

Health:
Issue: Climate change aggravates health risks due to the increased frequency of heat waves and wider geographic spread of vector-borne diseases, which put health systems under pressure.

Solution: Developing integrated health surveillance and early warning systems is essential to anticipate and respond effectively to climate-related health crises. It is also necessary to modernize healthcare infrastructures, in particular in the most vulnerable areas.

Defence:
Issue: Armed forces and defence infrastructures are increasingly exposed to threats related to extreme climate conditions likely to compromise operational preparation and the capacity to react fast in times of crisis.

Solution: It is essential to strengthen cyber-defence systems, improve the resilience of military bases in the face of natural catastrophes, and develop advanced surveillance technologies (drones, satellites) to anticipate the risks related to geopolitical and climate changes. Another priority is to develop materials and infrastructures capable of resisting extreme conditions.

Space:
Issue: The space sector plays a key role in monitoring the impacts of climate change. Images and data provided by satellites are crucial for forecasting and climate models, visualizing situations and warnings, and for monitoring the state of soil and water.

Solution: More precise images are required that cover a much wider range of domains, ideally in real time. This calls for the deployment of more satellites, the development of new instruments, and closer international cooperation.

6.2. Overview

Risk evaluations and scenarios: These must be updated and improved as climate conditions evolve and scientific knowledge progresses. Although models and climate forecasts still fall short in terms of certainty, precision and coherence, they are becoming more precise thanks to international cooperation, and the same is true for observation and monitoring instruments. This progress will usefully benefit from the mapping of risk areas, risk management, and adaptation plans.

Systemic approach, cooperation and coordination: Climate change adaptation requires a systemic approach that takes into account the interdependence between physico-chemical phenomena and the different sectors of activity, while optimizing the integration of technological solutions. It must also associate all stakeholders, including citizens, and clarify responsibilities. This requires effective coordination of public policies, from European scale to local communities, reinforced support for both public and private technological innovation, and more information and awareness-raising aimed at public opinion.

Financing, consideration of existing capital, changes needed: Judging the amount of investment needed for adaptation remains a challenge, even though the benefits are more immediately visible than for mitigation. Taking a cost-benefit approach, one method involves measuring the damages avoided, which is what insurance companies attempt to do.

This challenge is nevertheless made slightly easier thanks to the synergy with investments into mitigation, for example for electricity networks. In addition, a large share of expenditure is already met by operators pursuing a public service mission. France benefits from some of the most efficient infrastructures in Europe – railways, roads, electricity, telecommunications – constituting a considerable asset. Maintaining and improving these infrastructures could be part of the national adaptation effort.

The main changes required do not involve major expenditure. They mostly concern organization, coordination, information and adoption by actors. These issues are particularly crucial in the sectors of water, agriculture, urban planning and transport.

6.3. R&D requirements

Climate change adaptation calls for significant research and development (R&D) efforts that combine technological innovations, scientific modelling and interdisciplinary approaches. These efforts must draw from existing R&D on the mitigation of climate change impacts, and add another objective, i.e. guaranteeing the resilience of systems in extreme conditions.

Priority themes for technological R&D

1. **Energy and smart grids:**
   - Balance and control of a decentralized electric grid integrating intermittent sources and inter-seasonal storage solutions.
   - Flexibility and availability of nuclear power stations in extreme conditions.
   - Development of smart grids, batteries and new technologies to inject renewable sources.
   - Resilience of energy infrastructures to deal with disruptions and attacks (e.g. cybersecurity).
2. **Electrification and industrial processes:**
   - Transition towards electricity-powered industrial processes, reducing reliance on external energy supplies.
   - Optimization of energy efficiency in critical manufacturing sectors.
3. **Data processing and artificial intelligence (AI):**
   - Development of large computers, servers and databases for climate modelling.
   - Emergency simulation and processing of massive quantities of data related to extreme climate events.

These focus areas constitute strategic challenges, often subject to strong international competition and sovereignty issues.

Adaptation-focused R&D

Research specifically dedicated to adaptation receives less media attention but is nevertheless essential to protect people and ecosystems in the face of more intense climate disruptions. This research, which often involves international partnerships, is crucial in the mid to long term. The priorities include:

1. **Modelling and observation :**

— Improvement of climate models for greater precision in time and space.

— Development of instruments to measure air, water and soil, including by satellite, and processing of the corresponding data.

— Simulation of extreme events (floods, storms, heat waves) and their impacts on infrastructures and populations.

2. **Biological and environmental sciences:**

— Microbiology, to better understand the interactions between living organisms, improve soil quality, optimize agriculture and forests, and study the impacts of the environment on human microbiota.

— Study of interactions between water, plants and bacteria, in particular the bacterial content of water and how temperature impacts its quality.

— Analysis of the combined effects of heat and humidity on human health.

3. **Construction and standards:**

— Building science, including the design of resilient, low-energy structures.

— Establishment of scientific bases for the evolution of building standards and rules adapted to future climate conditions.

4. **Economic and sociological aspects:**

— Economic assessment of the investments into adaptation and analysis of the short- and long-term benefits.

— Study of value chains to optimize the effectiveness of public support.

— Research into the social acceptability of the necessary changes, flexibility of behaviour, and adoption of the solutions proposed.

Importance of interdisciplinary approaches

In addition to these technological priorities, the human and social sciences are indispensable to understand the complex interactions between technologies, human behaviour, and regulatory frameworks. Cooperation between disciplines is essential to meet the challenges of adopting adaptation solutions and effectively implementing climate strategies.

Synoptic Table of Priority Action for Climate Change Adaptation in France

Domain	Key Technologies	Impact	Technical Readiness	Acceptability Economic and social
Water	Reuse of treated water Groundwater recharge Water desalination	Average High Average	Average Average Average	Average Average Average
Energy	Reinforcement of supply networks Development of smart grids Energy storage (batteries, pumped storage hydropower)	High High High	Strong Average Average	Strong Average Average
Agriculture	Selection of resistant varieties Agroecology and agroforestery Optimization of irrigation and micro-irrigation	High High High	Strong Average Strong	Average Average Average
Cities & Buildings	Adaptation of buildings to heat Management of rainwater and flooding Resilient urban planning (cool islands)	High High Average	Strong Average Average	Average Average Forte
Health	Development of warning systems for heat waves Proactive management of health risks	Average Average	Moyenne Moyenne	Average Average
Industry	Modernization of energy infrastructures Supply chain security Resilience of production tools	High High Average	Average Average Average	Strong Average Average
Transport	Reinforcement of infrastructures Development of new transport technologies	High Average	Average Average	Strong Average
Defence	Resilience of bases and infrastructures Adaptation of military vehicles and equipment	Average Average	Strong Strong	Average Average
Space	Satellite surveillance of climate impacts Development of satellite relay capacities in case of crisis	High Average	Strong Average	Strong Average

Moderate = Average • **Strong** = Significant • **High** = Critical

Annexes

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